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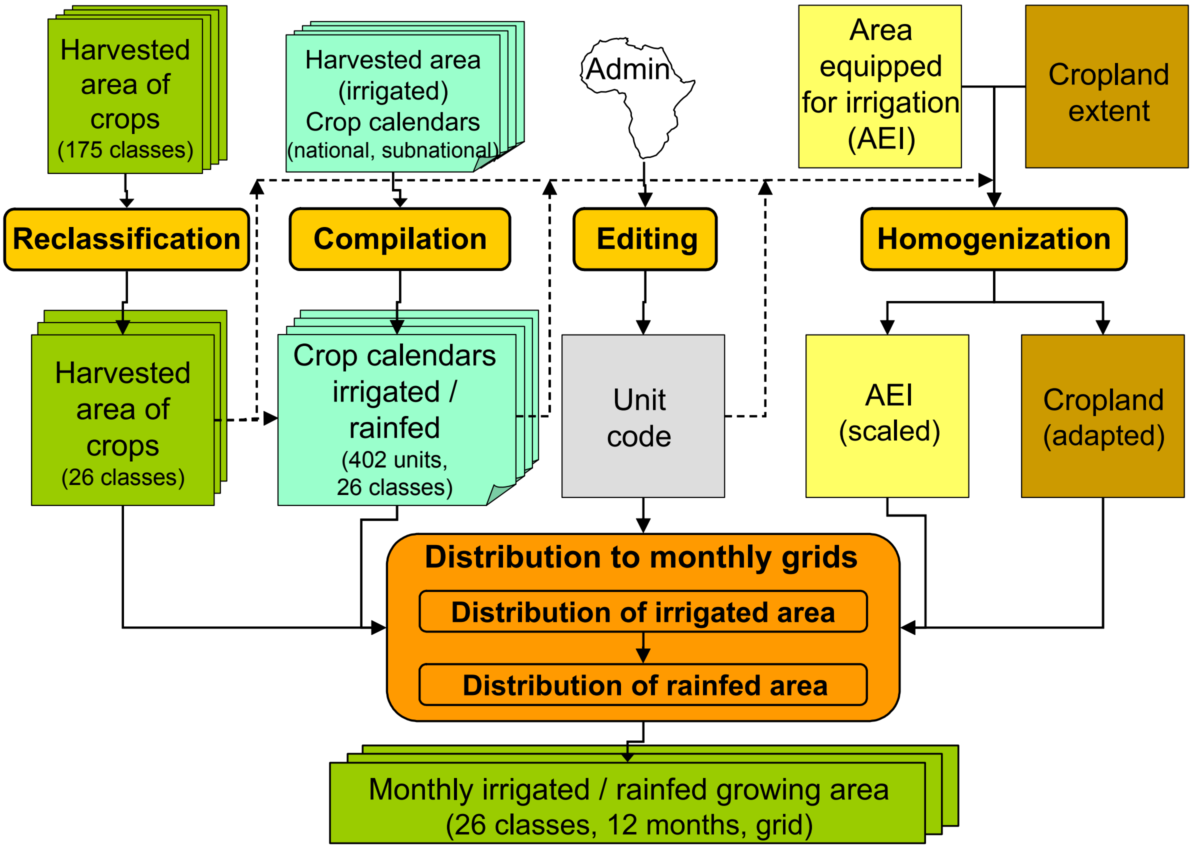
Global estimation of monthly irrigated and rainfed crop areas on a 5 arc-minute grid



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Global estimation of monthly irrigated and rainfed crop areas on a 5 arc-minute grid

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zur Erlangung des Doktorgrades
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von
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Summary

Agriculture of crops provides more than 85% of the energy in human diet, while also securing income of more than 2.6 billion people. The foundation of global food security is built on four major cereal production systems, two of which are based on irrigation of rice and wheat and that include multi-cropping, too, while the other two are based on cultivation of maize and wheat under favorable rainfed conditions. To investigate past, present and future changes in the domain of 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. The current global land use or land cover data sets are based on remote sensing and agricultural census statistics. In general, these only contain one or very few classes of agricultural land use. When crop-specific areas are given, no distinction of irrigated and rainfed areas is made, whereas it is necessary to distinguish rainfed and irrigated crops, because crop productivity and water use differ significantly between them.

To support global-scale assessments that are sensitive to agricultural land use, the global data set of Monthly Irrigated and Rainfed Crop Areas around the year 2000 (MIRCA2000) was developed by the author. With a spatial resolution of 5 arc-minutes (approximately 9.2 km at the equator), MIRCA2000 provides for the first time, spatially explicit irrigated and rainfed crop areas separately for each of the 26 crop classes for each month of the year. The data set covers all major food crops as well as cotton. Further crops are grouped into three categories (perennial, annual and fodder grasses), covering the complete crop production on cropland and enabling a holistic calculation of water fluxes. Also for the first time, crop calendars were consistently linked to annual values of harvested area at the 5 arc-minutes grid cell level, such that monthly growing areas could be computed that are representative for the time period 1998 to 2002. Finally, MIRCA2000 is the first global agricultural land use data set that includes multi-cropping and that covers both large and small countries and also islands all around the world.

The MIRCA2000 data set includes four core product subsets, each separately for 26 irrigated and 26 rainfed crops:

1) 5 arc-minute grid cell level Monthly Growing Area Grid (MGAG),
2) 5 arc-minute grid cell level Maximum Monthly Growing Area Grid (MMGAG),
3) 5 arc-minute grid 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).

In addition to that, two more products were developed:

5) 5 arc-minute grid cell level Maximum Monthly Cropped Area Grids for the sum of all irrigated and rainfed crops (MMCAG), and
6) 5 arc-minute grid cell level annual harvested area (AH) for each of the 26 irrigated and 26 rainfed crops and their group-specific total (AHI & AHR).

To generate MIRCA2000, harvested area of irrigated crops was provided from agricultural census statistics at national and sub-national level [for irrigation e.g. *EUROSTAT*, 2007b; *FAO*, 2005a; *USDA and NASS*, 2004]. Crop calendars defining start and end of cropping periods were obtained from several inventories or national reports, and were available for 142 individual countries but mostly for selected crops only [e.g. *FAO*, 2005a, 2005b; *USDA*, 1994]. Climatological data of FAOCLIM2 [*FAO*, 2001] helped to validate and extend the crop calendars to further (especially rainfed) crops and countries. Grid-based input data included cultivable area in form of cropland extent [*Ramankutty et al.*, 2008], total harvested area [*Monfreda et al.*, 2008], and area equipped for irrigation [*Siebert et al.*, 2007]. During the spatial downscaling of the crop calendars of the final 402 spatial units, consistency between the monthly growing areas, the cultivable area in form of cropland extent and area equipped for irrigation has been maximized.

According to MIRCA2000, about 25% of the global harvested areas of about 13 million km^2 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. Alike, the share of irrigated harvested area is larger than the area equipped for irrigation that equals 18% of the total cropland extent. 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 the data set consistently for the calculation of crop water productivity in the Global Crop Water Model (GCWM) [*Siebert and Döll*, 2010], 33% of global crop production and 44% of total cereal production were found to come from irrigated agriculture. 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.

Most of the monthly growing area of these three dominant crops and of cotton is located in the Northern Hemisphere, where the irrigated share is much larger and where the irrigated growing area of rice is larger than the respective rainfed area. The seasonal cycle of irrigated rice reflects multi-cropping in the major production regions, with two peaks in July to August and November to February, and a relative maximum during the summer season of each hemisphere. In contrast, the rainfed crops in general have unimodal seasonal cycles, except wheat with two peaks in June and in November, depending on multi-cropping of winter and summer varieties. The consistent calculation of crop water consumption with GCWM showed that the seasonal rainfed (green) water consumption globally peaks in July, with somewhat lower values in August, while irrigation (blue) water consumption has two peaks, a major in July to August, and a minor in March. Globally, rice follows this general pattern, cotton has always its peak consumption in July and August, while wheat has its peak consumption in April to May as rainfed crop and in March to April as irrigated crop [*Siebert and Döll*, 2010].

The methodology, quality and results of MIRCA2000 were discussed. The data set is the result of processing a large amount of different data at different spatial scales such that maximal consistency is achieved. Quality parameters on e.g. crop occurrence, crop classification accuracy, and grid cell level deviation from the input data are given and are discussed with respect to scaling issues. The spatial pattern of cropping intensity which results from the monthly growing areas appears to be plausible. This supports the validity of the chosen approach. Comparison to a sub-national European data set showed that MIRCA2000 reflects rather well the differences in irrigated harvested area of maize and grapes among countries (calendar units) but not necessarily within countries. This is due to the application of only one crop calendar per country in Europe. Decreasing the size of the spatial units of the crop calendars should decrease the differences.

The comparison of growing periods between data-based MIRCA2000 and the dynamic global vegetation model LPJmL, which simulates growing periods using biophysical constraints, reveals different strengths and weaknesses of the approaches. While LPJmL allows that, with the exception of double cropping of rice, only one sub-crop can be represented within the same grid cell, e.g. either winter or summer wheat, MIRCA2000 allows more than one until a maximum of five, e.g. rainfed upland rice, deepwater rice, and three growing periods of paddy rice. The simplification is especially critical for the currently prevailing grid cell resolution of 0.5 degrees in global models and the resulting inconsistency to census statistics. Besides, human decisions on crop production and crop rotation are based on complex reasoning that cannot be captured by macro-scale modeling approaches. In MIRCA2000, such long-term average decisions can implicitly be included in the crop calendars. While MIRCA2000 represents wheat in tropical zones, LPJmL fails to model correctly wheat growth in tropical Africa and northern India. Nevertheless, future work should be invested in improving grid cell level data of harvested area that are an input to MIRCA2000. More 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.

MIRCA2000 has an unsurpassed level of detail covering large and small countries alike. In contrast to other datasets that represent only dominant crops, it contains shares of each of the 26 crop class in each 5 arc-minute grid cell, so that the grid cell level sub-national spatial distribution should be better represented. It is a valuable basis for many different applications, with the scope on the global present day situation. So far, it has been applied to estimate extent of fallow land and crop land use intensity, crop yield gap, blue and green crop water use, crop water productivity, and virtual water content. Further applications could include the quantification of virtual water flows and water footprints, studies on food security and other agricultural aspects, as well as assessments that require a good characterization of crop production, especially the area and seasonality of irrigated crops.

Zusammenfassung

Landwirtschaft von Feldfrüchten stellt mehr als 85% der Energie für die menschliche Ernährung bereit. Gleichzeitig ist sie für mehr als 2,6 Milliarden Menschen eine wichtige Einkommensquelle. Die Basis dieser globalen Ernährungssicherung bilden vier große Getreide-Produktionssysteme: Zwei beinhalten Bewässerung und Mehrfachanbau, im Zweifach- oder Dreifachanbau von Reis und in der Reis-Weizen-Fruchtfolge. Die anderen zwei bilden der Regenfeldbau von Mais beziehungsweise Weizen. Um die Verfügbarkeit von Nahrungsmitteln unter Berücksichtigung von Wasserressourcen, Nährstoffen und Intensität des Managements für die Vergangenheit, die Gegenwart und die Zukunft zu untersuchen, muss die Flächennutzung in der Landwirtschaft bekannt sein, insbesondere, welche Feldfrüchte wo und wann angebaut werden. Die bisherigen globalen Datensätze zur Landnutzung basieren auf Fernerkundungsdaten oder landwirtschaftlichen Statistiken. In der Regel werden in diesen nur eine oder wenige Klassen landwirtschaftlicher Bodenbedeckung ausgewiesen. Wenn feldfruchtspezifische Flächen erwähnt sind, dann ohne Unterscheidung bewässerter Flächen und Regenfeldbau. Genau diese Unterscheidung ist wichtig, da sich die entsprechenden Flächen im Hinblick auf Produktivität, Wassernutzung und Konkurrenz zu anderen Sektoren deutlich unterscheiden. Bewässerungskulturen benötigen „blaue“ Wasserressourcen aus Grundwasser und Oberflächengewässern, die auch von Industrie und Haushalten genutzt werden und ökologisch bedeutsam sind (Feuchtbiotope), während die im Regenfeldbau benutzten „grünen“ Wasserressourcen keine Nutzungskonkurrenz aus diesen Sektoren haben.

Um entsprechende Untersuchungen zu unterstützen, wurde vom Autor der globale Datensatz monatlicher Anbauflächen bewässerter und Regenfeldbau-Feldfrüchte charakteristisch für das Jahr 2000 (*Monthly Irrigated and Rainfed Crop Areas around the year 2000*, MIRCA2000) entwickelt. Der Landnutzungsdatensatz hat eine Auflösung von 5 Bogenminuten (etwa 9,2 km am Äquator) und ist repräsentativ für die Zeitspanne 1998 bis 2002. MICRA2000 kombiniert Ernteflächenstatistiken mit Anbaukalendern. Als erstes globales Produkt unterscheidet es räumlich explizit zwischen bewässerten Anbauflächen und solchen, die im Regenfeldbau bewirtschaftet werden. Die Anbauflächen werden differenziert für jeden Monat im Jahr und für 26 verschiedene Feldfrucht-Klassen zur Verfügung gestellt. Der Datensatz beinhaltet alle für die menschliche Ernährung wichtigen Feldfrüchte, Baumwolle und unspezifische jährliche Kulturen, Dauerkulturen, sowie Futtergräser. MIRCA2000 ermöglicht so insbesondere eine Berechnung der blauen und grünen Wasserflüsse und legt die Grundlage zur Ermittlung virtueller Wasserflüsse, die feldfruchtspezifisch sein müssen. Schließlich stellt MIRCA2000 den ersten globalen Landnutzungsdatensatz dar, der Mehrfachanbau berücksichtigt und gleichzeitig große wie kleine Länder und auch Inseln weltweit abdeckt.

Der MIRCA2000-Datensatz beinhaltet vier Kern-Produkte, jedes getrennt für 26 bewässerte und 26 im Regenfeldbau angebaute Feldfrüchte:

1) Monatlich bestellte Fläche im Gitter (*Monthly Growing Area Grid*, MGAG) mit 5 Bogenminuten Auflösung,
2) Maximale monatlich bestellte Fläche im Gitter (*Maximum Monthly Growing Area Grid*, MMGAG) mit 5 Bogenminuten Auflösung,
3) Liste der Anbauperioden (*Cropping Period List*, CPL, mit Ernteflächen, Beginn und Ende der Anbauperioden) auf 5 Bogenminuten - Gitter,
4) Klassifizierte Feldfrucht-Anbaukalender auf dem Niveau von 402 räumlichen Einheiten (*Condensed Crop Calendars*, CCC, d.h. CPL auf Niveau der räumlichen Einheiten).

Zusätzlich wurden zwei weitere Produkte entwickelt:

5) Maximale monatlich bestellte Flächen im Gitter für die Summe von bewässerten beziehungsweise im Regenfeldbau angebauten Feldfrüchten (*Maximum Monthly Cropped Area Grid*, MMCAG) mit 5 Bogenminuten Auflösung, und
6) Jährliche Ernteflächen (*annual harvested area*, AH) für die bewässerten sowie die im Regenfeldbau angebaute Feldfrüchte, für jede einzelne der 26 Feldfrucht-Klassen und für die gruppenspezifischen Summen (*irrigated harvested area* AHI und *rainfed harvested area* AHR), im Gitter mit 5 Bogenminuten Auflösung.

Methodisch basiert MIRCA2000 auf Ernteflächen, welche von landwirtschaftlichen statistischen Erhebungen auf nationalem und sub-nationalem Niveau stammen [für Bewässerung z.B. *EUROSTAT*, 2007b; *FAO*, 2005a; *USDA und NASS*, 2004]. Teilweise werden in den Erhebungen statt der Ernteflächen auch die pro Jahr mindestens einmal bestellten Flächen oder die ausgesäten Flächen angegeben. Weiterhin waren als Eingangsdaten Anbaukalender, die den Monat des Beginns und des Endes der Anbauzeiten liefern, aus einigen weltweiten Erfassungen sowie nationalen Berichten für 142 Länder verfügbar, aber meistens nur für ausgewählte Feldfrüchte [z.B. *FAO*, 2005a, 2005b; *USDA*, 1994]. Mittels klimatologischer Stationsdaten von FAOCLIM2 [FAO, 2001] zu Niederschlag und Lufttemperatur konnten diese Kalender validiert und auf weitere, insbesondere im Regenfeldbau angebaute Feldfrüchte sowie andere Länder ausgedehnt werden. Eingangsdaten mit 5 Bogenminuten Gitterauflösung umfassten Anbauflächen in Form von landwirtschaftlicher Nutzfläche (*cropland extent*, welche zeitweise nicht bestellte Brachflächen beinhaltet) [*Ramankutty et al.*, 2008], jährlicher Gesamt-Erntefläche der einzelnen Feldfrüchte (*total annual harvested area*, ohne die Unterscheidung von bewässerten und im Regenfeldbau angebauten Flächen) [*Monfreda et al.*, 2008], und für die Bewässerung ausgerüsteter Flächen (*area equipped for irrigation*) [*Siebert et al.*, 2007]. Beim Verfahren der Regionalisierung (räumliches Downscaling) der Anbaukalender der insgesamt 402 räumlichen Einheiten wurde die Konsistenz zwischen den monatlich bestellten Flächen und der bestellbaren Fläche in Form von *cropland extent* und der *area equipped for irrigation* auf verschiedenen Skalen maximiert, sowohl auf räumlicher Ebene der Einheiten als auch der Gitterzellen. Dieser Abgleich geht über die Verfahren anderer Datensätze hinaus und besitzt besondere Bedeutung für Modellanwendungen.

Die Ergebnisse von MIRCA2000 zeigen, dass rund 25% der globalen Erntefläche von 13 Millionen km^2 bewässert sind und diese eine globale Anbauintensität von 1,12 aufweisen, letztere berechnet als Erntefläche geteilt durch die bestellbare Fläche, hier inklusive zeitweise nicht bestellter Brachflächen. Ohne die Unterscheidung von bewässerten und Regenfeldbau-Flächen beträgt diese Anbauintensität global nur 0,84. Etwa 28% der 16 Millionen km^2 großen landwirtschaftlichen Nutzfläche liegen zumindest zeitweise brach. Gleichzeitig ist der genannte Anteil an bewässerter Erntefläche größer als jener 18% Anteil, welcher die für Bewässerung ausgerüstete Fläche global an der gesamten bestellbaren Fläche annimmt. Für die dominierenden Feldfrüchte Reis (1,7 Millionen km^2), Weizen (2,1 Millionen km^2) und Mais (1,5 Millionen km^2), welche 40% der globalen Erntefläche abdecken, sind 62%, 31%, beziehungsweise 20% bewässert, und etwa die Hälfte bei Zitrusfrüchten, Zuckerrohr und Baumwolle. Während Weizen und Mais die größten im Regenfeldbau angebauten Ernteflächen aufweisen (1,5 beziehungsweise 1,2 Millionen km^2), ist Reis mit eindeutigem Abstand die Feldfrucht mit der größten bewässerten Erntefläche (1,0 Millionen km^2), gefolgt von Weizen (0,7 Millionen km^2) und Mais (0,3 Millionen km^2). Die Bedeutung der Bewässerung für einzelne Feldfrüchte ist, neben Reis, am größten für Dattelpalmen mit 79% der Erntefläche, während Maniok (englisch *cassava*), Ölpalmen, Kakao und Kaffee fast ausschließlich im Regenfeldbau angebaut werden (unter 2% bewässert). Weiterhin stehen mit je etwa 1,0 Millionen km^2 Erntefläche die restlichen jährlichen Kulturen (19% bewässert) und Futtergräser (11% bewässert) an vierter und fünfter Stelle der globalen Nahrungsmittelproduktion, und die restlichen Dauerkulturen (18% bewässert) folgen kurz hinter den an sechster Stelle stehenden Sojabohnen (8% bewässert), nur wenig vor den Leguminosen (8% bewässert) (je etwa 0,7 Millionen km^2). Das zeigt, dass trotz der hohen Anteile der drei großen Getreide als Grundlage für die Welt-Ernährungssicherung, Futterpflanzen und weitere Pflanzen als die spezifisch erfassten 23 Feldfrüchte die Landnutzung zumindest regional beeinflussen. Auf MIRCA2000 konsistent basierende Berechnungen mit dem Global Crop Water Model (GCWM) [*Siebert und Döll*, 2010] zeigen, dass 33% der globalen Feldfruchtproduktion und 44% der gesamten Getreideproduktion aus bewässerter Landwirtschaft stammen. Potenzielle globale Ertragsausfälle bei einem Szenarium ohne Bewässerung belaufen sich auf 18% bei Feldfrüchten und 20% bei Getreide.

Regional gesehen befinden sich 67% der globalen für die Bewässerung ausgerüsteten Fläche und 77% der gesamten bewässerten Erntefläche in Asien. Der Anteil der bewässerten Erntefläche an der gesamten Erntefläche beträgt 41% für Asien, 13% für Amerika, 11% für Ozeanien, 9% für Afrika und 7% für Europa. Allerdings gibt es große Unterschiede zwischen den verschiedenen Kontinenten, ihren Unterregionen und den einzelnen Ländern. Jeweils unterschiedliche Feldfrüchte dominieren die Regionen und weisen damit auf die Diversität der Anbausysteme hin. In der bewässerten Landwirtschaft ist Reis der Spitzenreiter in 7 von 19 Regionen der Vereinten Nationen, was nicht überrascht, jedoch Futtergräser in immerhin 3 Regionen, Mais und Weizen in je 2 Regionen, und Zuckerrohr, Baumwolle, Kartoffeln, restliche Dauerkulturen, sowie restliche jährliche Kulturen in je einer Region. Im global dominierenden Regenfeldbau führt Weizen in 7 Regionen, Mais in 3 Regionen, Reis in 2 Regionen und Maniok, Sorghum-Hirse (englisch *sorghum*), Pennisetum-Hirse (inklusive anderer „kleiner“ Hirse-Arten wie Eleusine, englisch *millet*), Zuckerrohr, Sonnenblumen, Futtergräser, sowie restliche jährliche Kulturen in je einer Region. Dabei besitzen in den meisten Regionen die zwei dominierenden Feldfrüchte, wenn sie bewässert werden, deutlich höhere Anteile an der Erntefläche als die dominierenden Früchte im Regenfeldbau. Das deutet darauf hin, dass der Regenfeldbau vielfältiger gestaltet ist und zumindest innerhalb der Regionen weniger von bestimmten Feldfrüchten dominiert wird.

Weizen als die Feldfrucht mit der größten Erntefläche wird intensiv mit einer Erntefläche von mehr als 10% (oder sogar mehr als 30%) der jeweiligen Gitterzellenfläche im Regenfeldbau in Nordamerika, Europa, im nordöstlichen China und in Australien angebaut, und unter Bewässerung im nördlichen Indien, in Pakistan und im nördlichen China. Reis als zweitwichtigste Feldfrucht wird mit einer Erntefläche von mehr als 30% der Gitterzellenfläche im Regenfeldbau im tropischen Südost-Asien in Bangladesh, Indien, Thailand und Myanmar angebaut, aber auch mit bis zu 10% der Gitterzellenfläche im westlichen Afrika, besonders in Nigeria. Die größte Bewässerungsintensität pro Gitterzelle ist ebenfalls im genannten tropischen Südost-Asien zu finden, sowie dort wo fehlender Niederschlag durch Bewässerung ersetzt wird, nämlich in Indien, China und Indonesien, sowie bei geringerer Intensität außerhalb der Tropen in den zentralen USA, im südlichen Brasilien und im nördlichen Italien.

Die Verwendung monatlicher bestellter Flächen ermöglichte die Berechnung der maximalen und der minimalen Anbauintensität für jede Gitterzelle weltweit:

Die maximale Anbauintensität (*maximum cropping intensity*, CI_max, Erntefläche geteilt durch maximal monatlich bestellte Fläche) berücksichtigt keine Brachflächen und ist groß in Regionen wo die klimatisch begrenzte potenzielle Anbauperiode und die feldfruchtspezifische Anbaudauer es dem Bauer ermöglichen, mehr als eine Ernte einzufahren. Die potenzielle Anbauperiode ist besonders lang in den Tropen, wegen hoher Temperatur und Niederschlagssumme, sowie in den Subtropen, wo fehlender Niederschlag durch Bewässerung ausgeglichen wird. Andererseits können Anbauperioden besonders kurz sein für bestimmte jährliche Feldfrüchte wie Gemüse oder Reis. Daher liegt der aus Gitterzellen abgeleitete Wert von CI_max zwischen 0,67 für *cassava* und 3,0 für Mehrfachanbau. Weltweit haben die meisten Gitterzellen eine maximale Anbauintensität zwischen 0,8 und 1,2, sind also nur einmal jährlich bestellt. Besonders hohe Werte über 1,6 finden sich in Asien in humiden Zonen mit Paddy-Reis-Anbau (etwa China und Bangladesh) oder in semi-ariden Zonen mit Bewässerung (Nordindien und Pakistan). Werte über 1,6 finden sich auch in Afrika am Nil unter Bewässerung sowie unter Regenfeldbau-Bedingungen im südlichen Sudan, in Äthiopien und in Westafrika, dort mit kleinerer Ausdehnung. Im südamerikanischen Peru sind solche Flächen bewässert, während sie im südöstlichen Australien mit Regenfeldbau verbunden sind.

Die minimale Anbauintensität (*minimum cropping intensity*, CI_min, als Erntefläche geteilt durch die landwirtschaftliche Nutzfläche von MIRCA2000) berücksichtigt hingegen Brachflächen. Hohe Werte findet man wie bei CI_max in Regionen mit warm-feuchten Klimaten oder wo Niederschlag durch Bewässerung ersetzt wird, hauptsächlich in Asien und in Afrika. Allerdings sind die räumlichen Muster modifiziert und weniger Gitterzellen betroffen, so etwa in Afrika nicht mehr im Sudan und in Westafrika. Durchaus viele Gitterzellen weisen CI_min-Werte zwischen 0,8 und 1,2 auf, etwa in Indien und ansonsten hauptsächlich dort wo genügend Regen fällt, in Süd-Ost Asien, Europa außer Russland, nördliche Teile der USA, Zentral-Südamerika und Teile Sub-Sahara-Afrikas. Dennoch sind noch geringere Werte zwischen 0,4 bis 0,8 mit größeren Anteilen von Brachland in ähnlich vielen Gitterzellen zu finden, in den Great Plains der USA oder in Russland.

Kleine Unterschiede zwischen CI_max und CI_min in Verbindung mit einem großen Anteil an *cropland extent* zeigt einen großen Druck auf Landressourcen an, d.h. Gitterzellen in denen nicht viel Land brach fallen kann. Beeindruckenderweise finden sich diese insbesondere in Zentren hoher Bevölkerungsdichte, etwa im Osten Chinas, in Indien, Bangladesh, auf Java in Indonesien, in Nigeria, Tansania, Europa und im Nildelta. Große Differenzen treten in ariden Gebieten mit Regenfeldbau (Namibia, westliche USA, Süd-Australien und Zentral-Asien) oder in Gebieten mit Wanderfeldbau auf.

Der größte Teil der monatlich bestellten Flächen der drei dominierenden Feldfrüchte Weizen, Reis und Mais sowie jener von Baumwolle befindet sich auf der Nordhalbkugel. Dort befindet sich auch der im Vergleich zur Südhalbkugel größere Anteil bewässerter Flächen und ist für Reis die bewässerte bestellte Fläche größer als die im Regenfeldbau bestellte Fläche. Der saisonale Zyklus von Reis zeigt deutlich den Mehrfachanbau in den Hauptanbaugebieten, welche in Asien auf der Nordhalbkugel liegen, mit zwei Spitzenzeiten im Nordsommer von Juli bis August, beziehungsweise von November bis Februar. Weiterhin ist in der Sommerperiode der jeweiligen Halbkugel der Anteil der bewässerten Reisflächen an der gesamten mit Reis bestellten Fläche größer als im Winter. Im Gegensatz dazu haben die im Regenfeldbau angebauten Feldfrüchte in der Regel eingipflige saisonale Zyklen. Eine Ausnahme hiervon stellt Weizen dar, der global zwei Gipfel im Juni und im November besitzt, bedingt durch den Mehrfachanbau als Winter- und Sommergetreide, deren Flächen zeitweise nebeneinander bestellt sind.

Die Berechnung des konsumptiven Wasserverbrauchs mit GCWM zeigt, dass der globale Wasserverbrauch im „grünen" Regenfeldbau von Juli bis August am höchsten ist, während er unter Bewässerung im März ein weiteres, kleineres saisonales Maximum aufweist. Global folgt Reis diesem Schema, während Baumwolle global von Juli bis August am meisten Wasser verbraucht. Dahingegen verbraucht Weizen unter Regenfeldbau von April bis Mai am meisten Wasser, unter Bewässerung jedoch im März und April [*Siebert und Döll*, 2010].

Eingangsdaten, Methoden, Qualität und Ergebnisse des Datensatzes wurden diskutiert. Methodisch gesehen, ist der Datensatz das Ergebnis der Verarbeitung einer großer Menge unterschiedlicher Daten auf verschieden räumlichen Skalen unter Maximierung der räumlichen Konsistenz. Die Qualität der Eingangsdaten für die Ernteflächen der bewässerten Feldfrüchte wurde in einer früheren Publikation des Autors ausführlich diskutiert. Die dort erwähnten länderspezifischen Datenquellen sowie die jeweils benutzten Wege zur Klassentransformation mit Aggregation beziehungsweise Disaggregation der Ernteflächen wurden aktualisiert und vertieft. Bei der Regionalisierung sind die auf die Gitterzellen verteilten feldfruchtspezifischen Flächen beziehungsweise ihre Ernteflächen deterministisch von den Eingangsdaten der 402 räumlichen Einheiten abhängig, jedoch nicht streng linear im Sinne einer stets gleichmäßigen räumlichen Verteilung auf alle landwirtschaftlich genutzte Gitterzellen innerhalb der Einheiten. Da weiterhin mögliche Validierungsdaten eine unbekannte oder nicht identische räumliche Zuordnung besitzen, wurde eine quantitative Validierung nur mit auf der Ebene der räumlichen Einheiten aggregierten Maßen durchgeführt. Mögliche systematische Abweichungen betreffen beispielsweise jene zwischen Ernteflächen in den bewässerten Kalendern der Eingangsdaten und den aus anderer Quelle stammenden Gesamternteflächen, bei denen nicht zwischen bewässerten und im Regenfeldbau angebauten Feldfrüchten unterscheiden wird.

Ein weltweiter Vergleich mit Ländersummen der Erntefläche einer externen Datenquelle zeigt für Weizen, Reis, Mais und Sojabohnen eine ausgezeichnete Übereinstimmung.

Der Vergleich mit einem europaweiten Datensatz mit sub-nationaler administrativer Auflösung von fruchtspezifischen Ernteflächen zeigt für Mais und Trauben, dass MIRCA2000 bei bewässerten Flächen ziemlich gut die Unterschiede zwischen den Ländern, d.h. den Kalendereinheiten, wieder gibt, aber schlechter die Verteilung innerhalb der Länder trifft. Dies rührt von der Anwendung nur eines Anbaukalenders pro Land in Europa. Es wird erwartet, dass eine Verkleinerung der räumlichen Einheiten der Anbaukalender, welche in die Regionalisierung als Rahmenbedingung eingehend, die Abweichungen verringert.

Trotz der komplexen Methodik und der Einschränkungen in den Eingangsdaten erscheint das oben geschilderte räumliche Muster der Anbauintensität, welche sich aus den monatlich bestellten Flächen ergibt, plausibel und unterstreicht damit die Gültigkeit des gewählten Verfahrens.

Ein Vergleich der Anbauperioden des datenbasierten MIRCA2000 Datensatzes mit jenen des dynamischen globalen Vegetationsmodells “Lund-Potsdam-Jena managed Land” (LPJmL), das diese anhand biophysikalischer Einschränkungen berechnet, wurde durchgeführt und zeigt die Stärken und Schwächen der Ansätze. Während LPJmL mit Ausnahme von Zweifachanbau bei Reis, nur eine Anbauperiode pro Feldfrucht in einer Gitterzelle erlaubt, etwa Winter- oder Sommer-Getreide, können MIRCA2000 mehrere gleichzeitig vorhanden sein, bis zu einer maximalen Anzahl von fünf, etwa unter Regenfeldbau sowohl Hochland-Reis (*upland rice*), Tiefwasser-Reis (*deepwater rice*), und drei Anbauperioden für Paddy-Reis. Die Vereinfachung ist besonders problematisch für die im Augenblick für globale hydrologische Modelle am meisten genutzte Gitterzellengröße von 0,5 Grad und die daraus folgende Inkonsistenz zu Zensusstatistiken. Außerdem sind Entscheidungen der Bauern über Anbauzeiten und Fruchtfolge komplexen Entscheidungsverfahren unterworfen, die von groß-skaligen Modellierungsansätzen nicht wiedergegeben werden können. In MIRCA2000 sind solche langfristigen mittleren Entscheidungen implizit in den Anbaukalendern enthalten. Während MIRCA2000 Weizenanbau in den Tropen immer berücksichtigt, gibt LPJmL Weizenanbau im tropischen Afrika oder im Norden Indiens nicht vollständig wieder. Zukünftige Arbeit sollte in die Verbesserung der Ernteflächen in den Gitterzellen investiert werden. Bei der Regionalisierung der Zensusdaten der Ernteflächen könnten im Gegensatz zum gegenwärtig genutzten Ansatz mehr biophysikalische Beschränkungen berücksichtigt werden. Bislang werden hierbei Beschränkungen nur für ausgewählte im Winter angebaute Getreide der gemäßigten Klimazonen (Weizen, Roggen und Gerste) angewendet. Weiterhin könnte die Methode der zeitlichen Disaggregation der Anbaukalender auf die monatlich bestellten Flächen in den Gitterzellen um detaillierte biophysikalische Beschränkungen oder Bevorzugungen erweitert werden, die in eine Priorisierung bestimmter Anbauperioden münden.

MIRCA2000 deckt mit bislang unerreichter Detailliertheit große wie kleine Länder mit räumlich expliziten Daten ab. Der Datensatz ist eine wertvolle Basis für viele verschiedene Untersuchungen der heutigen globalen Situation. Bislang wurde er in Studien zur Abschätzung der Ausdehnung von Brachflächen, der Anbauintensität, der Ertragsverbesserung durch Bewässerung, „blauen“ und „grünen“ Anteilen des Wasserbedarfs in der Landwirtschaft, der Produktion pro eingesetzter Wassermenge, und des virtuellen Wassergehaltes eingesetzt. Weitere mögliche Anwendungen sind unter anderem die quantitative Abschätzung von Flüssen virtuellen Wassers und von Wasser-„Fußabdrücken“ einzelner Länder und Flusseinzugsgebiete, die ähnlich wie andere ressourcenbasierte Fußabdrücke berechnet werden können, sowie Untersuchungen zur Ernährungssicherung und zu vielen weiteren Fragestellungen, zu deren Beantwortung eine detaillierte Wiedergabe der Anbau-Verhältnisse, insbesondere der räumlichen wie zeitlichen Verteilung bewässerter Feldfrüchte, benötigt wird.

Table of contents

Supplement:

List of figures

Here only figures of the main document until Appendix H are listed. For the supplementary Appendices I, K and L separate lists, if applicable, are found at the beginning of these Appendices.

Figures in the text

Figures in Appendices A – H

List of tables

Here only tables of the main document until Appendix H are listed. For the supplementary Appendices I, K and L separate lists, if applicable, are found at the beginning of these Appendices.

Tables in the text

Tables in Appendices A – H

1 Introduction

1.1 Importance of irrigated and rainfed crops, global land use data sets, and the novel MIRCA2000 data set

The survival and well-being of humanity depends on agricultural production which is sustained by rainfall and irrigation. Food security depends on the physical basis of crop growth on field plots and on additional socio-economic factors and, of course, on climate change that may change the input factors. This thesis essentially aims to enlarge the often scarce knowledge on the spatially explicit distribution of crops at global scale, separating rainfed and irrigated crops. The work uses as input data appropriate global land use data sets. Thus, it enables more detailed analyses related to the source of water used for production, e.g. stress on water resources or flows of so-called virtual water as explained below. In this Chapter, first the necessity to distinguish irrigated from rainfed crops is demonstrated (Chapter 1.1.1), and the terminology of land use versus land cover is clarified (Chapter 1.1.2). Then, the general aspects of global land use and land cover data sets (Chapter 1.1.3), as well as the usage of irrigation in global hydrological models (Chapter 1.1.4) are described. Finally, the products of the novel MIRCA2000 land use data set developed by the author are presented (Chapter 1.1.5).

1.1.1 Importance of irrigated and rainfed agricultural land

Agricultural land is of paramount interest for human food security. Agriculture of crops provides more than 85% of the energy in human diet and supports the income of more than 2.6 billion people [*FAO*, 2007b, 2007c]. Cereals provide on global average 47% of the human diet energy (period 2001 - 2003), but may be up to 82% in case of Bangladesh. In humid tropical countries, cereals in human diets are partially substituted or extended by roots and tubers [*FAO*, 2007b]. The three main cereals wheat, rice, and maize provide about 60% of human diet energy [*Cassman*, 1999]. According to the current knowledge, the foundation of global food security is built on four major cereal production systems in which modern farming practices are used. These land use systems include: (i) irrigated annual double- and triple-crop continuous rice systems in the tropical and subtropical lowlands of Asia, which account for about 25% of global rice production, (ii) irrigated annual rice-wheat double-crop system, which is the primary cereal production system in northern India, Pakistan, Nepal, and southern China, (iii) temperate maize-based, rainfed cropping systems of the North American plains, which contribute more than 40% of global maize supply, (iv) the favorable rainfed wheat systems of northwest and central Europe, which account for more than 20% of global wheat supply [*Cassman*, 1999: 5952]. Remarkably two of them are based on double- or triple-crop systems with irrigation, while the other two are annual rainfed systems.

To investigate past, present and future changes in the domain of 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. In addition to that, food produced on irrigated and rainfed areas is traded on sub-national, bi-national and global level. Therefore, like for energy, the location of production is not anymore the location of consumption. As a consequence, consumption e.g. in Europe has an impact on the water balance of the Aral Sea in Central Asia. The concept of "virtual water", also called "embedded water" or "hidden water", fills this knowledge gap when associated quantitative values are calculated. Virtual water is the water needed to produce agricultural commodities (or, in principle, other commodities) [*Allan*, 2003; *Chapagain and Hoekstra*, 2004a], the virtual water content being the amount of water needed to produce a standard quantity, e.g. expressed in m^3 per kg, and the crop water productivity being the inverse ratio. It results in the "water footprints" of countries in analogue to ecological footprints that consider the conversion of areas of natural ecosystems to man-made ecosystems [*Chapagain and Hoekstra*, 2004a, 2004b; *Haddadin*, 2007; *Berrittella et al.*, 2007].

Since crop productivity and water use differ significantly between rainfed and irrigated agriculture [*Bruinsma*, 2003; *Rost et al.*, 2008a; *Rost et al.*, 2008b; *Saseendran et al.*, 2008; *Döll et al.*, 2009] it is furthermore required to distinguish rainfed and irrigated crops. From a farmer's perspective, irrigation reduces or minimizes the risk of failure to harvest and secures food productions of other inputs, as do other techniques such as fertilizer inputs, choice of appropriate crop varieties, etc. An alternative for irrigation would be to minimize the inputs. But where natural precipitation is small and water is available, irrigation replaces natural precipitation. In addition, supplementary irrigation might support natural precipitation for bringing higher and more secure yields. On the other hand, irrigation is a relevant cultural factor and common practice in countries with small natural precipitation heights such as Egypt, Iraq, Pakistan, and India. Irrigation is also practiced with multiple cropping in tropical humid climate zones of countries like China where high rural population densities have to be supported. Irrigation increases the yields of cereals to about the double of the rainfed crops for developing countries [*Bruinsma*, 2003]. Even higher increases are possible in developed countries [*Saseendran et al.*, 2008]. About 60% of the cereal production in developing countries was from irrigated fields in 1997 – 1999 [*Bruinsma*, 2003].

Furthermore, human societies and food production depend on both so-called "blue water" (the water available in rivers, lakes, reservoirs [*Postel et al.*, 1996] and groundwater aquifers [*Döll et al.*, 2006], and used e.g. for irrigation) and "green water" (the precipitation water that is stored in the soil and eventually evaporates or transpires through natural and agricultural vegetation, also possibly including "white" water evaporated from surfaces after rainfall). Globally, through irrigation, agriculture has the biggest share in withdrawal and consumption of renewable "blue" freshwater resources of all sectors [*Bruinsma*, 2003; *Postel et al.*, 1996]. The "blue" water resources have competitive uses of industry, households, and agriculture. The reported or calculated withdrawal shares of the different sectors differ to a great extent from one bibliographic reference to another, and their sector consumption is even more uncertain. For the year 2000, the most widely cited figures are from the AQUASTAT data base of the Food and Agriculture Organization of the United Nations (FAO) with a total water withdrawal of 3821 km^3 yr^{-1}, of which 2660 km^3 yr^{-1} are withdrawn for agriculture (70%), 379 km^3 yr^{-1} for domestic usage (10%), and 772 km^3 yr^{-1} for industry (20%) [*FAO*, 2009]. The published total industry withdrawals, like those for agriculture, vary considerably according to sources [*Vassolo and Döll*, 2005; *FAO*, 2008b; *Postel et al.*, 1996]. The total water withdrawal for 1995 was consistently estimated on 0.5° grid cells to be 3572 km^3 yr^{-1} [*Alcamo et al.*, 2003b]. The "consumption" of water is used here to mean the volume of water that is withdrawn and then either transpires, evaporates, or percolates to deep groundwater [*Alcamo et al.*, 2003a]. For 1995, the global total consumption was estimated to be 61% of withdrawal, but the sector shares vary largely from one application to another [*Shiklomanov*, 1998]. Their global sector shares for consumption are estimated to be 9% for industry and 17% for domestic use [*Postel et al.*, 1996]. The agricultural consumption for irrigation, being the "blue" water that evaporates and that is no longer available e.g. as return flows, is calculated using different assumptions, depending on the model, that sometimes is spatially explicit. Ranges of the global volume consumed for irrigated agriculture are at least from 600 to 1426 km^3 yr^{-1} [*Rost et al.*, 2008a; *Molden et al.*, 2007]. Consumption has been estimated to be between 38% of the agricultural withdrawal for 90 developing countries [*FAO*, 2008b] and 65% globally [*Postel et al.*, 1996].

The agricultural water consumption has different effects depending on whether its sources are "blue" water that is in concurrence to human use for domestic purposes or for industry and to environmental water requirements, or whether its sources are "green" water from precipitation where only natural ecosystems are alternative users [*Döll et al.*, 2006]. As a consequence, this distinction between "blue" and "green" water consumption, and thus of irrigated and non-irrigated areas, is necessary when calculating the true stress on the water resources [*Döll et al.*, 2006; *Fader et al.*, 2010]. In analogue to the aforementioned sources of water, "blue virtual water" and "green virtual water" can be distinguished.

Following current estimations, about one third of all food is produced globally under rainfed conditions, i.e. with "green" water, and in some semiarid regions such as Sub-

Saharan Africa food production even almost entirely depends on "green" water. Accordingly, rainfed "green" agricultural consumption is globally larger (ca. 7200 km^3 yr^{-1}) than irrigated "blue" agricultural consumption (between 600 and 1400 km^3 yr^{-1}, depending on level of irrigation). This dominance of "green" water in agriculture and ecosystem services becomes even more striking if "green" water requirements for permanent grazing land are included (ca. 8100 km^3 yr^{-1}) [*Rost et al.*, 2008a: 5]. But nevertheless, irrigation has a noticeable signature in the terrestrial water balance in intensively irrigated areas [*Rost et al.*, 2008a: 8].

The assessment of current and future agricultural water demand either as withdrawal or consumption is often based on rather crude global or country-wide assumptions of parameters or conditions, because of lack of detailed knowledge or for simplicity purposes, as is shown in the following introductory Chapters.

1.1.2 Land use versus land cover

To perform the estimation of agricultural water demand sufficiently, it is useful to introduce a clear definition of the terms "land use" and "land cover" that are used later, but which often are mixed in other texts [*Cihlar and Jansen*, 2001]. Readers that are acquainted with these terms may skip this Chapter.

According to the Millennium Ecosystem Assessment (MEA) [*Millennium Ecosystem Assessment*, 2005; *Hassan et al.*, 2005], land use is "the human use of a piece of land for a certain purpose (such as irrigated agriculture or recreation). It is influenced by, but not synonymous to, land cover". According to *Erb et al.* [2007] MEA defines land use also as "a process at the interface of social and ecological systems. It is the sum of arrangements and activities aimed at harnessing ecosystem services, sometimes at the expense of other ecosystem services". On the other side, there is land cover which is "the physical cover of land, usually expressed in terms of vegetation cover or lack of it" [*Millennium Ecosystem Assessment*, 2005; *Hassan et al.*, 2005]. Currently, besides cropland and pasture, the land surface is also used as forestry, urban areas, infrastructure areas, and areas without land use [*Erb et al.*, 2007; *Klein Goldewijk et al.*, 2007]. Nevertheless, land cover classes and land use classes are often mixed. Even a special publication on land use change modeling is ambiguous in the use of the terms: While it mentions that many authors make a distinction between the land cover that can be observed (such as grass or building), and land use as the actual use to which the land is put (such as grassland for livestock grazing or residential area), the term land use is used for both land cover and land use [*Koomen and Stillwell*, 2007]. In this thesis, both terms are distinguished. Land cover is characterized by the biophysical features of the terrestrial environment, typically based on a classification system consisting of discrete classes and formulated for a specific purpose [*Cihlar and*

Jansen, 2001; *Brown and Duh*, 2004]. Land use refers to the manner in which these biophysical assets are used by people. It is the intended employment of and management strategy used on a specific land cover type by human agents, or land managers [*Baulies and Szejwach*, 1997: 19]. Concerning agriculture, often only one agricultural land use class is distinguished [*Cihlar and Jansen*, 2001]. The transformation of a land use classification to a land cover classification is easily possible by semantic translation rules [*Brown and Duh*, 2004; *Cihlar and Jansen*, 2001]; while one land cover class can be attributed to different land uses, e.g. grass to grazing or regularly cut meadows.

1.1.3 Large-scale data sets on land use and land cover

There are three major approaches for developing large-scale land use data sets, each have specific advantages and shortcomings: remote sensing-based methods, census-based methods and modeling.

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; *JRC*, 2008] contain only 1 to 6 agricultural land classes, do not distinguish specific crops and detect only the dominant land cover category (without sub-pixel information). Other products [*EEA*, 2008; *FAO*, 2003; *MRLC*, 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 multi-cropping and source of water [*IWMI*, 2007]. However, the low spatial resolution of satellite imagery and the classification algorithm results 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

Census-based land use data sets [e.g. *FAO*, 2008a; *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, e.g. restricted to specific administrative levels. Furthermore it is difficult to maintain global census data bases that provide high spatial resolutions because boundaries and names of sub-national units change from year to year. Also, definitions of census variables and accuracy of the results vary from country to country, and sometimes also with time from census to census within one country.

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 based on 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].

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 dataset that provides the dominant crop class for each 5 arc-minute cell, but without sub-grid 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-minute 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 geo-spatial data such as satellite imagery or GIS vector layers and/or crop suitability modeling were used to define the spatial pattern inside the statistical unit (spatial downscaling). 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; *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 based on 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 multi-cropping practices when generating the crop distribution pattern, besides two exceptions: multi-cropping factors for major crops to limit irrigated area [*Cai et al.*, 2007], and multi-cropping for rice in tropical Asia [*Bondeau et al.*, 2007]. Crops growing at the same time of the year cannot grow on 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 multi-cropping 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.

1.1.4 Consideration of land use and irrigation data in global models

Many global models or global assessments published so far are still based on grid data representing the status of the 1990ies, such as the 1992 cropland extent of *Ramankutty and Foley* [1998] and the 1995 crop areas of *Leff et al.* [2004], e.g. [*Rost et al.*, 2008a; *Gerten et al.*, 2008; *Bondeau et al.*, 2007; *Döll and Siebert*, 2002; *Gerten et al.*, 2004; *Liu*, 2007; *Liu et al.*, 2007]. Others like *Gordon et al.* [2005]; *Scanlon et al.* [2007] use the land use data of the History Database of the Global Environment (HYDE) in a former version [*Klein Goldewijk*, 2001; *Klein Goldewijk and Ramankutty*, 2004] than the current one [*Klein Goldewijk et al.*, 2007]. Used reference statistical data series also often end between 1990 and 1995 [*Scanlon et al.*, 2007; *Postel et al.*, 1996]. This adds considerable uncertainty in studies that aim to investigate present-day conditions. The cropland extent for 1992 according to older estimation [*Ramankutty and Foley*, 1998] is 18.0 million km^2, while following newer estimations it is about 15.1 million km^2 [*Ramankutty et al.*, 2008; *Pongratz et al.*, 2008]. This does not mean that cropland extent has decreased from 1992 to 2000, but that the difference is a result of changes in methodology [*Ramankutty et al.*, 2008]. As a consequence, using the older cropland extent data set, without changes of further information, implicitly increases modeled cropland evapotranspiration. This occurs, first, when percentual crop shares are applied to the cropland extent. Secondly, when the rest of the used cropland is constant, relatively larger fallow land also has a non-negligible evapotranspiration, from its mostly assumed grass vegetation in rainfed regimes. Also, agricultural yields may be smaller when calculated from constant production data, and divided by possibly larger actually used areas. Similarly, besides increased evapotranspiration changes in hydrological behavior will be observable through different interception and land use at the grid cell level, leading to changed water balance terms such as groundwater recharge or changed runoff.

Furthermore, when computing agricultural water withdrawal or consumption on a spatially explicit basis, this is mostly made on grids with 0.5 degree resolution [*Rost et al.*, 2008a; *Gerten et al.*, 2008; *Bondeau et al.*, 2007; *Gordon et al.*, 2005; *Döll and Siebert*, 2002; *Gerten et al.*, 2004]. When processes at sub-grid level occur, e.g. two different land uses of nearly the same extent rather than only one dominant land use that is considered in the model, this may lead to considerable bias in the model results such as evapotranspiration or runoff.

Also, in the climate system, feedbacks between irrigation and the atmosphere may occur, altering regional pressure, wind and precipitation patterns. It has been shown in sensitivity experiments for climate models that the representation of water used for irrigation in the models is extremely important for the simulation of the South Asian summer monsoon. Without representation of irrigation, a warm bias over the Indus basin and a subsequent overestimation of the monsoon heat low is perceived in several global and regional climate models, e.g. ECHAM4, REMO, and RegCM3 [*Saeed et al.*, 2009; *Ashfaq et al.*, 2009]. When irrigation with unlimited water supply up to potential evapotranspiration is allowed, the bias and the overestimation of the monsoon heat low are removed, allowing the monsoon and its associated rainfall to penetrate much deeper into India from the south-eastern direction [*Saeed et al.*, 2009].

In addition to that, currently no distinction between irrigated crops and rainfed crops is made in the input data of crop area or cropland extent in most global hydrological models or global land surface schemes with hydrological component [e.g. *Alton et al.*, 2009]. Sometimes the surrogate of areas equipped for irrigation [*Siebert et al.*, 2007] is used. This maximum irrigable area is mostly used in the form of percentage of grid cell area that is assumed to be irrigated with (most often) unlimited or (sometimes) limited water supply, depending on the model or the simulation assumptions [e.g. *Rost et al.*, 2008a; *Gordon et al.*, 2005; *Döll and Siebert*, 2002]. This has is also a consequence on the calculated water demand. When the complete total area equipped for irrigation is used, the resulting consumptive water uses are in general overestimated when irrigation is only used as supplementary irrigation. In this case, plants are irrigated only from time to time depending on current weather conditions in a given year, and often on only parts of the area equipped for irrigation. Furthermore, parts of the area equipped for irrigation may be left fallow in a given year, also leading to an overestimation of the actually irrigated area, and thus, consumptive water use. Finally, the assumption of unlimited water supply may lead to an overestimation of water consumption, when water supply is in reality limited. This limitation may be the result of actually limited water resources in a specific part of the year or of arbitrarily sub-optimal limited application of irrigation water at specific plant development stages to the increase the water use efficiency [e.g. *Saseendran et al.*, 2008].

Only a few land use models explicitly account for crop-specific irrigated area. *Heistermann* [2006] reviewed several large-scale models that simulate global land use or land cover and established an algorithm to calculate irrigated crop area for the DayCent model. The dynamic global vegetation model “Lund-Potsdam-Jena managed Land” (LPJmL) [*Bondeau et al.*, 2007; *Rost et al.*, 2008a; *Fader et al.*, 2010] and the “GIS-based environmental policy integrated climate” (GEPIC) model [*Liu and Yang*, 2010] are further models accounting explicitly for irrigated crops on a 0.5 degree grid. Nevertheless, many land use models do not explicitly consider irrigated crops, because of the lack of data. Through the “Global Crop Water Model” (GCWM) that considers explicitly irrigated and rainfed crop areas and crop calendars on a 5 arc-minute grid, a fully consistent calculation of “blue” irrigated and “green” rainfed water consumption was made, using the data set presented here [*Siebert and Döll*, 2008, 2010], while others used the data set in an slightly adapted form [*Fader et al.*, 2010; *Liu and Yang*, 2010] or only the same input data with unspecific grid cell irrigation fractions derived from area equipped for irrigation [*Hanasaki et al.*, 2010; *Wisser et al.*, 2010] (Chapter 5.5).

1.1.5 The novel MIRCA2000 data set and its products

As has been stated before, the distinction between “blue” and “green” water consumption is necessary when calculating the true stress on water resources, the source of which determines whether traditionally considered “blue” (rivers, lakes, aquifers) or also “green” (precipitation) water resources are at stress or not [*Döll et al.*, 2006; *Fader et al.*, 2010].

With the aim to enable spatially explicit calculations of “blue” and “green” agricultural water fluxes, the novel global data set of Monthly Irrigated and Rainfed Crop Areas around the year 2000 (MIRCA2000) on a 5 arc-minutes grid was established by the author. It distinguishes irrigated and rainfed areas for 26 crop classes, among them 21 major crops including cotton and the crop groups of pulses, citrus crops, fodder grasses, other perennial crops and other annual crops. Thus, the complete crop production is covered, and enables a holistic calculation of water fluxes and water use efficiencies. MIRCA2000 aims to be consistent to agricultural census data, such as the widely used FAOSTAT and AQUASTAT databases and reports with national data that constitute a basis for many assessments [*Molden*, 2007; *Bruinsma*, 2003; *Faurès et al.*, 2000]. MIRCA2000 aims to maximize consistency also with sub-national statistics collected by national institutions and by the FAO. For the first time, crop calendars were consistently linked to annual values of harvested area at the grid cell level, such that crop-specific growing areas for each month of the year could be computed, representative for the time period 1998 to 2002. Consistency between the monthly growing areas and the limits of the cultivable area in form of cropland extent and area equipped for irrigation has been maximized also on grid cell level. Finally, MIRCA2000 is the first global agricultural land use data set that includes multi-cropping, for large countries, but also small islands world-wide. The data and methods used to compile the data set are described in Chapter 2, while in the following paragraph the products of MIRCA2000 are introduced.

MIRCA2000 consists of four different core products which are likely to be applied for different purposes by the data users:

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 arc-minute by 5 arc-minute grid cell (on land).
2. *Condensed Crop Calendars for irrigated and rainfed crops (CCC-I & CCC-R)* report harvested area, start and end of crop-specific cropping periods for each of the 402 spatial units distinguished in this inventory. Up to five distinct sub-crops are used in order to represent multi-cropping practices.
3. Similarly, *Cropping Period Lists (CPL)* provide harvested area, start and end of cropping periods for each 5 arc-minute grid cell.
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.

In addition to that, two additional secondary products derived from the other are of interest:

5. *Maximum Monthly Cropped Area Grids for irrigated and rainfed crops (MMCAG-I & MMCAG-R)* that report the maximum of aggregated irrigated and rainfed growing area, respectively. It should be noted that the sum of both does not necessarily represent the total maximum monthly growing area, as the maximum extent of irrigated and rainfed crops can be located in different months.
6. *Annual harvested area for each of the 26 irrigated and rainfed crops*, and the *total annual harvested area of all irrigated and rainfed crops (AHI & AHR)*.

The first three products provide harvested area and crop seasonality as a consistent bundle. Users who prefer to simulate cropping periods by themselves (e.g. using a dynamic vegetation model) are referred to the fourth data product; the MMGAG. These users should analyze consistency of derived harvested areas with statistical data. Additionally, all products are provided aggregated consistently to the 30 arc-minute (0.5 degree) resolution that is still the standard in many global models and data preparation efforts [*Gerten et al.*, 2008; *Dürr et al.*, 2005]. The products are available for download at http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/index.html.

MIRCA2000 can serve multiple purposes for consistent global or regional modeling including the distinction of irrigated and rainfed crops, e.g. of agricultural water consumption and "blue" and "green" virtual water content or water use efficiency [*Siebert and Döll*, 2010; *Fader et al.*, 2010; *Liu and Yang*, 2010] (see Chapter 5.5), of biogeochemical cycles, or of land use changes. Spatially explicit "blue" and "green" water fluxes, water use efficiency, or virtual water content on the 5 arc-minute grid cell level can be aggregated for river basins which are the better unit for assessment of water stress than the currently available "water footprints" at country level [*Chapagain and Hoekstra*, 2004a, 2004b].

1.2 Ecosystem conversion to cropland and MIRCA2000

How large is the influence of conversion of natural ecosystems to agricultural systems? This can, first, be expressed in terms of the transformed area of the land surface compartment of the earth [*Ellis and Ramankutty*, 2008; *Foley et al.*, 2005]. The specific extent to which mankind has influenced the earth's surface differs in intensity from the considered land use system [*Erb et al.*, 2007]. The latest estimation specifies that more than 75% of earth's ice-free land shows evidence of alteration as a result of human residence and land use, with less than a quarter remaining as wilderness [*Ellis and Ramankutty*, 2008]. Other sources specify smaller values: At least between one-third and one-half of the land surface has been transformed by direct human action [*Vitousek et al.*, 1997]. Most of the high-quality land is already used for agriculture and depends on human-regulated nutrient inputs and water management [*Tilman et al.*, 2002; *Young*, 1999]. The estimates of the area that is barely influenced by humans are also quite different: According to *Sanderson et al.* [2002] only about one-fifth of the land surface was still largely untouched by human activities in the year 2000. The current version of the HYDE data set [*Klein Goldewijk et al.*, 2007] uses the delineation of UNEP/GRID that made a thorough analysis of wilderness areas in small-scale maps where wilderness areas are defined as "undeveloped land still primarily shaped by the forces of nature" [*McCloskey and Spalding*, 1989]. Thus, 50 million km^2 or one-third of the land surface is wilderness, while the aforementioned most current source [*Ellis and Ramankutty*, 2008] mentions less than one-quarter. The conversion of natural ecosystems to agricultural systems introduced related land use practices that have strongly influenced and altered many compartments of the earth system besides the already mentioned earth surface, e.g. the biogeochemical cycles [*Galloway and Cowling*, 2002; *Van Oost et al.*, 2007] or the water cycle [*Rost et al.*, 2008a; *Rost et al.*, 2008b; *Scanlon et al.*, 2007].

Although land use or land cover data sets exist that, unlike MIRCA2000, consider both cropland and pasture (grazing land), these do not distinguish irrigated and rainfed areas [*Ramankutty et al.*, 2008; *Klein Goldewijk et al.*, 2007]. MIRCA2000 concentrates on land use expressed as monthly land cover of specific crop classes. It focuses on agricultural cropland for a variety of reasons. One important reason is that the definitions of pasture are not globally consistent in the census statistics and some confusion with managed grassland areas on cropland is possible. As a result, the extent and spatial pattern of pasture is even more subject to errors than that of cropland. Already for cropland alone, adjustments between grid cell level data of cropland extent, area equipped for irrigation, and harvested area were necessary (see Chapter 2.2.4). Additionally, statistics on irrigated pasture are often not available. MIRCA2000 has its clear strength to represent as best as possible current crop area on cropland. It describes spatially and temporally explicit the four cereal production systems that are the foundation of the global food production plus regionally important crops, while equally distinguishing irrigated and rainfed crops in a consistent way.

1.3 Milestones and structure of this thesis

The milestones achieved by this thesis are:

1. To show the position of the MIRCA2000 data set established by the author within other global or regional data sets,
2. To document the basic input data sets and the methodology of the MIRCA2000 data set generation,
3. To present the main outcomes, such as the global crop-specific shares of rainfed versus irrigated harvested areas, their spatial distribution pattern on a 5 arc-minute grid, spatial pattern of cropping intensities (separately without fallow and with fallow), and global crop-specific monthly growing areas distinguishing rainfed and irrigated areas, as well as respective contributions of the Northern and Southern Hemisphere.
4. To explain and document the technical procedure necessary for updating the data set.

The current Chapter 1 sets the framework for the MIRCA2000 data set within comparable efforts to represent land use.

Chapter 2 documents the basic input data sets and shows the methodology how the irrigated and rainfed areas were distinguished to form the 6 sets of output data of which MIRCA2000 consists, especially 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) (see the list of MIRCA2000 products in Chapter 1.1.5). Here also an example of the inconsistency of the input data sets is shown. The input sources of data specifically compiled for MIRCA2000, e.g. on crop calendars for irrigated crops, are discussed, while for the detailed analysis of quality of externally compiled data sets the references to the respective publication are given in the text.

Chapter 3 presents the main results of the MIRCA2000 data set in its current version 1.1, concerning global distribution of harvested area of irrigated and rainfed crops (Chapter 3.1), the seasonality (Chapter 3.2), and the cropping intensity (Chapter 3.3).

Chapter 4 shows comparisons of the results to external data. For selected crops the results are compared on a global country-based level (Chapter 4.1), on regional level for Europe (Chapter 4.2), and compared to cropping periods of the dynamic global vegetation model LPJmL (Chapter 4.3). Quality parameters and an overall quality mark are developed and discussed (Chapter 4.4).

Chapter 5 contains the discussions, with special emphasis on scaling issues (Chapter 5.1), uncertainties (Chapter 5.2), comparison of the methodology to other approaches (Chapter 5.3), possible improvements (Chapter 5.4), and applications to estimate irrigated and rainfed crop yields, crop water use, virtual water content, and cropland use intensity (Chapter 5.5).

Chapter 6 contains the conclusions, with an outlook on possible applications of the data set.

Chapter 7 is dedicated to the bibliographic references.

In the Appendices Chapter 8, further scientific information is given in Appendices A to F, while technical information for a possible update of MIRCA2000 is provided in Appendix G. Appendix H is dedicated to the curriculum vitae of the author. Finally, supplementary Appendices I and K document extensively information on crop calendars and data sources, while Appendix L shows input data for quality parameters. In detail, the Appendices contain the following information.

Appendix A contains a glossary of the critical terms and the most important acronyms.

Appendix B shows country-level characteristics of the MIRCA2000 irrigated and rainfed agriculture.

Appendix C shows global maps of harvested area for the 26 crop classes of MIRCA2000, distinguishing irrigated and rainfed areas.

Appendix D shows quality parameters of the data set for level of countries, climate zones and units in form of tables.

Appendix E shows the reclassification of 175 FAO crop classes to the 26 MIRCA2000 crop classes.

Appendix F shows United Nation (UN) regions and the included countries according to *United Nations Statistics Division* [2010].

Appendix G presents information how updating MIRCA2000 can be managed in form of a systematic overview concerning the elements, and a description of the technical sequence and interaction of programs.

Appendix H lists the academic and professional curriculum vitae of the author.

Appendix I (Supplement) shows extended Condensed Crop Calendars for irrigated and rainfed crops (CCC-I and CCC-R) for each of the 402 spatial units.

Appendix K (Supplement) documents the data sources of harvested area and of the cropping periods of the crop calendars for irrigated crops for the spatial units (or entities) as an update of the version in *Portmann et al.* [2008].

Appendix L (Supplement) documents the input data at unit-level or country-level that were used for the calculation of the quality parameters and the generation of maps. Furthermore, the code and name of each unit are listed.

The scientific part of this PhD thesis is mainly based on two basic text sources that are already published. In a report the data set and its generation have been described concerning irrigated crops and the data sources of crop calendars for irrigated crops [*Portmann et al.*, 2008]. In a second document the methodology has been extended to rainfed crops. The manuscript was published by the renowned peer-reviewed international journal Global Biogeochemical Cycles and was subject to external editing during the review [*Portmann et al.*, 2010]. For both publications, the author of this thesis is the first author having designed and executed the writing of most of the text, and having generated the final text version, all tables and all figures. Selected tables and figures of this published text have been used in this PhD thesis text, too, with respective citation.

The short English summary is a completely revised and extended version of the summaries previously published. The maps of harvested area in Appendix C are an updated version of *Portmann et al.* [2008] with irrigated harvested area now of MIRCA2000 version 1.1 (previously 1.0) and rainfed crops as a completely new element. The German summary, and the Appendices on data set quality (Appendices D and L), on extended CCCs (Appendix I) are completely new creations of the author and have not been published before. The introduction (Chapter 1) is a completely restructured version of the introductory section of the journal publication, with extensions especially on the definition of land use vs. land cover, the discussion on land use and representation of irrigated areas in global hydrological and climate models, and additional MIRCA2000 products. In the following Chapters the texts of the aforementioned publications were extended or adapted where necessary. This concerns especially three aspects: First, in the presentation of results of harvested area (Chapter 3.1), now also the spatial patterns of crop-specific rainfed and irrigated harvested areas as shown in Appendix C are included. Second, the assessment of quality of the data set has been substantially enlarged (Chapter 4). This concerns the discussion of the comparison to the cropping periods of a dynamic global vegetation model (Chapter 4.3). Besides further theoretical considerations on data quality, a set of quantitative quality parameters for MIRCA2000 on the final level of countries and units is introduced, based on information of the crop calendars on unit level and of differences on grid cell level (new Chapter 4.4). Third, in the discussion (Chapter 5), the MIRCA2000 data set is now also classified with respect to the terminology of “land use” and “land cover”, and theoretical and practical aspects of scaling (new Chapter 5.1). Also, the methodology is discussed with respect to other scaling methods (enlarged Chapter 5.4). The part with applications of MIRCA2000 was enlarged with the content of new publications, some of them with the author of this text as co-author [*Siebert et al.*, 2010a; *Siebert et al.*, 2010b] (Chapter 5.5).

The glossary (Appendix A) was slightly updated to include additional products of MIRCA2000 mentioned in this text. The crop class reclassification table (Appendix E) was only submitted to editorial changes, and the list of United Nations regions (Appendix F) was updated with the current standard names (at the date of submission) that were also introduced in the table of the country-level characteristics (Appendix B) and in the data sources by country (Appendix K). In Appendix K, as most important update, the data sources of areas and cropping periods of the crop calendars for irrigated crops have been completely revised and enlarged with special emphasis to support the data quality parameters mentioned in Chapter 4.4. Now the data sources are explicitly cited in a crop-specific manner when disaggregation of crop area of the original raw data was performed.

The bibliographic citation rules have been updated, too. Most important, the list of references now includes as far as possible electronic resources to enable easy access to the information. The few citations in the text using excellent text formulations of other authors that were included after some editing are explicitly accompanied by the number of the page from which the text was drawn.

This document and the Supplement are available through the Uniform Resource Name (URN) urn:nbn:de:hebis:30:3-230136, which was linked in November 2011 to http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/23013.

2 Data and methods

To generate MIRCA2000, several input data sets were used. Depending on their characteristics and possible interactions the methodology to define cropping periods of 26 crop classes and up to five sub-crops at the 5 arc-minute grid cell level was developed. Therefore, in this Chapter first the characteristics and sources of input data (Chapter 2.1) and then the methods (Chapter 2.2) are described. 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 sub-national units for China, India, the United States of America, Brazil, Argentina, Indonesia, and Australia.

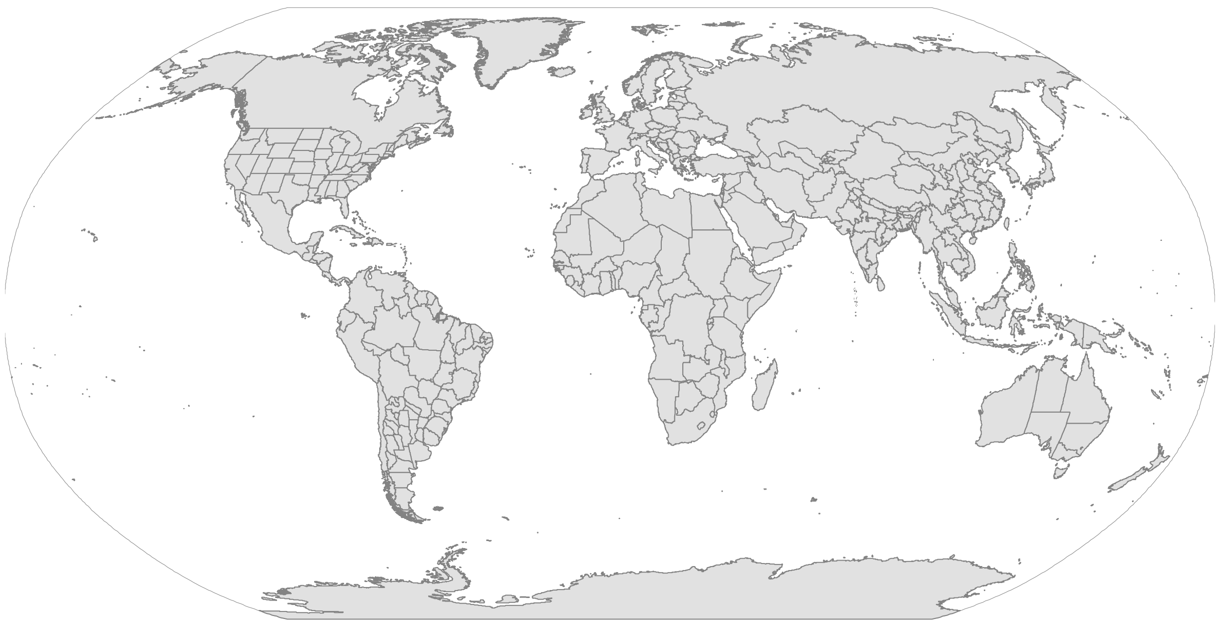

Figure 1. Spatial units for which crop calendars were established. Same units as in *Portmann et al.* [2010].

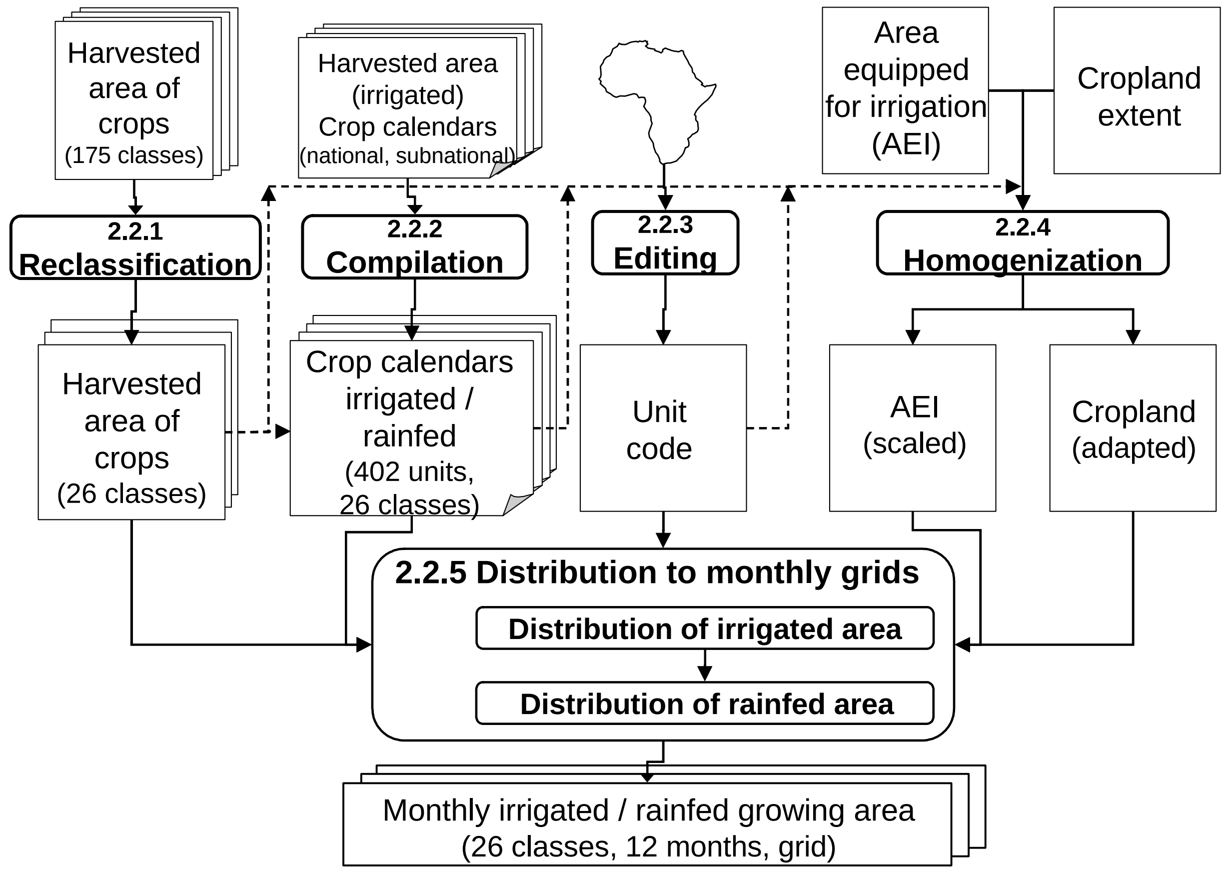

Figure 2. Data processing scheme for the derivation of monthly growing area grids of irrigated and rainfed crops [*Portmann et al.*, 2010].

2.1 Data

Seven categories of input data were used to develop this inventory (Table 1). A more detailed documentation of data sources related to cropping periods and harvested areas of irrigated crops is found in Appendix K which is drawn from [*Portmann et al.*, 2008].

Crop calendars defining start and end of cropping periods were obtained from several inventories [e.g. *FAO*, 2005a, 2005b; *USDA*, 2006, 1994; *IRRI*, 2005] or national reports. This data was available for 142 individual countries but mostly for selected crops only. For China, India and Indonesia, *FAO* [2005a] provided information on start and end of cropping periods for 3, 4 and 2 climatically different sub-zones, respectively.

Crop-specific harvested areas of irrigated crops were derived from several census-based inventories [e.g. *FAO*, 2005a, 2005c; *USDA and NASS*, 2004; *EUROSTAT*, 2008a; *Indiaagristat*, 2005; *ABS*, 2002, 2001; *National Bureau of Statistics of China*, 2001; *IBGE*, 1997; *INDEC*, 2002]. For the 179 spatial units with area 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 (Chapter 2.2.2) (Figure 2).

Table 1. Characteristics and sources of input data used to develop Monthly Growing Area Grids of 26 irrigated and rainfed crops [*Portmann et al.*, 2010].

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. *USDA and NASS*, 2004], national reports, databases [e.g. *EUROSTAT*, 2007b], FAO [e.g. *FAO*, 2005a], United States Department of Agriculture (USDA) [e.g. *USDA*, 1994]; for detailed information on data sources see Appendix K or *Portmann et al.* [2008].
Harvested area of irrigated crops	Census-based statistics for 402 spatial units	National reports [e.g. *USDA and NASS*, 2004], databases [e.g. *EUROSTAT*, 2007b], FAO [e.g. *FAO*, 2005a]
Crop-specific annual harvested area	5 arc-minute grid, data layers for 175 different crops	*Monfreda et al.* [2008]
Cropland extent	5 arc-minute grid	*Ramankutty et al.* [2008]
Area equipped for irrigation	5 arc-minute grid	*Siebert et al.* [2007]
Administrative boundaries of countries and sub-national 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-minute resolution, mean elevation at 5 arc-minute resolution	*FAO* [2001], own expert knowledge on climatology and cropping periods, *New et al.* [2002], *National Geophysical Data Center* [1988]

To define total annual harvested crop area an inventory at 5 arc-minute resolution was used [*Monfreda et al.*, 2008]. This data set consists of grids for 175 crops consistent to the FAOSTAT crop categorization of the statistical data base of the FAO (FAOSTAT) and refers to the period around year 2000. This dataset does not distinguish rainfed and irrigated crops in a crop-specific manner. It was developed by distributing harvested crop areas derived from sub-national 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 was 12.8 million km^2 and at the grid cell level, the harvested area can be larger than the total cell area if multi-cropping occurs. The data set can be downloaded from http://www.geog.mcgill.ca/landuse/pub/Data/175crops2000/.

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-minute grid cell the fraction that was used as cropland. It is available at http://www.geog.mcgill.ca/landuse/pub/Data/Agland2000/.

The fraction of each 5 arc-minute 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 sub-national units to geo-spatial 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.

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 dataset of national and sub-national unit boundaries. For this purpose, a geo-data package distributed along with standard GIS-software was used [*ESRI*, 2004].

To define start and end of cropping periods in crop calendars in case of missing data (Chapter 2.2.2) and to define grid cells suitable for growing winter cereals with vernalization requirements (Chapter 2.2.5) climate and elevation data were used. 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-minute 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) dataset [*New et al.*, 2002]. Mean elevation for each 5 arc-minute grid cell was taken from the ETOPO5 elevation data set [*National Geophysical Data Center*, 1988].

2.2 Methods

In this Chapter the combination and processing of the input data to develop monthly growing area grids at the 5 arc-minute resolution are described (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, crops were classified into 26 classes comprising all major food crops (wheat, rice, maize, barley, rye, millet, sorghum, soybeans, sunflower, potatoes, cassava, sugar cane, sugar beet, oil palm, rape seed/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 grass, annual) (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 first the reclassification of grid cell-based (Chapter 2.2.1) and unit level-based (Chapter 2.2.2) input data is described. By combining these reclassified harvested area statistics, the crop calendars at the unit level were compiled (Chapter 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 (Chapter 2.2.3) and to preprocess input data sets of cropland extent and area equipped for irrigation to reduce inconsistencies of these to data of harvested area (Chapter 2.2.4). The process of spatial downscaling itself is described in Chapter 2.2.5.

2.2.1 Reclassification of total harvested crop area at the grid cell level

Total crop-specific harvested area (without distinction of irrigated and rainfed crops) was available for 175 crops [*Monfreda et al.*, 2008]. Each of these 175 crops was assigned 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 original crops (Appendix E). Harvested areas of rye and sorghum was 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 “fodder grasses” (Appendix E). 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 “fodder grasses” and “other annual crops” (Appendix E).

2.2.2 Compilation of Condensed Crop Calendars (CCC)

“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 (Chapter 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 (CCC-I)

Harvested areas of irrigated crops on a national or sub-national level were derived from agricultural statistics and survey reports [e.g. *FAO*, 2005a; *USDA and NASS*, 2004; *EUROSTAT*, 2008a; *Indiaagristat*, 2005; *ABS*, 2002; *IBGE*, 1997; *INDEC*, 2002]. Cropping periods of irrigated crops (if available also for sub-national 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 mentioned 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 and *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 sub-national cultivation zones (3 for China, 4 for India, 2 for Indonesia) or to establish calendars according to climatic zones and climatic classifications based on station data or reports (6 for Argentina, 8 for Australia, 5 for Brazil, 8 for the United States of America). The sub-national 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 sub-national units within the respective zone.

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 for 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 sub-crops were defined in the resulting Condensed Crop Calendars (CCC-I). Thus, sub-crops can represent multi-cropping systems, e.g. double cropping or triple cropping of rice in southern Asia. They can also represent different specific sub-groups 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”.

The whole procedure of developing the CCC-I is described in detail in *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 (CCC-R)

Rainfed harvested areas were computed for each spatial unit from the difference between the 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 Chapter 2.2.1 over all grid cells belonging to that unit. Due to 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 consistency to the total sum of harvested area over all crops, it was tried to compensate in those cases in the groups of “others annual” or “others perennial” for the difference between irrigated harvested crop area and total harvested crop area.

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*, 2006, 1994]. 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 crop.

2.2.2.3 Multi-cropping systems and varieties of rice, cassava and temperate cereals

If a crop is grown more than once a year, the sum of the growing areas of the sub-crops equals the crop-specific total (annual) harvested area, which follows general definitions of multi-cropping e.g. by the FAO. In MIRCA2000, the growing area of each sub-crop can be different, e.g. spring wheat can have a smaller share of the total annual harvested area than winter wheat, or vice versa.

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 3 cropping periods per year. For rainfed rice, three groups were distinguished in the CCCs: upland, deepwater and paddy rice. 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]. A cropping period of mainly 7 to 8 months was assigned 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 pre-flood, flood, and post-flood conditions, a standard growing period of 7 months was defined [*Catling*, 1992; *CRRI*, 2006; *Jupp et al.*, 1995]. For rainfed paddy rice, up to 3 cropping periods were established, typically each with an estimated length of 4 months. The number of cropping periods was defined based on FAOCLIM2 climate data [*FAO*, 2001]. Relative shares of upland, deepwater and paddy rice areas were close to those from IRRI [*IRRI*, 2005] after cross-check with data from *Catling* [1992]. Sub-national data [*Frolking et al.*, 2006] were used to define rice cropping periods for India.

For cassava, two different varieties as documented in the literature were distinguished: 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.

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.

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, it was assumed to be the globally dominating winter wheat and assigned a cropping period starting in autumn or winter. In some cases, a deviation from this principle was necessary, as described more in detail in Appendix K and *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 a second cropping period during summer was introduced in the sub-national 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.

Production statistics for wheat, rye and barley released by the Statistical Office of the European Communities (EUROSTAT) [*EUROSTAT*, 2007a] 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 latitude between 30 and 40 degrees, it was 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 based on monthly climate data of precipitation amount and air temperature [*FAO*, 2001] with up to 3 cropping periods of spring varieties. Relative shares of harvested areas of rainfed winter wheat and spring wheat for several Chinese provinces were defined based on 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 (CCC)

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 sub-crops the growing area, the start and end month of the cropping period are provided. California has the unit number 840005 (first column of Table 2). The crop class is given in the second column and the number of sub-crops in the third column. Beginning with the fourth column, total growing area, first month and last month of the cropping period are listed for each sub-crop. Thus, the first line can be interpreted as follows: In unit 840005 (California) there are two sub-crops of crop 1 (wheat). Sub-crop 1 is growing on 98,723.06 ha in the period September (9) to June (6) and sub-crop 2 is growing on 38,363.79 ha in the period April (4) to August (8). Here sub-crop 1 represents irrigated winter wheat while sub-crop 2 is irrigated spring wheat. For the permanent crops sugar cane (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). Only one sub-crop was assigned to these permanent crops. Crop class 26 (other annual crops) consists of 4 sub-crops (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.

Table 2. Example of Condensed Crop Calendar for irrigated crops in California listing growing area of each sub-crop (SC) in hectare and the calendar month of start and end of sub-crop cropping period [*Portmann et al.*, 2010].

Unit code	Crop class*	No. 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

*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: sugar cane, 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: others perennial, 25: fodder grasses, 26: others annual.

2.2.3 Development of a full coverage spatial unit mask

To combine information collected at the calendar unit level (CCCs) for all sub-crops with information available at the grid cell level (area equipped for irrigation AEI, cropland extent, harvested area of crops AH, Table 1) it was necessary to assign each grid cell to the related spatial calendar unit (country or sub-national 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 gridded input data

As data sources and methodologies used to generate the grid input data (AEI, cropland extent and AH) were different, 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, inconsistencies between the grid data sets and monthly growing areas in the CCCs were found. For example, it would be expected 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 due to 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 below, such inconsistencies were partially fixed. The method to downscale monthly growing areas from the unit level to the grid cell level accounted for the remaining inconsistencies (Figure 2).

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.

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 based on 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 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

The CCCs (Chapter 2.2.2) provide information on the monthly growing areas of each of the crop classes and related sub-crops (e.g. winter wheat and spring wheat), under irrigated and rainfed conditions, in the 402 calendar units (Chapter 2.2.3). This information was downscaled to provide growing areas within each of the 5 arc-minute by 5 arc-minute grid cells, using grid cell data of crop-specific AH (Chapter 2.2.1), AEI and cropland extent (as modified in Chapter 2.2.4), and applying a distribution procedure as described below (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, AH 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).

Table 3. Priority levels for downscaling of Condensed Crop Calendars to 5 arc-minute Monthly Growing Area Grids. Priority decreases from 1 to 3 [*Portmann et al.*, 2010].

Priority	5 arc-minute data set	Goal
1	Area equipped for irrigation [*Siebert et al.*, 2007, modified as described in Chapter 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 Chapter 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.

Downscaling of monthly growing areas of sub-crops 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 grid cell level growing areas distributed to the sub-crop was the same as the growing area of the sub-crop reported in the CCC. Furthermore, consistency to AEI (highest 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 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.

Irrigated crops

Step 1	Harvested area times fraction of irrigated cell area divided by number of sub-crops

Step	Cell-specific land resource	*Condition*
2	min (AEI, AH)	
3	AEI	*CE > 0*
4	AEI	*CE = 0*

Rainfed crops

annual

Step	Cell-specific land resource	*Condition*
5	CE	
6	AEI	*CE > 0*
7	95% cell area	*AEI > 0 or CE > 0*

perennial

Step	Cell-specific land resource	*Condition*
5	CE	*CE > AEI*
6	95% cell area	*CE > AEI*
7	95% cell area	*AEI > 0 or CE > 0*

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 sub-crop and cropping season, 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), preprocessed cropland extent (CE, compare Chapter 2.2.4) [*Portmann et al.*, 2010].

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 sub-crop by sub-crop. In step 1, the irrigated growing area of a sub-crop 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 sub-crops. Thus, equal shares of the irrigated harvested area were assigned to each sub-crop without surpassing AEI in any month.

Step 1 helped to obtain multi-cropping in case of non-overlapping growing periods, in particular in the case of rice sub-crops. Like 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 sub-crop starting with the sub-crop 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 sub-crop 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 sub-crop. 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 sub-crops, steps 5 to 7 were performed to assign growing areas for rainfed sub-crops 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.

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 it was tried to compensate at the grid cell level between AH of specific crops and AH in the “others annual” category to ensure consistency to crop calendars and total cell-specific AH.

Starting with step 2 in the distribution process, crops and sub-crops 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 sub-crop had to be processed first, for each of the 402 calendar units:

1. Specific perennial crops (sugar cane, oil palm, citrus, date palm, grapes/vine, cocoa, coffee) were processed first, followed by others perennial and fodder grasses, and then by specific annual crops (wheat, maize, rice, barley, rye, millet, sorghum, soybeans, sunflower, potatoes, cassava, sugar beet, rape seed / canola, groundnuts / peanuts, pulses). Finally the group of “others annual” was processed.
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.
3. If a crop class had several sub-crops, the sub-crops were processed in order of their growing area.

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 sub-crops 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.

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 sub-crops of these temperate cereals were defined by selecting all cropping periods (sub-crops) 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-minute resolution [*New et al.*, 2002] was downscaled to 5 arc-minute resolution by applying an altitude correction using the ETOPO5 dataset [*National Geophysical Data Center*, 1988] with the adiabatic lapse rate set to -0.0065 °C m^{-1}.

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

3 Results

The MIRCA2000 data set provides information on quite different aspects that are important depending on the application and viewpoint. Therefore in this Chapter three basic aspects are presented: First global values of crop-specific irrigated and rainfed harvested areas are presented and the importance of different irrigated and rainfed crops for UN regions and countries is described, followed by a description of the spatial distribution of the AHR and AHI for each of the crops (Chapter 3.1). Then, the seasonality of selected crops wheat, rice, maize, and cotton with the distinction of Southern and Northern Hemisphere (Chapter 3.2) and the spatial distribution of different types of cropping intensities (Chapter 3.3) are shown.

3.1 Harvested area of irrigated and rainfed crops and its spatial pattern

Results at the global scale

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.

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).

The importance of irrigation differs significantly among the crops. 79% of the date palm harvested area, 62% of the rice harvested area, and 49% of the cotton and sugar cane 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 “others perennial”, “others annual” and “fodder grasses” clearly indicate the diversity of today’s world agriculture (Table 4).

Table 4. Crop-specific harvested area around the year 2000: total, rainfed, and irrigated harvested crop area as area (km^2 yr^{-1}) and as a percentage of total harvested area (%) [*Portmann et al.*, 2010].

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
Sugar cane	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
Rape seed	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
Others perennial	731,402	602,872	128,530	17.6
Fodder grasses	1,046,725	929,885	116,840	11.2
Others annual	1,087,904	886,517	201,387	18.5
Total	13,053,334	9,929,175	3,124,159	23.9

Results at the regional scale

67% 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 sub-regions and continents (Table 5) or between specific countries (Table B in Appendix B).

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 sugar cane, cotton, potatoes, "others perennial" and "others 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, sugar cane, sunflower, fodder grasses and "others 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.

Table 5. Crop characteristics and dominant rainfed and irrigated crops in UN regions: 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 a percentage of total harvested area (%), dominant rainfed and irrigated crop classes (selected by harvested area, with represented percentage of total irrigated or total rainfed harvested area in brackets) [*Portmann et al.*, 2010].

Region*	CE_{MIRCA}	AHT	AEI	AHI		Dominant crops	
				area	%	irrigated	rainfed
Eastern	550,037	389,422	24,645	24,440	6	Rice (50), maize (12)	Maize (22), others annual (16)
Middle	279,680	149,898	1,623	1,419	1	Rice (36), others annual (23)	Cassava (20), maize (18)
Northern	419,963	317,212	82,019	99,573	31	Others 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), others annual (17)	Millet (17), pulses (12)
AFRICA	**2,317,889**	**1,675,413**	**134,578**	**149,601**	**9**	**Others annual (22), wheat (13)**	**Maize (14), sorghum (12)**
Caribbean	78,788	47,919	13,142	11,912	25	Sugar cane (44), Maize (14)	Sugar cane (21), others perennial (19)
Central	460,498	223,758	69,068	64,807	29	Maize (26), sorghum (12)	Maize (47), pulses (14)
Northern	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), others perennial (14)	Sunflower (27), maize (18)
AMERICA	**4,051,076**	**2,950,491**	**484,315**	**375,623**	**13**	**Maize (20), fodder grasses (13)**	**Maize (21), wheat (16)**
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)	Others annual (18), maize (14)
South-Eastern	1,217,671	968,210	167,957	240,553	25	Rice (82), sugar cane (6)	Rice (31), others 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), others annual (15)	Wheat (41), barley (21)
ASIA	**6,200,995**	**5,803,003**	**1,876,391**	**2,402,153**	**41**	**Rice (40), wheat (25)**	**Rice (16), wheat (12)**
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), others annual (19)	Fodder grasses (31), barley (22)
Southern	430,014	362,791	104,608	82,775	23	Others perennial (22), maize (20)	Wheat (21), others perennial (17)
Western	358,800	334,679	40,565	21,945	7	Maize (41), others annual (18)	Wheat (25), others annual (14)
EUROPE	**3,088,153**	**2,367,962**	**267,727**	**169,073**	**7**	**Maize (21), others annual (16)**	**Wheat (23), fodder grasses (20)**
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)**

* Compare Appendix F for a definition of the UN regions.

The spatial pattern of rainfed and irrigated harvested area as a percentage of grid cell area (Figure 4, top and center) represents a combination of cropland density and cropping intensity. It shows the absence or scarce occurrence of agricultural crops in higher latitudes where ice 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 South-East 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 of America and northern Mexico.

Harvested areas of rainfed crops (Figure 4, top) are concentrated in Western and Southern Asia, Europe, southern Canada, the eastern United States of America, the north-eastern part of Argentina, southern Brazil, West Africa, around Lake Victoria and along the south-western and south-eastern coast of Australia.

Irrigated harvested area (Figure 4, center) 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; *Frolking et al.*, 2006; *Frolking and Li*, 2007]. Large irrigated harvested areas also occur at specific places in other parts of Asia, the United States of America, 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, only up to 1% of the cell area is irrigated.

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, semi-arid 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, Figure C-3). In addition to that, grid cells with a large AHI as compared to total cell area (Figure 4, center) usually have large values of AHI as a fraction of AHT (Figure 4, bottom). On the other hand, low values of AHI (Figure 4, center) 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, the western United States of America, 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. But there are also some hot spots in Brazil, Colombia and Venezuela.

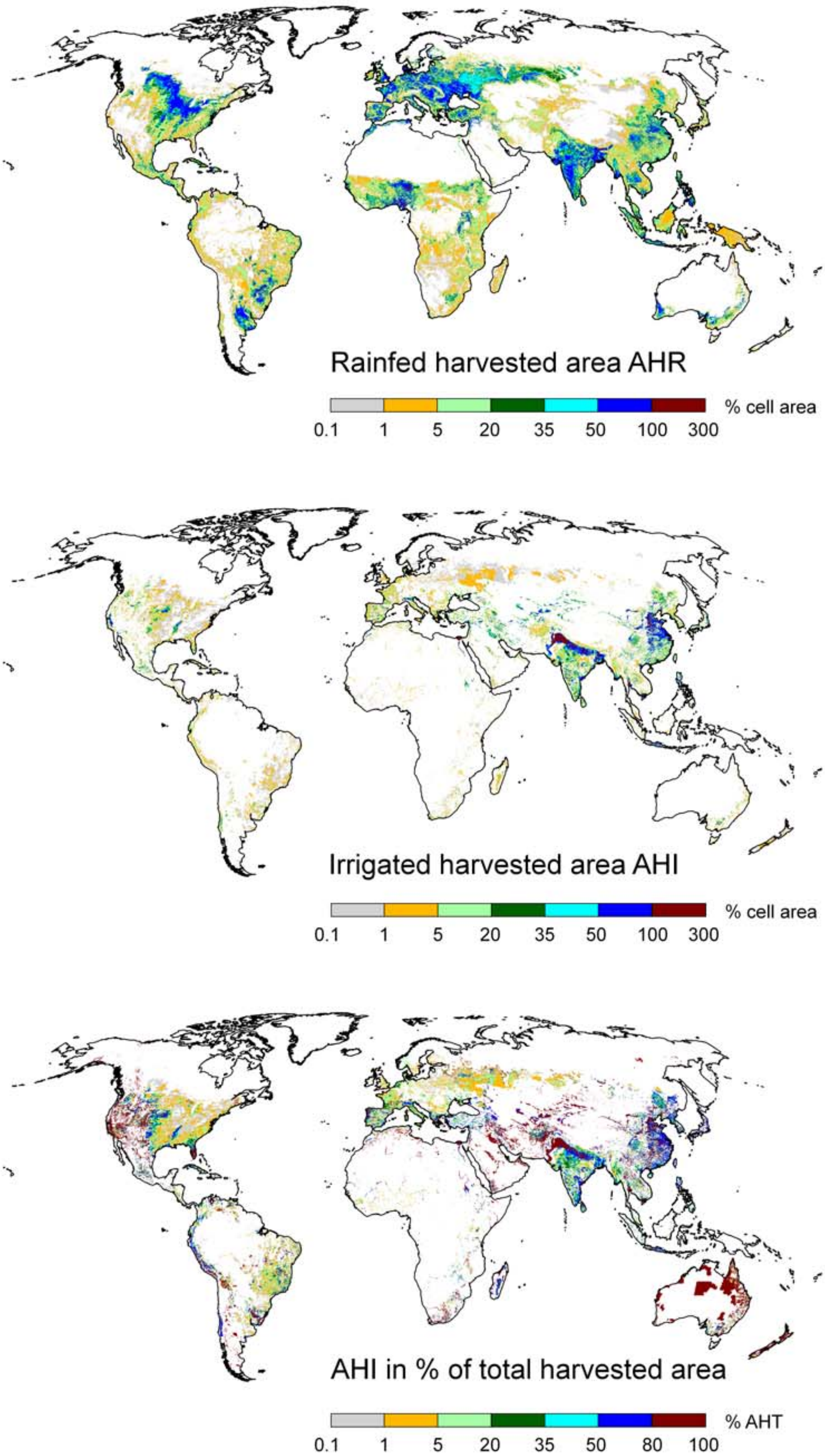

Figure 4. Global distribution of rainfed harvested area (AHR) as a percentage of grid cell area (top), irrigated harvested area (AHI) as a percentage of grid cell area (center), irrigated harvested area (AHI) as a percentage of total harvested area (AHT) (bottom), for 1998-2002 [*Portmann et al.*, 2010].

The high values of AHI as a percentage of AHT in northern and central Australia and New Zealand (Figure 4, bottom) are artifacts that have two reasons: First, harvested areas in the most affected zones are very small (compare to Figure 4 top and center), and, in GMIA, small areas of irrigation infrastructure reported for large administrative units were distributed equally over the whole administrative units because geo-spatial 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 a percentage of AHT.

Spatial pattern of harvested area of individual crops

The maps of the global spatial distribution pattern of harvested area of the 26 crop classes, separately for rainfed and irrigated conditions (Appendix C), underline the aforementioned general global tendency that rainfed harvested area AHR is larger than irrigated harvested area AHI, with the exception of 4 crops (Table 4): AHI is almost equal to AHR for two crops, sugar cane (102,000 km^2 vs. 108,000 km^2) and cotton (163,000 km^2 vs. 168,000 km^2). AHI exceeds AHR for two crops, rice (1.03 million km^2 vs. 626,000 km^2) and date palm (ca. 7230 km^2 vs. 1950 km^2). The spatial pattern of the individual crop classes are discussed following the crop list in Table 4 from top to bottom. Harvested area as a percentage of grid cell area was considered to be of very high intensity when AH was more than 30% of grid cell area, of high intensity between > 10 and 30% of grid cell area, and of medium intensity between > 3 and 10% of grid cell area. Low intensities were between 1 and 3 % of grid cell area, and very low intensities between > 0.1 and 1%. Extremely low intensities with not more than 0.1% of grid cell area were shown in order to check the maximum spatial dispersion due to the downscaling algorithm especially of small harvested areas of minor crops.

Wheat as the most important crop by global harvested area (rank 1) has predominantly rainfed harvested area (AHR 69% of total AH), but a strong share of irrigated harvested area (AHI 31% of AHT, Table 4). It is also, as mentioned before, the major crop in 7 UN regions (Table 5), a fact that is easily seen in the global distribution pattern of AH (Figure C-1). Wheat is grown with high (10 – 30% of grid cell area) and very high intensity (> 30% of grid cell area) as rainfed wheat in large areas of Northern America (United States of America and Canada), in Europe (mostly with high intensity, but with very high intensity in the Russian Federation), in Asia (mostly with high intensity, but with very high intensity in north-eastern China), and in Australia in extended areas in the southeastern and western parts. In South America, high intensities are found on large areas in Argentina and in some spots of southern Brazil. The AHI of wheat is of very high or at least high intensity in large areas of northern India, Pakistan and northern China. In the UN regions Central Asia and Western Asia, but also in the United States of America less intensive AHI of wheat exists. Relatively few spots of AHI with very low intensities exist in Australia, South America, and a more broad distribution in Europe.

Maize with rank 3 of global AHT is also predominantly rainfed (about 80% AHR), but a strong share of AHI (Table 4). It is a nearly ubiquitous crop which is broadly grown as rainfed crop in the northern part of the central United States of America, in northeastern China, Eastern Europe, in South Africa, Argentina and southern Brazil (Figure C-2). AHI of maize in medium, high and very high intensity, i.e. between 3 and more than 30% of grid cell area, is found more concentrated as compared to AHR: In the United States of America more to the south and in the west (California), in Mexico, all over northern China, Central Asia, northern and southern India, in Indonesia on the island of Java, in Africa mainly in Egypt and on some isolated spots, as also in South America in Chile and Ecuador. In Europe AHI is more widely spread, with medium to high intensity AHI between 3 and 30% of grid cell area found concentrated in special areas mainly in northern Italy, in France, Portugal, Spain, and at isolated spots in Eastern Europe.

Rice, the second largest crop by global harvested area after wheat (rank 2), has the least share of AHR (38% of total AH). The AHI is almost double the value of AHR, so it is a clearly predominantly irrigated crop (Table 4). Its AHR concentrates clearly in tropical southeastern Asia (with very high intensity of more than 30% of grid cell area especially in Bangladesh, India, Thailand, and Myanmar), while also being present up to high intensities in western Africa (especially Nigeria), and with medium intensity in South America (especially Brazil) (Figure C-3). Probably the AHR of rice in Pakistan is an artifact stemming from larger total harvested area in the input data set [*Monfreda et al.*, 2008], as the original source of the agricultural census for 2000 only specifies paddy rice that was assumed to be 100% irrigated (Appendix K). The AHI of rice is highest, like AHR, in tropical southeastern Asia. In addition to zones with AHR, the AHI is high in other zones of India, in China and in Indonesia. Medium to high intensities of AHI occur also outside the tropics on more isolated patches in the central United States of America, southern Brazil, Madagascar, and in Italy.

Barley with rank 9 of global AHT and about 92% AHR is a classical mostly rainfed crop, with less than 9% AHI like rye, millet, sorghum, soybeans, sunflower, and pulses (Table 4). Termed also a “temperate cereal”, it is grown as rainfed crop mainly in Europe, especially Eastern Europe, in Africa in northern Morocco and Algeria, in

Ethiopia, in America in Canada, the United States of America, Argentina, and southern Brazil (Figure C-4). It is only rainfed in Australia, predominantly rainfed in China, and partly rainfed and irrigated in northern India. Outside India, AHI of barley is found in other countries of Western Asia, e.g. in Iraq. AHI exists also in western United States of America, and in Europe especially in Spain.

Rye with rank 19 of global AHT and about 96% AHR is a classical mostly rainfed crop (Table 4). AHR of rye is concentrated in Europe, especially in Eastern Europe, Denmark, and northern Germany. It exists in very low intensity between 0.1 and 1% of grid cell area in America, mainly in Canada and Argentina, in Africa in Algeria, and in Asia in China (Figure C-5). AHI scarcely exists, but in very low intensities e.g. in Asia, in China, and the United States of America, while in Europe in Denmark it is irrigated with low intensity between 1 and 3% of grid cell area.

Millet and sorghum have less AHT than barely when counted separately (ranks 11 and 10, respectively), but their joint global AHT is much greater than that of barley, similar to the AHT of soybeans. Both of these “tropical cereals” have a majority of AHR, with 95% for millet and 93% for sorghum (Table 4), and are classical mostly rainfed crops. Their AHR is found in all continents (Figures C-6 and C-7). In Africa, the spatial pattern of both millet and sorghum is very similar, with the very high intensity AHR larger than 30% of the grid cell area found south of the Sahara, in Niger and Nigeria, and high intensity AHR also in Sudan. Sorghum is grown with very high intensity in Sudan, but not in Angola where only millet is found. Medium intensities with AHR between 3 and 10% of grid cell area exist for sorghum also in America in the United States of America, Mexico, and Brazil, and also in Australia, whereas millet is only present with much less extent in very small intensities, mostly in the USA and in Australia. On the contrary, millet has a second very high intensity area of AHR in Asia in the Indian sub-national zones of North India and West India, also being grown with very low intensity in northern China and Pakistan, while sorghum outnumbers millet only in the zone of West India. In Europe, millet has some low concentration between 1 and 3% of grid cell area in the Russian Federation, while sorghum is grown in France, Italy and Portugal only with very low intensity. The AHI of millet and sorghum is mostly found in the aforementioned countries, with the exception that in Africa almost no AHI of millet exists, while AHI of sorghum is mostly found with higher intensities in the Sudan and Egypt. AHI in Asia is mostly found in India with millet more to the north and sorghum more to the west and south, in Pakistan more AHI of sorghum than millet, while in China millet and sorghum have a similar distribution pattern.

Soybeans with rank 6 of global AHT are also a classical mostly rainfed crop with 92% AHR (Table 4), that is found in very high intensities (> 30% of grid cell area) extensively in America in the United States of America, Brazil, and Argentina, and in

Asia in western India (Figure C-8). High (10 – 30% of grid cell area) and medium (3 – 10%) intensities of AHR exist in many areas of China, in Indonesia, and in Africa in Nigeria, and some countries of Europe, e.g. in Italy. AHI of soybeans is found at best with low intensity mainly in the United States of America and eastern China, with even smaller presence in Brazil, Argentina, India and Europe.

Sunflower with rank 16 of global AHT is also a classical mostly rainfed crop with 94% AHR (Table 4), that is found in high and medium intensities in Europe, especially in Eastern Europe, in America in the northern United States of America and Argentina, and in Asia in India (Figure C-9). Low intensities of AHR are also found in China, Myanmar, and South Africa. AHI is found with much lesser extent typically up to low intensity, in Asia in India, China, and Iraq, in Europe e.g. in Spain, in America in Canada and the United States of America, and in Africa mainly on small concentrated spots in Egypt, Sudan, Morocco, and South Africa. Only in western India and in Spain medium AHI intensities up to 10% of grid cell area exist.

Potatoes with a similar global AHT than that of sunflower (rank 17) have a share of AHR (79%, Table 4) equal to maize, and thus are also a clearly (also) irrigated crop with ubiquitous distribution. They are found in medium to high intensity especially in all countries of Eastern Europe (Figure C-10). They occur in medium or small intensity in Asia in North and Eastern India, nearly all zones of China besides the extreme west, in America in northern United States of America and the Andes mountains in South America, and in some tropical countries of Africa. AHI is found typically also where rainfed potatoes are grown, but additionally also e.g. in Africa in Egypt, Sudan, and Ethiopia.

Cassava with global AHT between that of potatoes and rye (rank 18) is a classical rainfed crop. It is almost exclusively rainfed according to the current data (AHR 99.9%, Table 4); with possibly AHI missed in favor of the “others annual” crop class (Chapter 4.4). Being a tropical crop, the AHR is almost exclusively distributed in units with tropical climate, with the exception of China (Figure C-11). It is found in medium intensity especially in many African countries, in Asia in Thailand and Indonesia, and in America in Paraguay and Haiti. AHI is broadly distributed in Brazil with extremely low intensities, based on data of the agricultural census.

For sugar cane, with similar global AHT than sunflower (rank 15), almost half of the area is irrigated. AHR (51% of total AH, Table 4) is concentrated with medium intensity mostly to southern Brazil (up to very high intensity larger than 30% grid cell area), Cuba, and southern China, with some much smaller “hot spots” in India, the Philippines, Cameroon, northern Argentina, and Mexico (Figure C-12). Besides this concentration, sugar cane is present in many African countries other than Cameroon but with very low AHR values (not more than 0.1% of grid cell area), probably due to the distribution procedure that distributes the small AH with low priority even for this permanent crop and, therefore, with more dispersion than permanent crops with higher AH. The AHR of sugar cane in northern Pakistan is not necessarily an artifact like that for date palm mentioned later. The original agricultural census mentions also rainfed areas of sugar cane (Appendix K). Irrigated sugar cane is also found in many countries, but more concentrated in grid cells with AEI. For Brazil, Argentina, Cuba, Mexico, the United States of America, Australia, and Thailand, the locations are similar with somewhat different sub-national distribution patterns. In Indonesia, the concentration of AHI is on the island of Java, while for AHR it is more to the north on the other islands. In China, the AHI is more presented toward the north. In India, very high AHI values exist in the northern part toward the Himalaya, where also medium AHR intensities are found at some spots. But also small to medium AHI values exist in many areas of the southern half of India, where AHR is only present in the western part. Surprisingly, Bangladesh has only AHI, but not AHR of sugar cane. This could be because of higher AHI according to FAO (Appendix K) than the total sugar cane AH of the input data set [*Monfreda et al.*, 2008]. Not surprisingly, medium AHI intensities of sugar cane are found in arid Egypt and Pakistan. In Pakistan, also small AHR sums of about 200 km^2 are specified in the original agricultural census for 2000 (Appendix K), whereas the balancing with total AH in the input grid data set [*Monfreda et al.*, 2008] yielded a larger AHR of about 1800 km^2.

Sugar beet has global AHT of the same order of magnitude as citrus, grapes, and cocoa (rank 25, between 60,000 and 75,000 km^2), with an AHR share (75% of AHT) similar to that of grapes, and thus a clear tendency to be an (also) irrigated crop (Table 4). Medium AHR intensities are found in Europe (France, United Kingdom, Germany, Romania) and the northern United States of America, while areas with low (1 – 3% of grid cell area) or very low (0.1 – 1% of grid cell area) intensities are found all over Europe, in the UN region Central Asia, and in northern parts of China (Figure C-13). AHI with medium intensities occur on isolated spots in the southwestern United States of America, while also low intensities are found at spots all over Europe and in some countries of Central Asia, but also in Western Asia (Iran and Syria), and in Egypt. For Pakistan, it is suspected that the AHR of sugar beet is an artifact like that for date palm mentioned later, as sugar beet is not explicitly cited with AHI in the agricultural census. But sugar beet could possibly be contained in the AHI of crop group “vegetables” of the census that has been re-classified to the “others annual” crop class.

Oil palm has a somewhat higher global AHT than sugar beet (rank 21), although it is a classical rainfed crop like cassava (AHR 99.9%, Table 4). Very high AHR intensities are found in Nigeria, while high intensities exist in Malaysia (Figure C-14). In Indonesia medium intensities exist which are also found in western Africa. Zones with small intensities exist, besides in Indonesia also in tropical Central America and South America, surprisingly including Paraguay. In China, and in some countries of Africa, the oil palm AHR was distributed with low priority to many grid cells, resulting in extremely low intensity.

Rape seed has similar global AHT than groundnuts (rank 13), and with 86% AHR it is an (also) irrigated crop (Table 4). AHR exists with high intensities mainly in Canada, China, and northern India, while existing in central parts of Europe and in Australia up to medium intensities only (Figure C-15). AHI extensively exists in northern India with even very high intensity and with low intensity in Pakistan and Europe.

Groundnuts including peanuts have similar AHT than rape seed (rank 14). With AHR 84% of AHT, they are an (also) irrigated crop (Table 4). AHR of groundnuts exists in very high intensity in the sub-national zones South and West India, and in the UN region West Africa in Senegal and Gambia, and with high intensity also in Nigeria, in large areas of China, in the eastern United States of America and in central parts of Argentina (Figure C-16). AHR is extensively distributed in other countries of Sub-Saharan Africa. In contrast, AHI of groundnuts is only found with up to medium intensity extensively in India (also locally with high intensity) and in China, and more concentrated in southern and south-eastern parts of the United States of America. In Egypt and in Sudan, as well as in Niger, AHI of groundnuts is concentrated with medium intensity to the irrigation oases near the main rivers, e.g. rivers Nile and Niger.

Pulses have a global AHT sum between barley and soybeans (rank 8) and are also a largely rainfed crop (AHR 82% of AHT, Table 4). AHR exists in very high intensities in Africa in Nigeria, Niger, Rwanda, Burundi, Uganda, and Ethiopia, and in Asia in India (almost everywhere grown with medium intensity like in Bangladesh), in America in Mexico (Figure C-17). High intensities are also found in Myanmar and parts of Turkey. AHI exists in up to high intensities in Asia in northern parts of India and up to medium intensity in Iran and in Africa in Egypt, and on isolated patches surrounded by low to very low intensity in Mexico and the United States of America. AHR of pulses in Pakistan is mentioned in the agricultural census and is no artifact (Appendix K).

Citrus with rank 22 of global AHT is a classical largely irrigated crop (AHR 42% of AHT, Table 4). The AHR is spread widely within many countries, with (globally) low intensity between 1 and 3 % of grid cell area only in a few of them: Brazil (locally medium intensity), Nigeria, China, and India (Figure C-18). In contrast, AHI of citrus is concentrated often in other countries, and equally with low intensity in Egypt, Iraq, Italy, Spain, and China. The unexpected low-intensity AHI in Thailand is based on FAO data (Appendix K), while medium intensity AHI in Florida in the United States of America is based on AHT of the agricultural census for 2002 which was assumed to be 100% irrigated (Appendix K).

Date palm is a classical irrigated crop (AHR 11% of AHT, Table 4) and is the crop class with globally the smallest total AH (rank 26). AHI is extremely concentrated up to medium grid cell level intensity in the UN regions West Asia (Saudi-Arabia and Iran), and Northern Africa (Morocco and Algeria). AHR of date palm is often widespread because of the relative small harvested area and, as a consequence, low distribution priority in the downscaling procedure (Figure C-19). Areas with high concentration of very low AHR intensity are found in Egypt, Yemen, and Pakistan. It is suspected that for these countries, this spatial concentration is an artifact stemming from larger total date palm harvested area in the grid input data set [*Monfreda et al.*, 2008] than that explicitly stated in the data sources of the crop calendars for irrigated crops (Appendix K). In Pakistan, the AHI of date palm is probably contained in the AHI of fruit tree orchards, classified here as other permanent crops, because the original source of the agricultural census for 2000 did not specify crop-specific tree numbers separately for irrigated and rainfed conditions (Appendix K).

Grapes with global AHT similar to that of sugar beet (rank 23) have about one quarter of AHI (AHR 76% of AHT) and thus are an (also) irrigated crop (Table 4). AHR is distributed especially in Europe, where it reaches up to high intensity in Spain and up to medium intensity at some spots in the northwestern United States of America (Figure C-20). AHR exists also in Asia (India, China, and Iran), and in America in southern Chile. The AHR of grapes in Egypt, and possibly also that in Iran and Yemen is an artifact like that for previously discussed date palm. AHI exists typically with low intensity and with medium intensity at selected sub-national locations in southern Europe, in the UN region of Northern Africa, in South Africa and partly in the UN region of Central Asia, and in Australia. AHI exists with even very high intensity in extensive parts of the state of California in the western United States of America and at some concentrated irrigation oases in the Andean provinces of Argentina, like in the province of Mendoza. In contrast, on the other side of the Andes in Chile, AHI of grapes exists with typically only medium intensities.

For cotton, with global AHT comparable to that of millet (rank 12), is also a classical largely irrigated crop (AHR 51% of AHT, Table 4), high concentrations of AHI exist in Pakistan, central Asia, Egypt, the United States of America, China, and India (Figure C-21). AHR of cotton as a rainfed crop is also widespread. It is especially concentrated in India, China, the United States of America, but also additionally in Myanmar, in western and eastern Africa, and in South America, especially in Argentina. The very high concentration of AHR in the western Indian state of Gujarat could be also an artifact of the larger total harvested area in the input grid data set [*Monfreda et al.*, 2008] than in the data source of the crop calendar for irrigated crops (Appendix K).

Cocoa with similar AHT to that of grapes (rank 22) is an almost exclusively rainfed crop like oil palm (AHR 99.8% of AHT). AHR exists only in tropical climate zones in West Africa (up to high intensity), in Asia (up to medium intensity) and in Central and South America (up to very high intensities in Brazil and Ecuador) (Figure C-22). AHI of cocoa exists with very small intensity in eastern parts of Brazil.

Coffee, with roughly the same AHT than that of oil palm (rank 20) is also an almost exclusively rainfed crop like cocoa (AHR 98% of AHT). AHR is distributed similar to that of cocoa almost exclusively in tropical climate zones of the UN Regions of Central America (up to high intensity), South America (up to very high intensity in Brazil), Africa (up to high intensity in West Africa, up to medium intensity in East Africa and Madagascar), and Asia (up to medium intensity in Indonesia) (Figure C-23). AHI of coffee exists with up to medium intensity in mostly isolated spots in South America (Brazil and Venezuela), and in Africa (Tanzania and Ethiopia). The broad spread of very low intensity AHI in Brazil and AHR in China is obviously the result of low priorities because of (relatively) low harvested area that induced a low priority in downscaling.

The group of unspecific “other perennial crops”, with roughly the same global AHT than that of soybeans (rank 7) have a share of AHR (72%, Table 4) similar to that of other annual crops, maize and potatoes, and thus contains clearly (also) irrigated crops, too. It is a group with ubiquitous distribution on all continents, as this group includes the area of crops that were not given separately in the originals statistics. The group also aggregates individual crops not included in the list of MIRCA2000 specific crops that can be different from region to region. A typical case is that of fruit trees other than citrus, which are explicitly specified in statistics, e.g. olives in Spain (also elsewhere in Southern Europe), or generally known to be grown, e.g. apples in Western Europe and almonds in Southern Europe and California. The AHR of other perennial crops is broadly distributed with up to medium intensity in Asia, Africa, Europe, and America (Figure C-24). At specific sites, up to very high intensities exist: southern parts of the Philippines and of India, western Sri Lanka, Burundi, Rwanda, Uganda, and southern parts of Spain. Only Northern America and Oceania (except Papua New Guinea) have extremely low shares of AHR. In contrast, AHI is more concentrated. Nevertheless, broad areas of up to low intensity exist in India (especially sub-national zone of Northern India) and in China, at some spots with up to medium intensity. Further areas with AHI, mostly with not more than medium intensity, are more concentrated in Thailand, Western Asia (e.g. Iran, Iraq, Syria), Northern Africa (especially Egypt and Morocco), Southern Europe (Spain, Italy, Greece), and in America in California, western Argentina, and central Chile.

The group of “fodder grasses”, with roughly the same global AHT (rank 5) than that of other annual crops, between maize and soybeans, have a share of AHR (79%, Table 4) similar to that of soybeans, and thus are an only additionally irrigated crop group. Although it is a group with ubiquitous distribution on all continents, its patterns are not generally following those of overall AHR and AHI (Figure C-25). The AHR of fodder grasses is broadly distributed with up to high intensity in Northern America, in Southern America in eastern Argentina, Paraguay, and central Chile, and overall in Europe, especially in Eastern Europe in the Russian Federation, but surprisingly not in Poland. In Asia, up to medium intensity is found in Japan, but only low intensity in India. In Africa, AHR with up to medium intensity is found in South Africa and in Northern Africa in Algeria and Tunisia, but only low intensity in Morocco. The generally high and locally very high intensity in Egypt is certainly an artifact stemming from larger total harvested area in the grid input data set [*Monfreda et al.*, 2008], like e.g. for aforementioned rice in Pakistan. In contrast, AHI has high intensity at more concentrated sites in many countries of Central Asia, in Western Asia in Saudi-Arabia, some countries of Eastern Europe, and in the United States of America. In the Russian Federation and in the rest of Europe typically only low intensity AHI exists. In Africa in Sudan and in South Africa, and in Oceania in Australia and New Zealand typically up to medium intensity AHI with a broad distribution is found. In Australia in New South Wales and Victoria, larger concentrations of fodder grasses with up to very high intensity exist. The surprising non existence of AHR of fodder grasses in Poland is the correct result of zero area of respective crops listed in FAOSTAT which was used for the grid input of AHT [*Monfreda et al.*, 2008]. In contrast, the area of irrigated fodder grasses was estimated from another source that mentions alfalfa and grass and permanent grassland (see Appendix K).

The group of unspecific “other annual crops”, with roughly the same AHT (rank 4) than that of other perennial crops, between that of maize and soybeans, have a share of AHR (71%, Table 4) similar to that of the group of other perennial crops, maize and potatoes. As a result, it contains clearly (also) irrigated crops. It is a group with ubiquitous distribution on all continents. This group like that of other perennial crops includes the area of crops that were not specified separately in the originals statistics. It aggregates individual crops not included in the list of MIRCA2000 specific crops, different from region to region. Typical cases are vegetables, “roots and tubers”, sweet potatoes, “other cereals”, oats, and unspecific “others”. While the AHR of other perennial crops is broadly distributed with considerable intensity on all continents with the exception of Northern America and Oceania, the AHR of other annual crops exists on all continents and follows the general pattern of overall AHR (Figure 4, top), with some deviations: In Northern America, Canada has areas with AHR of other annual crops with up to medium intensity (sometimes also high intensity), while these are only spotty in the United States of America. In Southern America AHR exists with medium intensity in Paraguay, but to a much lesser degree in Argentina and Brazil. In Africa, AHR with medium or even high intensity is concentrated to the tropics, but not found in Southern Africa. In Asia, large areas with AHR with medium to high intensity exist in India, China, and Bangladesh (all three of them with even very high intensity at some spots), Myanmar, and on the Philippines, but not elsewhere. In Europe, AHR with medium intensity exists especially in Eastern Europe, in Poland also with up to high intensity like in Germany. Similarly, for AHI the general pattern also follows that of the overall AHI (Figure 4, center). In Asia, broad areas of AHI with low intensity are found in India, China, and Thailand, while in southern Viet Nam, in Pakistan and in countries of Western and Central Asia up to high intensity AHI exists. In Northern Africa, Egypt has up to very high intensity AHI of other annual crops, different from the high intensity areas elsewhere in this region which remain in this class. In Southern Europe, in France AHI up to low intensity exists, while in Spain, Italy, and Greece up to medium intensity AHI is found. In America, medium intensity AHI is found mainly in special zones, such as California or central Chile, or spotty in Mexico and Argentina. For AHI, the reason of the large amounts in some countries can be tracked from the detailed crop calendars (Annex B in *Portmann et al.* [2008]). The high AHI for other annual crops in Pakistan are due to annual fodder (about 22,000 km^2) and vegetables (3300 km^2). In Egypt, the area stems from fodder (12,000 km^2), vegetables (4700 km^2), sesame (300 km^2), and unspecific “other annual crops” (2100 km^2). In California, most of the area is from double-cropped vegetables (ca. 41,000 km^2), besides safflower, sweet potatoes, oats, and mint (Table 2).

3.2 Seasonality of irrigated and rainfed crop growing areas

Global sums of monthly crop-specific growing areas of irrigated wheat, maize, rice and cotton depict differences between rainfed and irrigated crops, and between the Northern Hemisphere and the Southern Hemisphere. As has been already shown previously for harvested area (Table 4), also the monthly maximum rainfed growing area over all four crops except rice is in general larger than the irrigated growing area. Also, often the Northern Hemisphere exhibits larger monthly growing areas than the Southern Hemisphere, especially for irrigated crops. On the Southern Hemisphere, growing areas of all four irrigated crops are generally very low (Figure 5, top), while larger areas and percentages of total area occur for rainfed maize and rice (Figure 5, bottom). The monthly growing areas show specific intra-annual seasonality. The distribution of irrigated rice (Figure 5, top) reflects multi-cropping in the major production regions, mainly Asia, with two peaks in July to August (0.595 million km^2 area each), and November to February (0.405 million km^2 area each), 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 Northern 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. On 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 the growing season in Northern Hemisphere summer. On 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.

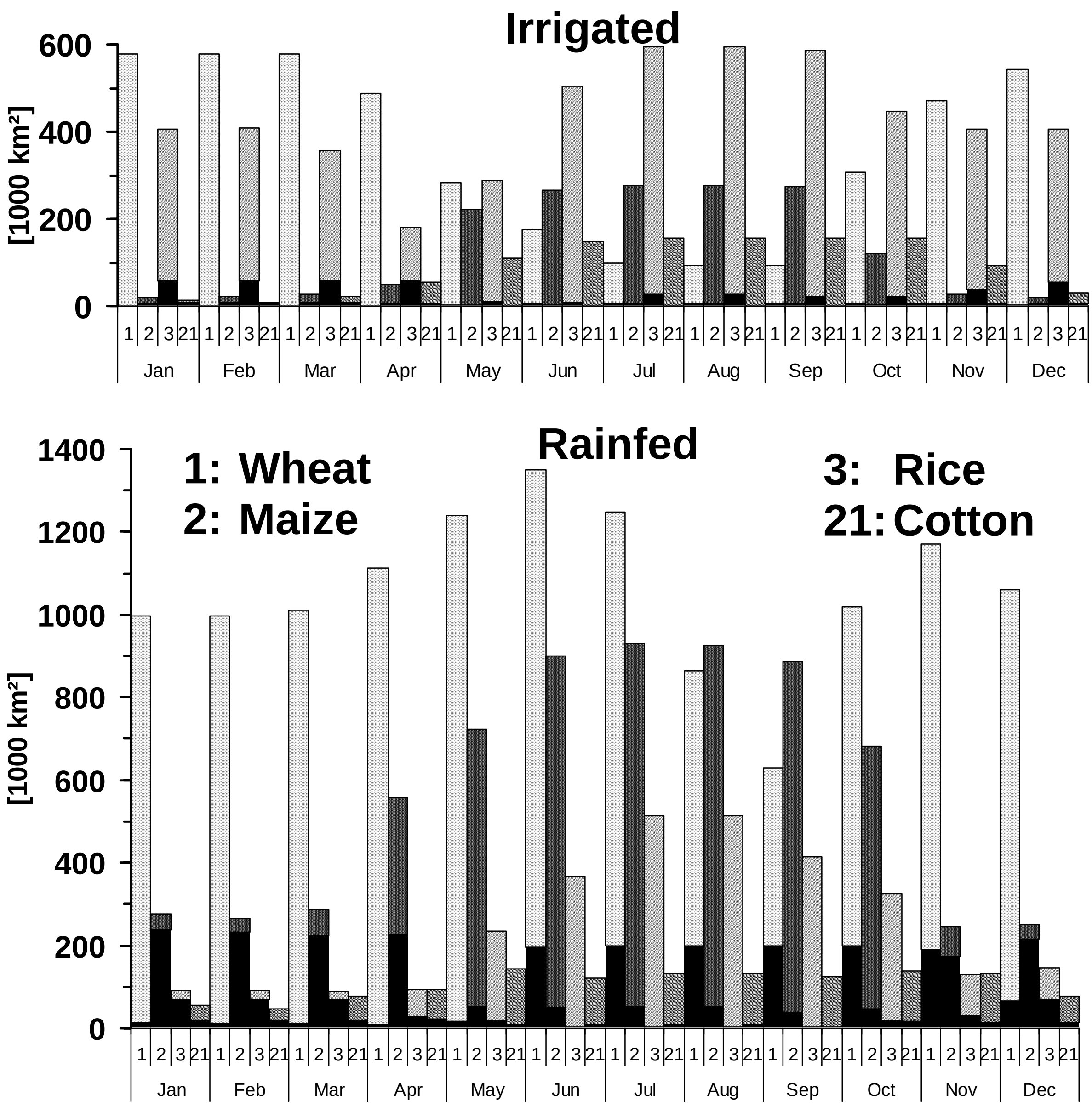

Figure 5. Global monthly growing areas of wheat (crop class 1), maize (crop class 2), rice (crop class 3), and cotton (crop class 21) irrigated (top), rainfed (bottom), with distinction of areas of Northern Hemisphere (upper part of columns) and of Southern Hemisphere (lower part of columns, in black), in km^2, for 1998-2002 [*Portmann et al.*, 2010].

As an example for the spatial pattern of monthly growing areas provided by MIRCA2000, 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 on the Southern Hemisphere (in Argentina, Brazil and Australia) rainfed wheat extent prevails in July, during winter.

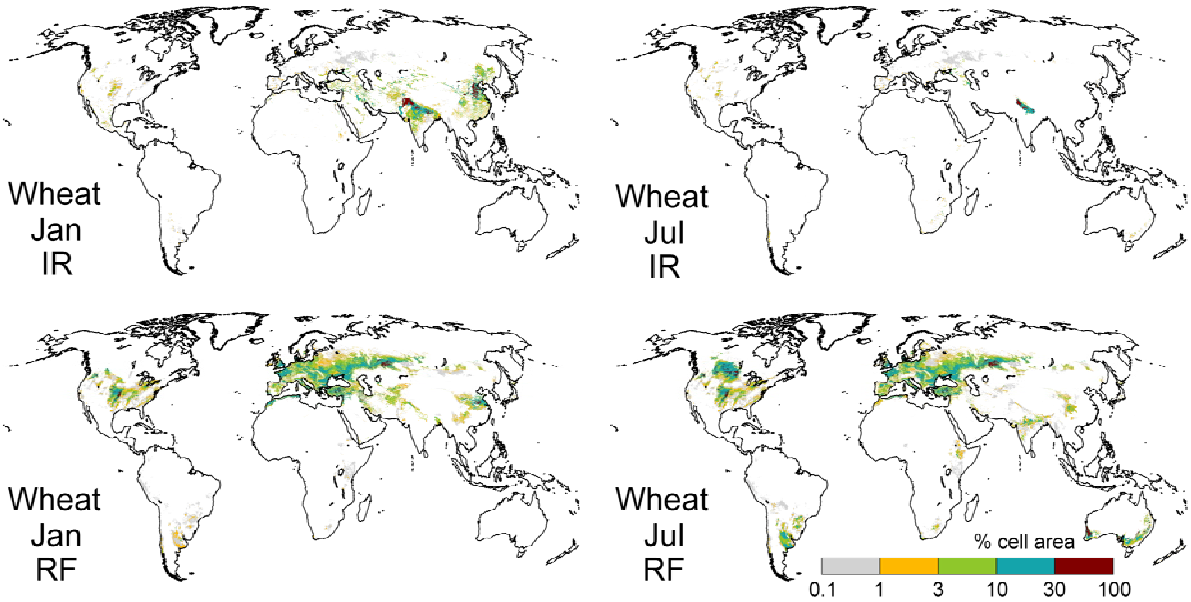

Figure 6. Irrigated (IR, top) and rainfed (RF, bottom) monthly growing area of wheat in January (left) and July (right), as a percentage of grid cell area, for 1998-2002 [*Portmann et al.*, 2010].

3.3 Cropping intensity

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. Therefore, a minimum cell-specific cropping intensity *CI_min(cell)* that takes fallow land into account was defined 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:

$$CI\_\max(cell) = \frac{AH(cell)}{MMGA(cell)} \tag{2}$$

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 afterwards 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 non-overlapping 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.

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 sub-tropical 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 semi-arid zones 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 south-western and south-eastern 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). But also tropical or sub-tropical 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 months cropping period.

CI_min is large in regions with warm temperatures and humid climates like south-east 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 South-eastern Asia, most of Europe (except the Russian Federation), northern parts of the United States, central Southern 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).

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 of America, South Australia, and Central Asia) or in the aforementioned regions with shifting cultivation.

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 B in Appendix B). 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 of America). 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 (Table 5 and Table B in Appendix B).

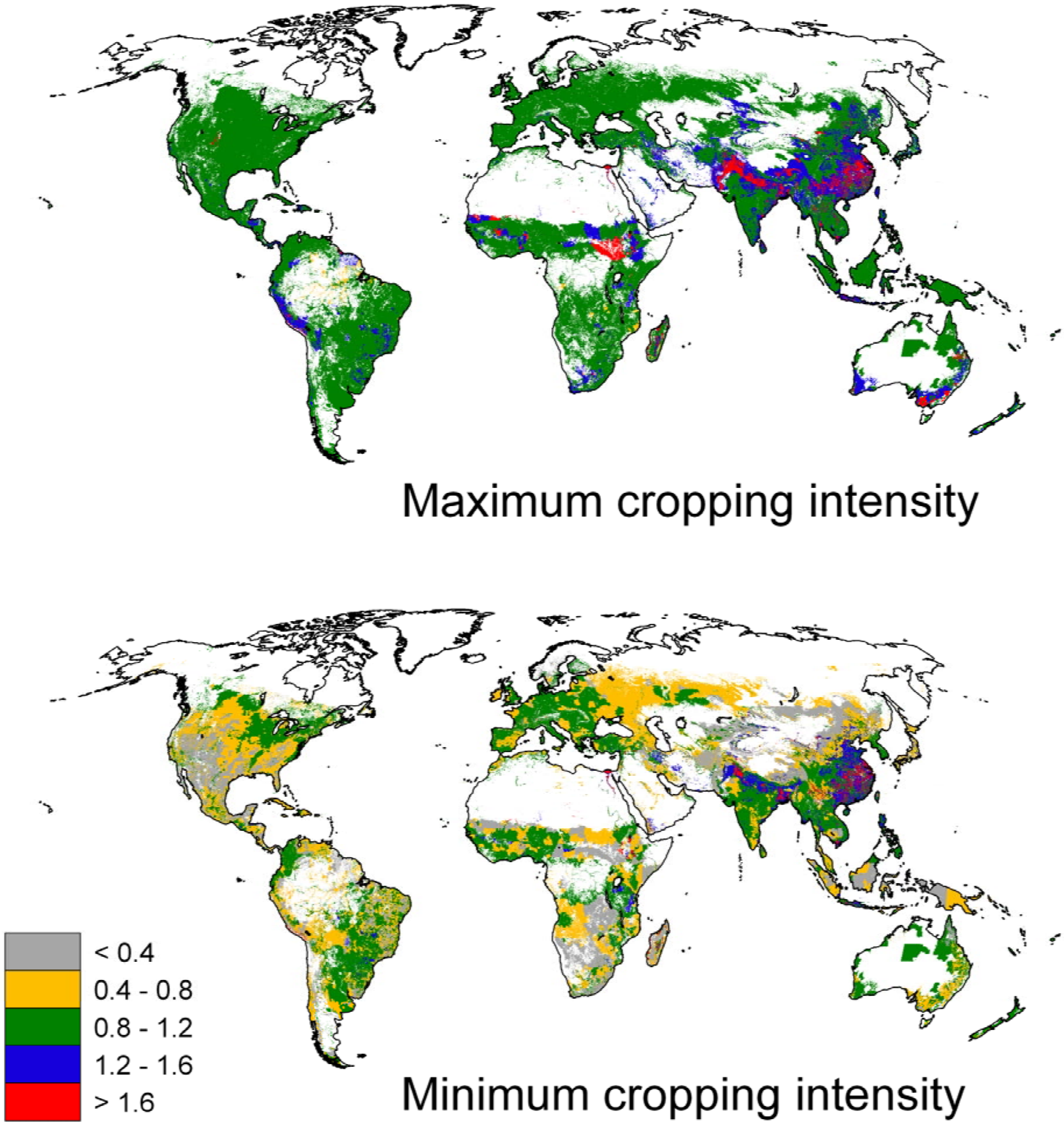

Figure 7. Cropping intensity for 1998-2002, defined by including fallow land (CI_min, bottom) or not (CI_max, top) [*Portmann et al.*, 2010].

4 Comparison to other data sets

A validation in strict sense of global data sets like MIRCA2000 is difficult, because independent reference information at appropriate levels like countries or grid cells is often not available. As an alternative, a comparison to other data sets with somewhat comparable information is possible. Nevertheless, the origin of differences to theses other data sets can result from e.g. different data sources or reference years of the input data, from the downscaling methodology, or from the estimation of cropping periods. Furthermore, depending on the subsequent application, one specific aspect can be especially important (e.g. consistency to total harvested area at the grid cell level of specific crops), while other aspects are less important. Therefore, for an exemplary assessment of accuracy of MIRCA2000 two basic aspects were selected: crop-specific harvested area with the distinction of irrigated and rainfed crops, and the seasonality. First, MIRCA2000 harvested areas of irrigated and rainfed crops were compared to different inventories per country (Chapter 4.1) or per sub-national statistical unit (Chapter 4.2). Second, at the 5 arc-minute 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 at 30 arc-minute resolution (Chapter 4.3). A more detailed assessment with respect to Condensed Crop Calendars and grid cell level differences yields quality parameters for each country, sub-national climate zone or unit (Chapter 4.4).

4.1 Comparison to crop statistics at country level

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, the Nash-Sutcliffe model efficiency E [*Nash and Sutcliffe*, 1970] was computed 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), $\overline{O}$ the arithmetic mean of the observed data and S 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.

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 based on 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 ten 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 re-examined for possible errors, but no transfer error was detected. For Australia, the totals are also of similar order of magnitude (ca. 118,000 km^2 in MIRCA2000 and ca. 95,000 km^2 in IFPRI) while the irrigated share is very different, ca. 1,000 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 1,670 km^2 irrigated harvested area of cereals other than rice [*ABS*, 2002, 2001].

Table 6. Comparison of MIRCA2000 harvested area to data from IFPRI, global harvested areas (km^2 yr^{-1}), the model efficiencies Nash-Sutcliffe E and coefficient of determination r^2 calculated from data for 21 individual countries with validation data, IR denotes irrigated, RF denotes rainfed [*Portmann et al.*, 2010].

Crop	Global harvested area				E		r^2	
	Irrigated		Rainfed		IR	RF	IR	RF
	IFPRI	MC2000	IFPRI	MC2000				
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

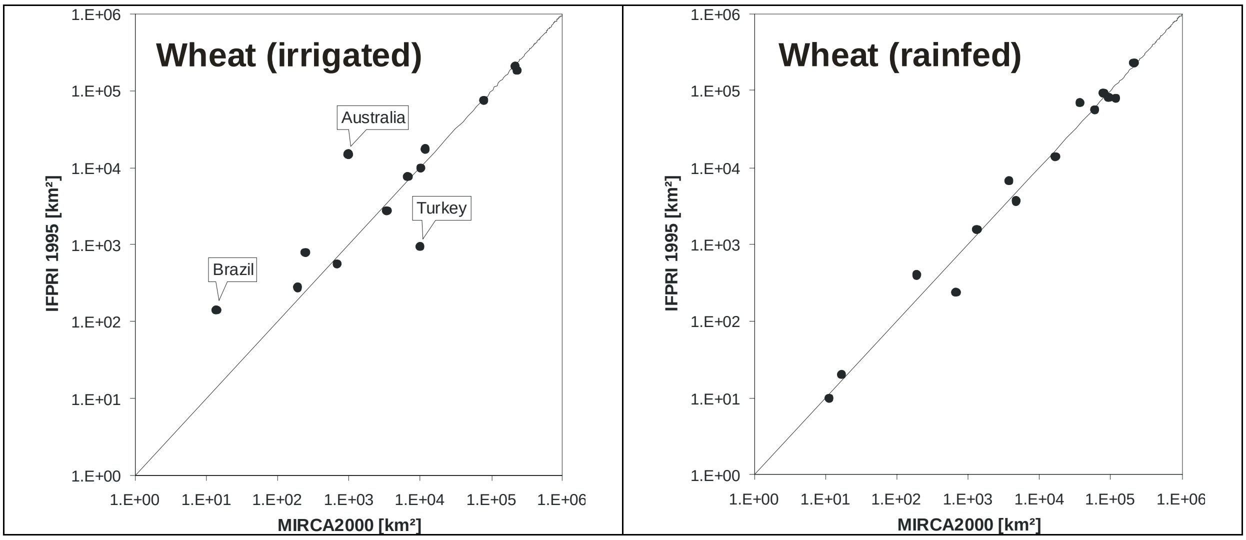

Figure 8. Irrigated and rainfed harvested area of wheat in 21 countries. Comparison of MIRCA2000 values to IFPRI values for 1995 [*Portmann et al.*, 2010].

4.2 Comparison to sub-national crop statistics

MIRCA2000 harvested areas of irrigated maize and irrigated grapes were compared to statistics of the Statistical Office of the European Communities (EUROSTAT) for 103 first-level sub-national 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 sub-national statistics that refer to year 2003. To compare the spatial distribution for both crops, irrigated harvested area [*EUROSTAT*, 2008a] as a 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 sub-national 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.

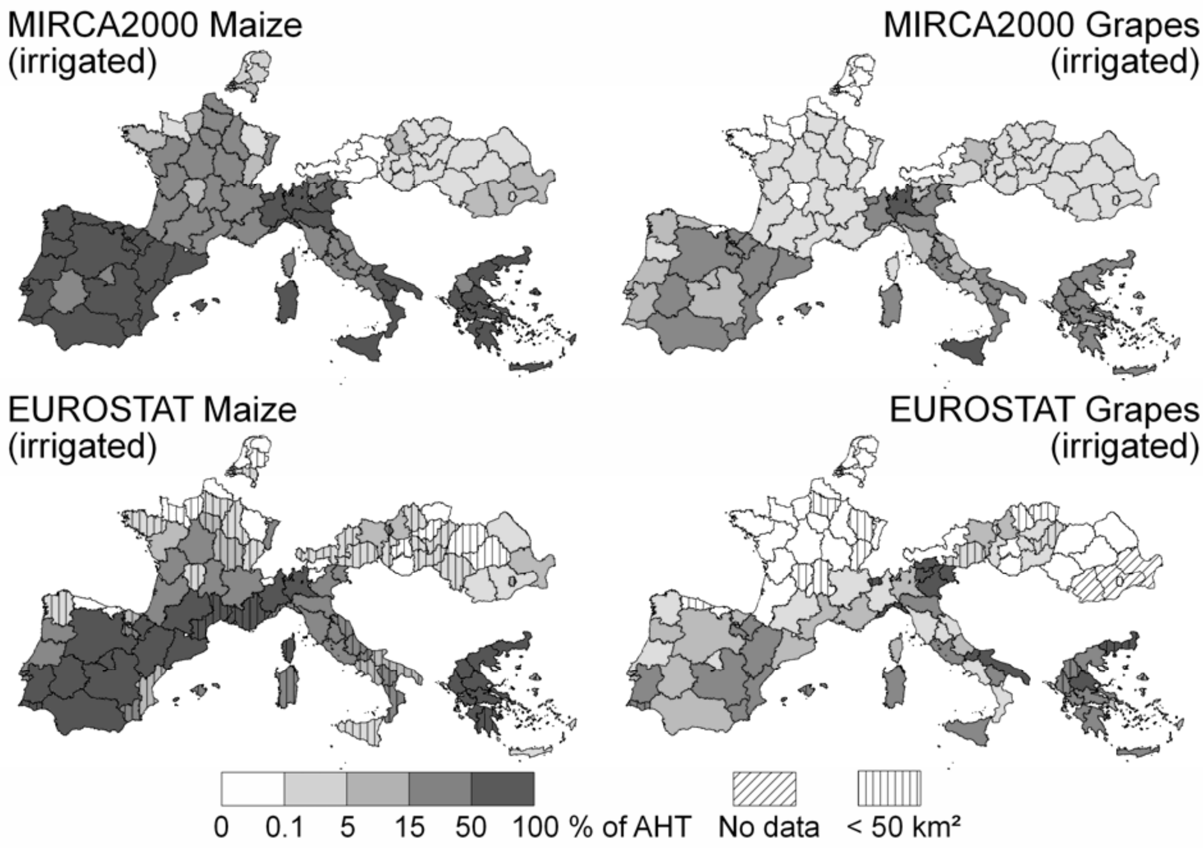

Figure 9. Irrigated harvested area as a percentage of total harvested area for maize and grapes according MIRCA2000 (top) and EUROSTAT for 2003 (bottom), by EUROSTAT NUTS administrative units of 2003. Units with EUROSTAT irrigated harvested area less than 50 km^2 are marked by vertical hatching, units with no EUROSTAT data for total harvested area are marked by diagonal hatching [*Portmann et al.*, 2010].

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 sub-national 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. But this only shows that the national data of irrigated and rainfed maize and grapes are consistent with the sub-national 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 sub-scale differences in the importance of irrigation for specific crops could be improved if Condensed Crop Calendars were defined for sub-national units, in particular for large countries that have zones with very different climate and soil conditions.

For a number of other crops, potatoes, sugar beet, and barley, the MIRCA2000 data have already been compared to the European Irrigation Map (EIM) which is based on sub-national EUROSTAT statistics combined with other input data such as GMIA and a regression on crop-specific irrigation probability [*Wriedt et al.*, 2009]. These three crops show consistent distribution patterns in both data sets. Local deviations follow differences in input data, disaggregation algorithm, and ancillary information and expert knowledge used to fill missing data. According to *Wriedt et al.* [2009], the areas in EIM are more concentrated than in MIRCA in the case of sugar beet, citrus, and grapes, due to the usage of general irrigation intensity. For grapes, Figure 9 underlines this external finding. Differences in total area exist: For barley in Germany, EIM assumes low priority irrigation, while in MIRCA2000 the non-existence of irrigated barley was estimated. The potatoes AHI area in Germany, Portugal and the United Kingdom are much higher in MIRCA2000 than in EIM [*Wriedt et al.*, 2009]. For Germany, the difference is explainable by a possibly wrongly estimated share of irrigated potatoes, which was used as no crop-specific EUROSTAT areas were available. For Portugal, the mentioned difference is surprising as MIRCA2000 used EUROSTAT areas for 2003, too. For the United Kingdom, the difference can be explained by different data sources. MIRCA2000 uses relative shares of irrigated crops including potatoes for 8 sub-national regions determined by a study of Cranfield University [*Morris et al.*, 2004] (see also Appendix K).

4.3 Cropping periods

MIRCA2000 cropping periods are compared in the following Chapter to simulation results of the dynamic global vegetation model LPJmL (“Lund-Potsdam-Jena managed Land”) [*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 multi-cropping 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 on harvested area 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 multi-cropping. 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.

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-minutes. For each grid cell, the start dates of the cropping periods in the MIRCA2000 Condensed Crop Calendars (CCC) were compared to mean sowing and harvesting dates simulated by LPJmL. Except for rice, LPJmL does not allow multi-cropping. The objectives of this comparison were:

1) To test the general agreement of the cropping periods between the MIRCA2000 data set to the simulation results of the vegetation model,
2) To explore the variability of planting dates inside the 402 spatial units as computed by LPJmL and not taken into account in MIRCA2000,
3) To 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) To evaluate the importance of multi-cropping practices considered in MIRCA2000 but not yet considered in LPJmL.

Maize and wheat were selected for this comparison, the latter being parameterized as temperate cereal in LPJmL. 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 multi-cropping systems during the winter period. To compare the data sets, the LPJmL results were downscaled to 5 arc-minute resolution by assigning the cropping periods of the 30 arc-minute grid cells to each of the 5 arc-minute cells located within the related 30 arc-minute 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, 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) was computed. If more than one sub-crop was reported in MIRCA2000, a mean difference was computed by weighting the differences computed for the specific sub-crops by their harvested area. Negative values indicated that the cropping period in MIRCA2000 started earlier (Table 7). The algorithm to calculate these differences is technically demanding, concerning both the difference in time and its weighting for relevant grid cells. Since the start of the cropping periods that had to be compared can be in different calendar years, it was required to test the difference of the start in both directions, forward and backward on the time axis, and to select the lowest absolute difference. If, for example, a cropping period in MIRCA2000 started on 1 December (Julian day 335) and in LPJmL on 5 January (Julian day 5), the final selected difference would be -35 days, indicating that the MIRCA2000 cropping period started 35 days earlier than that simulated by LPJmL. Weighted means for the higher aggregation levels such as spatial units and UN regions (Appendix F) were calculated based on absolute differences and crop-specific harvested area in the compared grid cells (Table 7).

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 South-Eastern 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.

The absolute area-weighted differences in the start of the cropping periods were relatively large, between 43 days (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 Northern 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 spatial 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.

A similarly complex pattern is observed in the United States of America, where winter wheat cropping periods start in MIRCA2000 between September and October [*USDA*, 1994]. In the predominantly winter wheat growing areas toward the South of the United States of America LPJmL simulates a start in November, resulting in a negative time difference. In the North, the mixture of winter wheat and spring wheat in MIRCA2000, as compared to only winter or summer wheat in LPJmL results in a complex pattern of positive and negative differences.

A large difference for irrigated wheat was found in Argentina for which a cropping period during summer was estimated while LPJ modeled winter wheat.

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.

Table 7. Absolute difference between start of cropping period as computed by MIRCA2000 and LPJmL, in days, together with the MIRCA2000 harvested area in grid cells where according to LPJmL constraints do not allow crop growth, as a percentage 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 cells in which both exist [*Portmann et al.*, 2010, reordered].

	Irrigated				Rainfed			
	Wheat		Maize		Wheat		Maize	
Region*	cAH	Start	cAH	Start	cAH	Start	cAH	Start
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
AFRICA	**17**	**75**	**1**	**98**	**22**	**39**	**8**	**51**
Caribbean	-	-	6	131	-	-	7	36
Central	84	62	1	117	98	131	1	31
Northern	0	62	1	15	0	34	3	34
South	11	85	15	75	17	37	5	60
AMERICA	**27**	**65**	**2**	**46**	**4**	**35**	**3**	**42**
Central	0	49	2	21	0	112	-	-
Eastern	2	46	2	28	4	64	5	62
South-Eastern	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
ASIA	**43**	**52**	**2**	**42**	**11**	**68**	**8**	**57**
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
EUROPE	**1**	**35**	**3**	**27**	**1**	**41**	**3**	**22**
OCEANIA	**2**	**31**	**1**	**94**	**8**	**16**	**35**	**73**
WORLD	**41**	**53**	**2**	**44**	**6**	**44**	**5**	**43**

* Compare Appendix F for a definition of the UN regions.

Large differences occur if LPJmL simulates only one cropping period defined by optimum climate conditions, while in MIRCA2000 multi-cropping practices are manifested. This concerns e.g. irrigated maize in South-East China or in India. Here, often maize is cultivated in rotation with other crops and farmers try to optimize the whole multi-cropping 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.

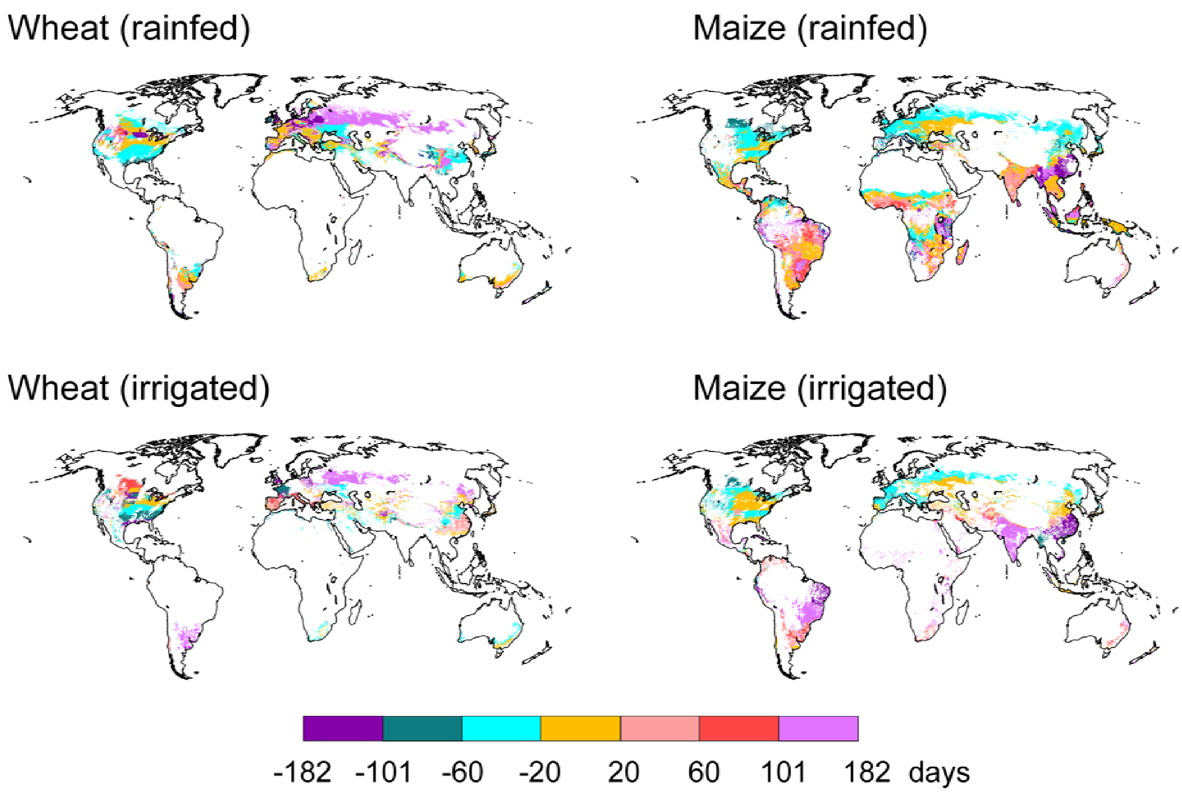

Figure 10. Differences between start of cropping period as computed by MIRCA2000 and LPJmL for wheat and maize as rainfed and irrigated crops, in days. Negative values denote that the period in MIRCA2000 starts earlier. In the case of wheat in MIRCA2000, the start date is an average of the start dates for winter and summer cropping periods in those cells in which both exist [*Portmann et al.*, 2010].

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 sub-tropical regions in particular if multi-cropping 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).

4.4 Quality parameters

In the previous Chapters 4.1 to 4.3 mainly absolute differences of the MIRCA2000 data set to other data sets have been described, considering the crop-specific irrigated or rainfed harvested area and the seasonality. In contrast, the MIRCA2000 quality parameters of this Chapter indicate relative quality differences between the crops (global parameter) or between the spatial units (i.e. countries, sub-national units, sub-national climate zones), based on comparable quantitative information at the level of units. Besides one global crop-specific quality parameter and several unit-specific (i.e. often country-specific) quality parameters also an overall country-specific quality mark was developed. In this Chapter first the methods for the calculation of the individual parameters (Chapter 4.4.1) and then the methodology to compute the overall quality mark are described (Chapter 4.4.2). Finally, the results of the calculations are shown in form of tables and maps and are discussed (Chapter 4.4.3). The detailed results at country level (and, if necessary, sub-national zones or units) are tabulated in Appendix D. Complete lists of parameter values on the level of units (or countryother aggregate levels, if applicable) together with spreadsheet tables that document also the respective calculations are provided in supplementary Appendix L. Table L-1 addresses the overall quality mark on a country level, Tables L-2 to L-6 contain details of individual quality parameters, while Table L-7 lists the code and name of each unit.

4.4.1 Methods for calculation of individual quality parameters

The most distinct quality measure can be specified on unit level (and thus, on country level) for the crop classes and the areas of irrigated crops found in the Condensed Crop Calendars. While areas of some crop classes were explicitly mentioned in the original data sources, others appeared only in crop groups different from the MIRCA2000 crop classes. This enables to derive a rough estimate of quality of classification of the irrigated crop classes, depending on the explicit or implicit mentioning of the crop class in the original source. In parallel, this also indicates the presence of certain crop classes in a given unit. In the case of rainfed crops, no fully consistent quality measure for the classification and the areas in the CCCs can be given. This is because the area of rainfed crops per unit was derived from unit-level balancing of the crop-specific total harvested area AHT with the crop-specific irrigated harvested area AHI, both from different data sources (Chapter 2.2). As a consequence, the occurrence of a crop as a rainfed crop and its rainfed area on the level of units are derived values rather than independent values. When AHT is larger than AHI, rainfed crop area may be “created” from scratch where it should not exist in reality on the process scale (for definition of this term see Chapter 5.1). This is suspected in countries with semi-arid and arid climates, e.g. Pakistan (rice, sugar beet, date palm), Egypt (date palm, grapes, fodder grasses), Yemen (date palm, grapes), and the Indian state of Gujarat (cotton).

The final interactions between the input data are on grid cell level. Absolute accuracies of the derived grid cell level information can hardly be given: First, appropriate reference data on grid cell level are missing. Second, if the areas were spatially distributed uniformly within the units, an estimation of accuracy in absence of any grid cell level reference data could have been made through statistical methods, e.g. the Bayesian theory and conditional probability distribution functions. But in the downscaling of MIRCA2000 the interference is not uniform between, on one hand, unit-level data in the Condensed Crop Calendar to distribute, and, on the other hand, the conditions of input data at a specific grid cell, where the relations of total harvested areas of the crops or sub-crops, AEI, and cropland extent are, in most cases, different to those at the unit level. A hypothetic example can demonstrate this: Irrigated potatoes area explicitly mentioned in the CCC on unit level could be distributed at a completely wrong location when crop-specific harvested area in the grid input data was at sites with only rainfed potatoes. Nevertheless, quality parameters based on grid cell level differences that are aggregated to the upper spatial levels, e.g. spatial units or countries, provide an indication on differences on grid cell level without predicting accuracies for specific cells.

Therefore, it was tried to find methods to assess important quality aspects with easily available and interpretable quantitative information. Three sets of quality parameters were eventually established, which are characterized by differences in scope (crops globally, calendars, units) and the sources of the input data (unit-level CCC, grid cell level values). The first quality parameter describes the global presence and classification quality of specific irrigated crops in the crop calendars. It indicates the relative quality between crops, across all spatial units. The other two parameter sets specify the relative quality between spatial units. The second set refers to the unit-level quality of crop calendars (irrigated and rainfed) which are the basis for the downscaling. Its quality parameters are based on unit-level detailed crop calendars and related climatologic values that are also evaluated for sub-national climate zones. The third set refers to the quality measures derived from grid cell level values. The grid cell level values were input data grids, MIRCA2000 grids, and their differences (AHI, AHR, AHT, cropland extent). In the case of AEI, external quality information on country level is cited.

Global presence and classification accuracy of specific irrigated crops (Q1_IR)

Not every crop class is present in each unit, and possibly their harvested area is disaggregated from an aggregated summary class or the presence is assumed. In the original source statistics of the detailed crop calendars for irrigated crops, the harvested areas of some crop classes were explicitly mentioned for a given unit (e.g. “3000 ha wheat” in a hypothetic example). Other crop classes (e.g. maize) were contained there in groups with a different classification (e.g. “2000 ha other cereals”) for which more or less reliable external auxiliary information could be used for disaggregation (e.g. “dominant cereals are wheat and maize”, derived value 2000 ha maize). But possibly besides 1500 ha of “lemon trees”, the rest area had to be attributed a specific crop class by own expertise: E.g. “500 ha other annual crops”, “1000 ha perennial crops” (from another, secondary source), and “500 ha fodder grasses / managed grassland”.

The crop-specific classification accuracy parameter is calculated in the following way: The absence of a crop class in a crop calendar of a specific unit (country or sub-national unit) is marked by a parameter value of 0. A crop class is defined to be present when any explicit non-zero area is mentioned. When the area of a crop class is explicitly mentioned in the original classification scheme, the parameter Q1_IR mark is 1 (Q1_IR_mark). In the hypothetic example, this is the case for wheat, citrus (lemon trees), and fodder grasses. The Q1_IR_mark is 2 when the area is disaggregated from a summary class (e.g. “other cereals”) or taken from a secondary or less reliable source (e.g. one that specifies an area while the first source does not), or when the occurrence of the crop class was estimated (e.g. “oil crops” to be sunflower). In the hypothetic example, this is the case for “other annual crops” that could have been assumed to be vegetables (but not, say, to be potatoes), and “perennial crops” (because of the area taken from a secondary source). Thus, on the level of the units, the Q1_IR_mark represents at the same time, first, the crop-specific presence (marks 1 or 2), and, second, the area-related classification quality that can be low (mark 2) or high (mark 1). Globally across countries, or across several sub-national units of a given country, the following additional indicators for a specific crop can be drawn: The number of non-zero marks, denoted by Q1_IR_count, is an indicator of explicit or implicit presence of the respective crop. It can be specified as absolute number or as a percentage of all units. The crop-specific percentage of high quality area data presence, denoted by Q1_IR_pct, is calculated as the frequency of occurrence of mark “1”, multiplied by 100 and divided by Q1_IR_count of the respective group of units.

Quality parameters of crop calendars (Q2)

Area-weighted deviation of the classification of irrigated crops, per country (or unit), across crops (Q2_1_IR)

In the case of the aforementioned hypothetic example of a crop calendar for irrigated crops for a specific unit (most often corresponding to the country), the 500 ha of harvested area (AH) “other annual crops” were assumed to be 100% vegetables (with respective area), as vegetables are often irrigated under all climatic conditions. The 1000 ha of “other perennial crops” could have been estimated to be olive trees, because it was generally known that besides the 1500 ha of lemon trees that fall into the MIRCA2000 class of “citrus”, also olive trees were irrigated in that unit. The 500 ha of “fodder grasses / managed grassland” fall into the MIRCA2000 class of “fodder grasses”. The aim was to calculate a parameter in form of an area-weighted deviation from ideal classification within the range of 1 to 3. To obtain the final Q2_1_IR parameter value, the crop-specific harvested areas are multiplied by a weighting factor equal to the Q1_IR_mark, except for the unspecific crop classes for which the factor is 3, and divided by the sum of the harvested areas. If all crop areas were within specific crop classes, then Q2_1_IR_mark would be 1 (for all crops Q1_IR_mark = 1 and crop-specific weight factor Q2_1_IR_factor = 1). If all areas (and no unspecific crop classes present) were disaggregated, then Q2_1_IR_mark would be 2 (all crops Q1_IR_mark = 2 and Q2_1_IR_factor = 2). Finally, if all areas were within unspecific crop classes, then Q2_1_IR_mark would be 3 (all crops Q2_1_IR_factor = 3). For the hypothetic example, the procedure to calculate the Q2_1_IR_mark value is as follows: the areas of specifically mentioned crops are multiplied by a Q2_1_IR_factor of 1 (wheat 3000 ha * 1, citrus 1500 ha * 1), the areas of disaggregated crops are multiplied by a Q2_1_IR_factor of 2 (maize 2000 ha * 2 = 4000 ha), while the areas of unspecific crops (others annual, others perennial, fodder grasses) are multiplied by a Q2_1_IR_factor of 3 (other annual crops 500 ha * 3 = 1500 ha, other perennial crops 1000 ha * 3 = 3000 ha, fodder grasses 500 ha * 3 = 1500 ha). The total accumulated multiplication sum of harvested area of (3000 + 1500) + (4000) + (1500 + 3000 + 1500) equals 14,500 ha and is divided by the total harvested area of all crops of (3000 + 1500) + (2000) + (500 + 1000 + 500) that equals 9500 ha, resulting in a Q2_1_IR_mark value of 1.53. For countries with several sub-national units, the country level quality mark is calculated by adding the multiplication sums of all sub-national units and dividing the result by the respective overall total harvested area for the whole country.

Seasonal climatic variability for precipitation and air temperature, per country (or sub-national climate zone, or unit) (Q2_2_P, Q2_2_T)

The cropping periods of the crop calendars for irrigated crops of the FAO [*FAO*, 2005a] built the starting point for the cropping periods of the MIRCA2000 crop calendars for irrigated crops for countries where these calendars existed. The FAO calendars were determined through FAO expertise and possibly the application of a crop model using climatologic time series of selected sites [*FAO*, 2008b]. As previously mentioned, the cropping periods of the MIRCA2000 crop calendars for rainfed crops were determined by a comparison of the crop calendars for irrigated crops with external calendar data [e.g. *FAO*, 2005b; *USDA*, 1994], textbook information on the length of cropping periods and air temperature requirements [*Doorenbos and Pruitt*, 1977], and with station-based monthly precipitation and air temperature climatologic data of the FAOCLIM2 data base [*FAO*, 2001]. The climatologic data were used as a cross-check for calendars for both irrigated and rainfed crops [*FAO*, 2001]. This means, that the start and end of cropping periods in the calendars were largely determined (or validated) by climatologic time series. The climatic variability quality parameters Q2_2_P and Q2_2_T of the calendars are based on the assumption that increased seasonal variability of mean monthly precipitation and air temperature at grid cells with cropland would increase the probability that the start and the end of irrigated (and rainfed) cropping periods were correctly identified in MIRCA2000.

To estimate the seasonal, or intra-annual, climatic variability within each unit, the range between maximum and minimum of climatologic mean monthly precipitation (or temperature, respectively) of the grid cells belonging to the considered unit is calculated. To calculate the mean value for the unit, the grid cell level values are weighted with the MIRCA2000 cropland extent CE_{MIRCA}. The value for the country or sub-national climate zone was determined through the same weighting procedure, using respective aggregated values. Separate values for precipitation (in mm d^{-1}) and for temperature (° Celsius) are specified. As source of the climatic data the 30 arc-minute mean climatologic values for the period 1961-1990 of the Climate Research Unit (CRU) as distributed by the IPCC Data Distribution Center were used [*IPCC Data Distribution Centre*, 2009; *Mitchell and Jones*, 2005; *New et al.*, 1999]. The data were downscaled to 5 arc-minute spatial resolution in the same manner than previously the LPJmL cropping periods by assigning the values of the 30 arc-minute grid cells to each of the 36 5 arc-minute cells located within the related 30 arc-minute cell. To estimate the reliability of the mean difference, the standard error was calculated with a standard textbook formula [*Sachs*, 1984]. To estimate the spatial variability of the weighted values would need complicated statistical or geostatistical evaluations that were deemed to be not efficient for the objectives.

The resulting seasonal differences were interpreted with a 3 level classification ranging from small, medium to large as follows for precipitation Q2_2_P: small (≤ 2.5 mm d^{-1}), medium (2.5 – 5 mm d^{-1}), large (> 5 mm d^{-1}), and for air temperature Q2_2_T: small (≤ 10 °C), medium (10 – 20 °C), large (> 20 °C). The quality of the calendar was considered to be potentially poor when the variability of both precipitation and temperature were classified to be small.

Quality parameters derived from grid cell level differences, per country or sub-national unit (Q3)

These quality parameters are calculated with grid cell level differences aggregated on the levels of countries or sub-national units.

Deviation of cropland extent (Q3_1_CE)

The grid cell level difference between MIRCA2000 cropland extent CE_{MIRCA} and the CE of the input data set [*Ramankutty et al.*, 2008] can indicate whether there were adjustments to the original data or not. It is only a measure on observation scale (for definition of this term see Chapter 5.1), but no absolute quality measure on process scale as the quality of the input data set on process scale is unknown, but may be up to 20% (Chapter 5.1). The parameter Q3_1_CE specifying deviation as a percentage of the reference area is calculated as the country-level (or unit-level) sum of grid cell level absolute deviation of MIRCA2000 cropland extent CE_{MIRCA} from the CE of the input data set [*Ramankutty et al.*, 2008], divided by the respective country-level (or unit-level, respectively) sum of the grid cell level maximum of CE of either source, and multiplied by 100.

A value of 0% would indicate a perfect fit, while larger values until a maximum of 100% indicate larger relative deviations. The resulting differences were interpreted with a 3 level classification ranging from small, medium to large as follows: small (≤ 10%), medium (10 – 25%), large (> 25%).

Deviation of total harvested area (Q3_2_AH)

The MIRCA2000 total harvested area AHT_{MIRCA} is not necessarily the same as the total harvested area of the input data set AHT_M [*Monfreda et al.*, 2008]. This could occur when crop-specific harvested area of irrigated crops surpasses the respective harvested area in the input data set and when no AH of unspecific other crops are available to compensate this, either on unit level or on grid cell level. Another source of difference could occur when different cropping intensities are assumed, as AHT_M

can contain up to 3 cropping periods (or crop rotations) in grid cells with irrigation, while this number is not necessarily the same in the CCC-I of MIRCA2000 [*Monfreda et al.*, 2008]. The parameter Q3_2_AH specifying deviation as a percentage of the reference area is calculated as country-level (or unit-level) sum of grid cell level absolute deviation of MIRCA2000 total harvested area AHT_{MIRCA} from the total harvested area of the input data set AHT_{M} [*Monfreda et al.*, 2008], divided by the country-level (or unit-level) sum of the grid cell level maximum of AHT of either source, and multiplied by 100.

A value of 0% would indicate a perfect fit, while larger values until a maximum of 100% indicate larger relative deviations. The resulting differences were interpreted with a 3 level classification ranging from small, medium to large as follows: small (≤ 10%), medium (10 – 25%), large (> 25%).

Quality of area equipped for irrigation (Q3_3_AEI)

During the downscaling of irrigated harvested area AHI the area equipped for irrigation AEI plays a key role. When grid cell level AEI is confident, then also the distribution of AHI is more reliable. But when quality of AEI remains poor, then AHI is probably distributed with bad quality, too. As quality parameter Q3_3_AEI the already existing country-level quality mark of the Global Map of Irrigation Area GMIA is used, with values theoretically ranging from 0 (excellent), 1 (very good), 2 (good), 3 (fair), 4 (poor) to 5 (very poor) [*Siebert et al.*, 2005; *Siebert et al.*, 2006; *Siebert et al.*, 2007]. It has to be noted that this overall quality mark for AEI is calculated based on two quantitative indicators. The first indicator, IND_A in the original notation, represents the density of the used sub-national irrigation statistics, as explained in *Siebert et al.* [2005: 124]: IND_A equals the average size of all sub-national units in a country if the irrigation density is the same all over the country. If all irrigated area (of a country) is concentrated in only one sub-national unit, IND_A is equal to the size of this sub-national unit. IND_A is lower than the country-level average size of the sub-national units if the irrigation density is higher in small sub-national units than in the larger sub-national units. Lower values of IND_A indicate a better GMIA quality. The second indicator IND_B presents an estimate of the density of geospatial information used to assign irrigated area to specific cells within the sub-national units. IND_B equals the fraction of irrigated area that could be assigned to specific grid cells by using geospatial records on the position and extent of known irrigation projects. Higher values of IND_B indicate a better GMIA quality. Specific equations for calculating the indicators are available [*Siebert et al.*, 2005; *Siebert et al.*, 2007].

Both indicators were assigned a country-level quality mark according to the classification in Table 8 [*Siebert et al.*, 2005]. The overall country-level Q3_3_AEI quality mark was then assigned from both indicator values with the assumption that the types of information that are reflected by IND_A may substitute IND_B and vice versa. Therefore, the GMIA overall quality mark was in general set to the better of the two individual marks assigned according to IND_A and IND_B. When there were doubts regarding the reliability of the information used for a specific country, the GMIA overall quality mark was downgraded, which was the case in 64 out of 211 countries, or 30% of the countries in GMIA version 3 [*Siebert et al.*, 2005]. With version 4 of GMIA, Q3_3_AEI is actually within the range of "very good" (1) to "poor" (4) [*Siebert et al.*, 2007].

Table 8. Classification of GMIA quality indicators IND_A and IND_B [*Siebert et al.*, 2005, modified].

Mark	Numerical representation of mark	Indicator IND_A	Indicator IND_B
		[ha]	[%]
Excellent	0	≤ 100,000	90 – 100
Very good	1	100,000 – 250,000	70 – 90
Good	2	250,000 – 500,000	50 – 70
Fair	3	500,000 – 1,000,000	25 – 50
Poor	4	1,000,000 – 3,000,000	10 – 25
Very poor	5	> 3,000,000	≤ 10

Spatial dispersion of AHI and AHR (Q3_4_AHI, Q3_4_AHR)

During the downscaling of the unit-level harvested area AH to the grid cells, the AH could be distributed to few or many grid cells with MIRCA2000 cropland. When there are only few cropland cells, then the distribution should be more exact. In case that the harvested area is distributed to a large number of cropland cells, the dispersion is greater, and the probability is higher that AH is distributed to cells where it possibly should not be located, thus increasing the inaccuracy. The spatial dispersion Q3_4 is calculated as the sum of the cell area of grid cells where AH is present, divided by the land area of the respective country (or unit), and expressed as a percentage of land (i.e. surface) area. It implies that MIRCA2000 cropland extent CE_{MIRCA} is larger than zero. The parameter is calculated separately for irrigated harvested area (Q3_4_AHI, with AEI larger than zero) and for rainfed harvested area (Q3_4_AHR). To calculate the correct land area of the countries (or units) a separate land mask was generated. This was necessary because the unit mask used in the MIRCA2000 downscaling covered the total area of the globe including all kind of water surfaces in order to include all areas from grid input data generated with different land masks (Chapter 2.2.3). The new land mask contained two sets of grid cells, a first set derived from converting directly the polygons of administrative boundaries to 5 arc-minute grid cells on terrestrial land with a standard GIS-tool, plus an additional set of grid cells for which CE_{MIRCA} existed but which were not included in the first set. In case that the official country land area in the attribute table of the polygon layer with administrative boundaries [*ESRI*, 2004] was larger than the area derived from the generated sets of grid cells, this larger area was used as land area. This was the case when information on cropland extent was missing in the input grids and when the standard GIS tool extracted no or only a few cells because of the size or the shape of the country polygon. This procedure ensured that especially for small countries (or units) a numerically correct reference area was used.

The larger the spatial extent of the cropland where harvested area is distributed, relative to the total land area, the larger is parameter Q3_4. If cropland and the distribution of AH are very concentrated at a few spots only, then the Q3_4 percentage of land area is small. Values calculated for total harvested area AHT are often nearly the same as those for AHR, while in general being larger than those for AHI, reflecting the dominance and broader distribution of rainfed agriculture. The only exception to this rule holds for arid countries such as Egypt where irrigation is (nearly) the only water source for agriculture (see supplementary Table L-6). Therefore, values for AHT were considered to provide no additional information and were excluded from further evaluation.

A value near 0% indicates a very concentrated distribution, while a value near 100% indicates that used agricultural area exists in almost the whole of the respective country (or unit). The resulting differences were interpreted with a classification of 5 classes ranging from very small to very large as follows: very small (≤ 10%), small (10 – 25%), medium (25 – 50%), large (50 – 75%), and very large (> 75%).

4.4.2 Calculation of the overall quality mark

The values of the directly calendar-based quality parameters (Q1_IR and Q2 sets) can be considered more or less absolute measures based on well-defined input data. However, the values of the individual cell-based quality parameters (Q3 set), that are like the Q2_2 sub-set parameters aggregated at the level of countries (or units), cannot be combined in a straightforward numeric way with Q2 set measures, nor with those of the other parameters of the Q3 set. The combination of the CCC with grid-based input data which result in the final grids of e.g. growing areas and harvested area in downscaling has strong nonlinear relationships. Thus, the cell-based quality parameters Q3_1_CE, Q3_2_AH, and Q3_4_AHI (and _AHR) rather indicate relative differences between the considered units (countries, administrative sub-national units) when looking at one single parameter, than give absolute quality measures for individual cells. However, it was tried to combine the information on quality of the various parameters into a single overall quality mark Q_MC. First, the individual quality parameters were standardized to a range of 0 (best performance) to 100 (least performance) within the theoretical minimum and the maximum value of all considered countries. This implied that for parameters Q2_2_P and Q2_2_T, where no theoretical boundaries existed and where the smallest values represent the least performance, the parameter values were rescaled within the range of globally observed minimum to maximum to the new range of 0 to 100, and then inverted by subtracting the result from 100. The quality mark of the area equipped for irrigation Q3_3_AEI, with a theoretical range from 0 to 5 was rescaled, too, but within these theoretical limits. Then Q_MC was calculated as the arithmetic mean of all rescaled and possibly inverted parameter values that were present for the specific country, leading to the same theoretical range from 0 to 100. In case that no irrigation existed, Q2_1_IR, Q3_3_AEI, and Q3_4_AHI were omitted from the calculation. In case that no data on harvested area existed, Q_MC was not calculated. As Q3_3_AEI is only available at country level, the final quality mark was also only determined at this level. The resulting Q_MC mark can be interpreted in terms of relative differences between countries in the overall mean of deviation, dispersion, and quality. The parameter should be interpreted with some caution, because it is an un-weighted mean and multi-collinearity between the individual quality parameters cannot be fully excluded, and because the distribution process to grid cells is highly non-linear.

4.4.3 Results and discussion of the quality parameters

The results of the quality parameters are discussed, parameter by parameter, in the sequence they were introduced in the previous Chapters 4.4.1 and 4.4.2.

The global crop-specific Q1_IR parameter indicates the global presence and classification quality of the crops in the detailed crop calendars for irrigated crops, and thus also the CCC-Is (Table 9). Its Q1_IR marks were established for all units, without differentiation of sub-national and national units. In the case of countries with sub-national units, not every country had a unique classification scheme in the data sources used for these units. For Australia, Brazil, and India always all classes were mentioned for each state, even if not all of the classes were filled in a specific state. For the United States of America, in each state, only the classes with reported areas were mentioned in the original data source, although a distinct general national classification scheme was applied. In order to represent all the data, they had to be transferred in a re-constructed general scheme of crop items that were not always filled. In the case of China and Indonesia, areas were given for zones (3 for China, 2 for Indonesia) in unified national classification schemes. Because of the relatively large extent of the zones, all classes were filled in each zone. In the case of China, during the establishment of the detailed crop calendars, the areas for the zones were scaled to the individual provinces using the relative AEI share of the GMIA, as on the level of provinces additional information was available. As a result, all of these six countries exhibit a uniform pattern of Q1_IR_marks “0”, “1”, or “2” across the 26 crop classes for all sub-national units. In the case of Argentina, each province had a different classification scheme, and, thus, presents a different pattern of Q1_IR_marks. The evaluation for the list of the 26 crop classes is shown in Table 9, while the unit-specific data are found in supplementary Table L-2.

Irrigated crops exist in about 86% (Q1_IR_pct) or 346 (Q1_IR_count) of the overall 402 units (including the two units Antarctica and Small Islands that have no cropland) (Table 9). Most often maize, potatoes, rice, and wheat are irrigated besides omnipresent unspecific classes “others annual” and “others perennial”, each in more than ca. 200 units (Q1_IR_count), corresponding to at least ca. 55% of the 346 units with irrigated crops. “Other annual” crops are even present in more than 95% of the 346 units (rank 1 of Q1_IR_count, i.e. occurrence), and “other perennial” crops in more than 82% of these units (rank 2). Also sugar cane and citrus are quite abundant, occurring in at least 43% of these units, while cotton is present in about 36% of these units with irrigation. Surprisingly, the globally dominant crops in terms of global harvested area (Table 4), rice (rank 4 with 56% occurrence), wheat (rank 5 with 58%), and maize (rank 3 with 67%), are not necessarily always specifically mentioned with high quality, maize with Q1_IR_pct of only ca. 75% of the units where maize is mentioned being the one with the least precision of the three (Table 9). Potatoes with rank 3 in occurrence of irrigated crops (Q1_IR_count 230 or ca. 65% of all units with crops) are only mentioned in high quality in 65% of the units where the crop occurs as irrigated. Not surprisingly, the unspecific classes “others annual” and “others perennial” are mentioned with detailed crop names in only 30% and 50% of the units, respectively, where they are contained in the crop calendars. The areas of the scarcely represented irrigated classes oil palm (2 units) and date palm (16 units) are only in ca. 50% of the units from explicit or confident sources. On contrary, the three crop classes also present in a small number of units, cassava (28 units), cocoa (7 units), and coffee (28 units) have relatively high classification accuracy (> 85% Q1_IR_pct), because the areas of these classes were almost completely drawn from explicit mentioning of the crop areas. But also rape seed area is often induced from secondary sources, as the percentage of about 25% of high quality mentioning in the 30 units with irrigated rape seed indicates.

Table 9. Crop-specific occurrence and classification accuracy of irrigated crops in the detailed crop calendars for irrigated crops, globally over all units. For the definition of the quality parameter items Q1_IR_count and Q1_IR_pct see text.

Crop name	Occurrence of irrigated crop class Q1_IR_count number of units	 % of units with any crop	Q1_IR_pct High-quality mentioning of crop area (% of units with specific crop)
Wheat	195	56.4	81
Maize	234	67.6	76
Rice	202	58.4	85
Barley	116	33.5	49
Rye	66	19.1	30
Millet	65	18.8	60
Sorghum	99	28.6	76
Soybeans	115	33.2	90
Sunflower	94	27.2	80
Potatoes	230	66.5	65
Cassava	28	8.1	93
Sugar cane	152	43.9	91
Sugar beet	48	13.9	69
Oil palm	2	0.6	50
Rape seed	30	8.7	27
Groundnuts	88	25.4	90
Pulses	119	34.4	76
Citrus	151	43.6	79
Date palm	16	4.6	50
Grapes	99	28.6	54
Cotton	126	36.4	85
Cocoa	7	2.0	86
Coffee	28	8.1	96
Others perennial	286	82.7	50
Fodder grasses	142	41.0	59
Others annual	329	95.1	31
Any crop	**346**		

The spatial pattern of the Q2_1_IR parameter of the area-weighted deviation of ideal classification (or homogeneity of source) of the crops in the detailed crop calendars for irrigated crops (Figure 11) is based on the spatial level of the units as these provide the area data for the evaluation. The parameter values are documented in Table D-1 in Annex D for the country level, and for the unit level in supplementary Table L-2.

From the group of countries with large agricultural production for which sub-national units were available, China and India with globally important harvested areas e.g. of rice and wheat, show relatively small classification deviations of the calendar sources, with a Q2_1_IR_mark value of less than 1.2 (the class with least deviation) or less than 1.8, respectively. In China the uniform values below 1.2 are mainly because the data sources are predominantly the FAO calendars from 3 zones for which the crop lists are identical, and because the classes of "other annual crops" and "other perennial crops" have only relatively small harvested areas of ca. 29,000 km^2 (2.9 Mha) out of a total of 856,000 km^2 (85.7 Mha). In India only some states fall into the second category of values between 1.2 and 1.8 because the sources of the data are mainly national statistics and partly from the secondary source of FAO calendars. The area of "other" crops is similar to that in China, while their proportion of harvested area is slightly higher, ca. 30,000 km^2 (3.0 Mha) out of a total of 687,000 km^2 (68.7 Mha).

In the United States of America the pattern is different: in the central part, deviations are similar to those in India, i.e. until 1.8, whereas in the eastern and western parts Q2_1_IR_mark values above 1.8 are prominent. In general, these are the consequences of relative large shares of "other" crop classes including fodder grasses. In the case of Florida, the reason for the elevated Q2_1_IR_mark value is the relatively large citrus area that was assumed to be irrigated, with Q1_IR_mark = 2 and Q2_1_IR_factor = 2. This pattern is similar in Argentina, where in the southern part the share of "fodder grasses" is big; while in the north-western province of Catamarca "other perennial" crops have a large share, leading to Q2_1_IR_marks of 3 and 2.5, respectively. In Brazil the pattern is determined by the unspecific "others" crop classes which dominate clearly in the western states the harvested area with more than 60% of the total harvested area. The same situation is found in Australia in the south in Victoria and Tasmania, in the west in Western Australia, and in the Northern Territories.

In Africa, the small Q2_1_IR_mark values of the Democratic Republic of the Congo, Mali, and Madagascar originate from a small list of crops of homogeneous sources almost without unspecific "others" crop classes. The latter dominate e.g. in Cameroon, the Central African Republic, and Ghana and lead to the higher deviation Q2_1_IR_mark in the highest class above 2.4.

In Europe, the quality is deteriorated especially in the UN region Eastern Europe. Reasons are disaggregation of classes (e.g. in the Russian Federation or the Netherlands), estimations (e.g. Norway, Sweden, and Switzerland), or larger shares of unspecific "others" crop classes (e.g. Czech Republic, Estonia, and Switzerland).

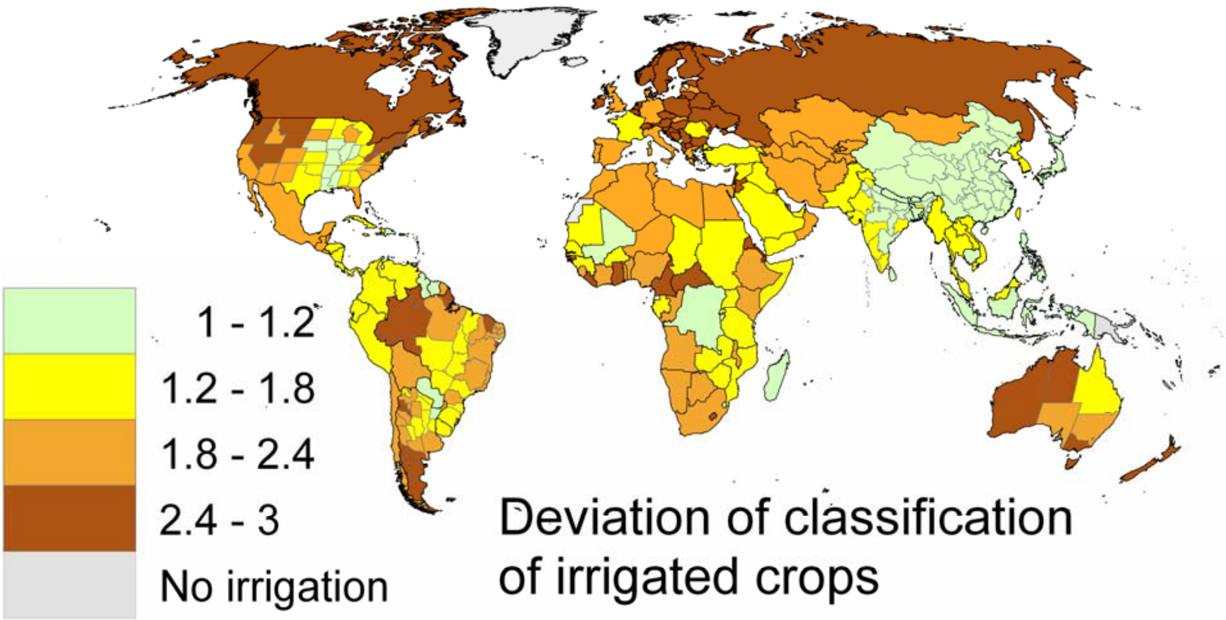

Figure 11. Quality parameter Q2_1_IR of area-weighted deviation of classification of crop calendars for irrigated crops, per unit. If all crop areas are well classified in the original source Q2_1_IR has a value of 1, if all crops (besides unspecific crops) are disaggregated Q2_1_IR is 2, and if all crops are "others annual", "others perennial" or "fodder grasses" Q2_1_IR is 3.

The Q2_2 parameters to check the seasonal climatic variability of the crop calendars with respect to precipitation (Q2_2_P) and air temperature (Q2_2_T) were evaluated at the level of units when these correspond to countries. In case of countries with sub-national units in addition to the country level and to the unit level also Q2_2 parameter values for the sub-national climate zones listed in Appendix K were calculated (Table D-1 in Appendix D and supplementary Table L-3). Therefore, for the seven concerned countries (Argentina, Australia, Brazil, China, India, Indonesia, and the United States of America) the variability within these climate zones (Table D-2) and also within the sub-national units was calculated (Table D-3). In general, the standard error of both parameters was minimal, i.e. below 2%, and increased with decreasing size of the unit. The values of the error are therefore not shown here, but supplied for the units in supplementary Table L-3.

Both sub-parameters display strong variability either in precipitation or in temperature, or in both: At country level, they range from 0.6 to 30.8 mm d^{-1} (Q2_2_P) and from 0.8 to 39.1 °C (Q2_2_T), respectively. At the level of sub-national units the range increases slightly: The minimum precipitation variability is 0.5 mm d^{-1} (Argentina, Santa Cruz province, included in the Argentine climate zone "Southern Patagonia and Fireland"), while the maximum temperature variability increases to 41.7 °C (China, Heilongjiang province, climate zone Northeast) (Table D-3).

To extract units where calendars are difficult to establish, thresholds were introduced. A variability of less than 2.5 mm d^{-1} precipitation and less than 10 °C air temperature was estimated to be a reasonable limit below which the crop calendars are difficult to establish from a climatic point of view. Only 6 units out of the total 400 units with agricultural area (omitting the 2 units with no cropland, Antarctica and Small Islands) met this constraint, covering 48,363 km^2 or 0.3% of the MIRCA2000 cropland extent (Table D-1, Table D-3, and supplementary Table L-3). As the concerned units are scarce and small, no map of these parameters is shown, but they are specifically marked in the Tables

Nearly all of them have oceanic climate: Tierra del Fuego (0.6 mm d^{-1}, 8.2°C, Argentina, climate zone Southern Patagonia and Fireland, 0.09 km^2 MIRCA2000 cropland), Tasmania (1.9 mm d^{-1}, 9.5°C, Australia, with own climate zone, 1495 km^2), and Ireland (1.8 mm d^{-1}, 9.96°C, 11,503 km^2) (Tables D-1 and D-3). Obviously, for these units, the definition of the cropping periods is quite difficult, and remains uncertain as no specific further external reference to determine cropping periods for these units exists. But a least for Tierra del Fuego, the area can be neglected.

In another case, for the unit of Santa Catarina (2.3 mm d^{-1}, 9.1°C, Brazil, climate zone South, 18,793 km^2), the parameter value for precipitation is slightly below the arbitrarily chosen limit (Table D-3). For Brazil, specific calendar information at least for irrigated crops, but also partly for rainfed crops were available to establish the calendar [*FAO*, 2005a; *USDA*, 1994; *FAO*, 2005b]. So the Brazilian calendar appears to be quite reliable.

For a last group of units in the Middle East, the neighboring countries of Djibouti (1.3 mm d^{-1}, 8.7°C, 20 km^2) and Yemen (1.0 mm d^{-1}, 8.5°C, 16,551 km^2) regionally depict very low rainfall that leads to the small seasonal variability (Table D-1). For both countries, specific FAO crop calendars for irrigated crops were available [*FAO*, 2005a], while for rainfed crops information on neighboring countries of Eritrea and Saudi-Arabia, or neighboring regions had to be used [*USDA*, 1994; *FAO*, 2005b]. Therefore, probably the rainfed calendar of these countries could be improved or the rainfed area will have to be assumed to be irrigated.

The parameters of deviation of cropland extent (Q3_1_CE) and that of harvested area (Q3_2_AH) show broad similarities in the spatial patterns between each other (Figure 12, Table D-1, and supplementary Table L-4). Therefore, they are discussed jointly.

On a global level, deviations between the MIRCA2000 values of cropland extent CE_{MIRCA} (or harvested area AH_{MIRCA}, respectively) and the values of the input data sets CE (or AH_M, respectively) sum up to 1.0 million km^2 for cropland extent, or 6.5% of the grid cell maximum of CE_{MIRCA} and CE (i.e. the reference CE of this quality parameter), while for harvested area they are 1.6 million km^2 or 11.4% of the grid cell maximum of AH_{MIRCA} and AH_M (i.e. the reference AH of this quality parameter). Deviations of cropland extent up to 10% in a given unit globally account for 0.37

million km^2, which is 2.3% of the global reference cropland extent and 35.5% of the global sum of deviation of cropland extent (see supplementary Table L-4). Deviations of cropland extent with more than 25% in a given unit globally account for 0.24 million km^2, which is 1.5% of the global reference cropland extent and 23.3% of the global sum of deviation. Deviations of harvested area up to 10% in a given unit globally account for 0.28 million km^2, which is 2.0% of the global reference AH, and 17.7% of the global sum of deviation of harvested area. Deviations of harvested area with more than 25% in a given unit globally account for 0.65 million km^2, which is 4.7% of the global reference harvested area and 23.3% of the global sum of deviation.

Concerning the spatial pattern of Q3_1_CE and Q3_2_AH, small deviations up to 10% of the reference value occur in a larger number of units for CE than for AH.

For cropland extent, units falling into this class are found within the group of countries with globally important agricultural production especially in the central and eastern United States of America, India, half of China (many central and north-eastern provinces), the southern part of Australia, and the Wet Pampas climate zone of Argentina. The small deviations are also found in most of Europe, as well as the Russian Federation, and surprisingly most of the African countries.

For harvested area, the main centers of small deviations are again the central and eastern United States of America, India, the Wet Pampas climate zone of Argentina, most of Europe, and the Russian Federation. But only the southwestern part of Australia and a smaller number of countries in Africa (not the large producers Nigeria and South Africa) fall into this class.

Deviations of AH and of CE larger than 25% of the reference value occur in eastern Asia in the southern provinces of China and in Japan, in America in the arid southwest of the United States of America, southern and western Argentina, neighboring Chile, Paraguay, the Brazilian state of Amapá, French Guiana and Suriname. In Africa units with this deviation are found in Egypt and Libya, and also in neighboring states of the Arabian Peninsula besides Yemen, in central Asia in Turkmenistan and Kyrgyzstan, in Oceania in the state of Northern Australia, Tasmania, and New Zealand.

“New” units with large deviations of AH, but less deviation of CE include many countries of the Middle East, South Africa, Madagascar, and the island of Java in Indonesia.

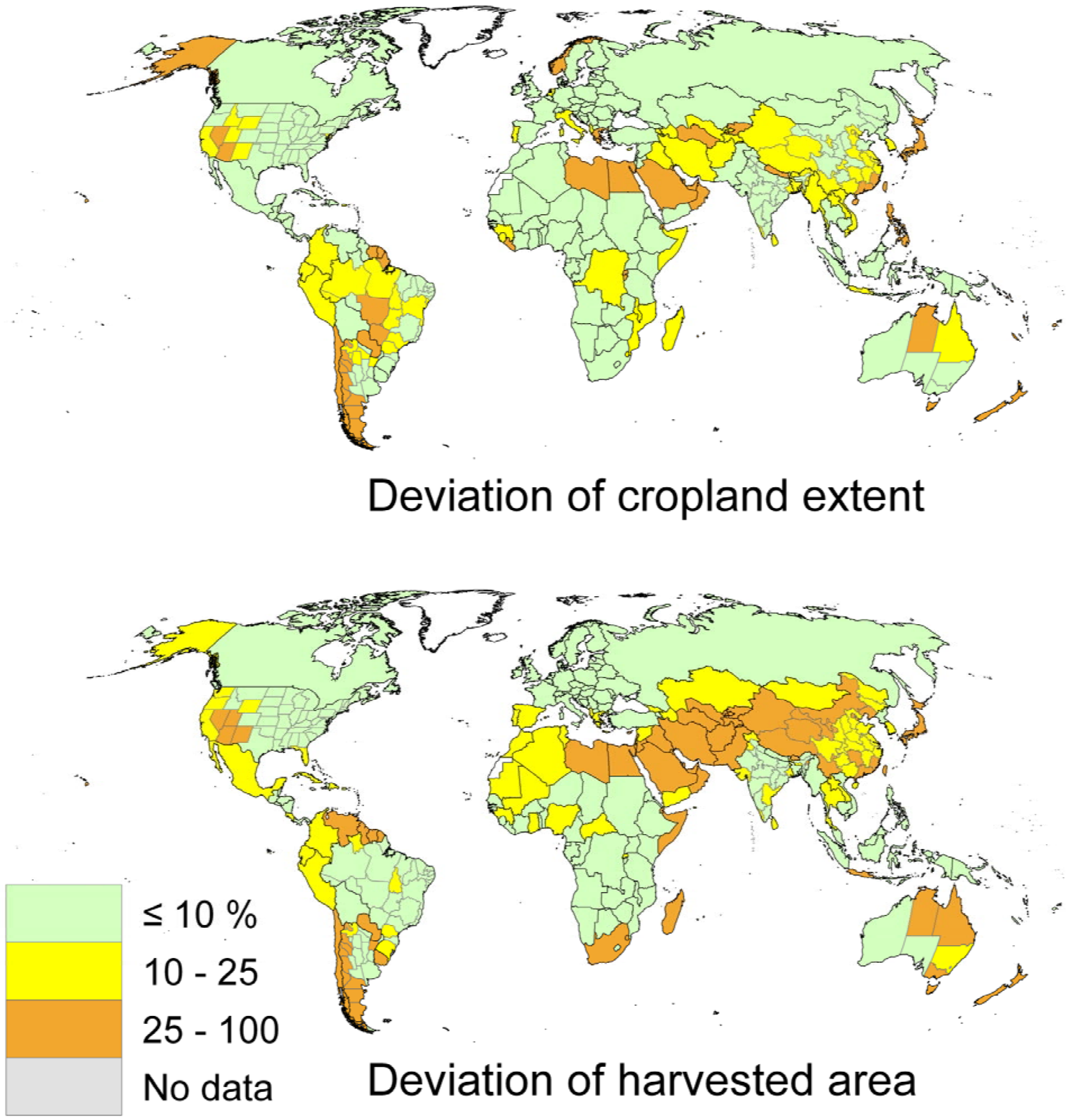

Figure 12. Quality parameters Q3_1_CE (top) and Q3_2_AH (bottom). Q3_1_CE is the grid cell level deviation (difference) of MIRCA2000 cropland extent CE_{MIRCA} and cropland extent of input data set CE, as a percentage of grid cell level maximum cropland extent of either source, per unit. Q3_2_AH is the grid cell level deviation (difference) of MIRCA2000 total harvested area AHT_{MIRCA} and harvested area of the input data set AH_M, as a percentage of grid cell level maximum harvested area of either source, per unit.

For the globally important major crop-producing regions, the following conclusions can be drawn: only small deviations of both CE and AH (up to 10 %) occur in the major regions in the central and eastern United States of America (besides California), the Wet Pampas zone of eastern Argentina, India, and most of Europe, including Turkey and the Russian Federation. In Australia, Western Australia falls into this group, but major deviations can occur, especially in terms of AH, in New South Wales, Queensland, Victoria, and Tasmania.

Especially important are the deviations in rice-producing countries China, Indonesia (island of Java), Japan, Viet Nam, Myanmar, and Thailand. A reason there could be the discrepancy between different total AH and cropping intensity on irrigated areas, that can be up to 3 in the grid input data set of harvested area AH_M [*Monfreda et al.*, 2008], but is not necessarily the same in AH_{MIRCA}.

Also the large deviations of CE and AH in Egypt are striking. Reasons for this have been discussed intensively elsewhere [*Portmann et al.*, 2008], and are summarized here: First, the input data set of cropland extent CE [*Ramankutty et al.*, 2008] does not indicate everywhere cropland where the input data set of AEI does, e.g. in western Egypt on the coast. Second, the input AH_M is higher than AH_{MIRCA}, and rainfed harvested areas are "generated" by the balancing of the crop-specific total harvested areas and the irrigated harvested areas. As a consequence of the distribution algorithm, first irrigated and then rainfed harvested area is distributed to areas where the input CE and input AH_M is zero or at least smaller than required, but where AEI exists [*Portmann et al.*, 2008, Figures 2.3 and 3.8].

The parameter of quality of the area equipped for irrigation Q3_3_AEI is drawn from the country-level quality mark of the GMIA [*Siebert et al.*, 2006; *Siebert et al.*, 2005]. It has to be noted that the full range of classes is not filled, as no country has excellent (class 0) or very poor (class 5) data quality in GMIA version 4 [*Siebert et al.*, 2007].

The AEI-weighted overall quality mark is 1.88 (good) for the total of 2.788 million km^2 of AEI (Table D-1). Very good (1) quality data accounts for ca. 0.65 million km^2, which is 23.4% of global AEI, and good (2) quality for 1.87 million km^2, which is 66.9% of global AEI. Less quality is only observed to lower percentages: fair quality (3) for 0.21 million km^2, which is 7.7% of global AEI, and poor quality (4) for 0.055 million km^2, which is 2.0% of global AEI (see supplementary Table L-5).

Very good data quality is present in many small countries, but only a few countries with large country-level sums of AEI (> 20,000 km^2), namely the following countries: the United States of America (AEI ca. 279,000 km^2), Thailand (ca. 49,900 km^2), Afghanistan, Uzbekistan, Australia, Egypt, South Africa, Spain, and Italy.

Other countries with large AEI such as India (ca. 570,000 km^2), China (ca. 538,000 km^2), and Pakistan (ca. 144,000 km^2) have only good data quality.

From countries with poor data quality, the Russian Federation (ca. 48,900 km^2) is by far the largest (Figure 13, Table D-1, and supplementary Table L-5).

According to GMIA, irrigation is not only practiced in the main irrigation areas, but also, to a minor extent in almost any populated area of Latin America or Europe (Figure 4, center) [*Siebert et al.*, 2006]. This is important for the parameter that describes the dispersion of the irrigated harvested area, Q3_4_AHI.

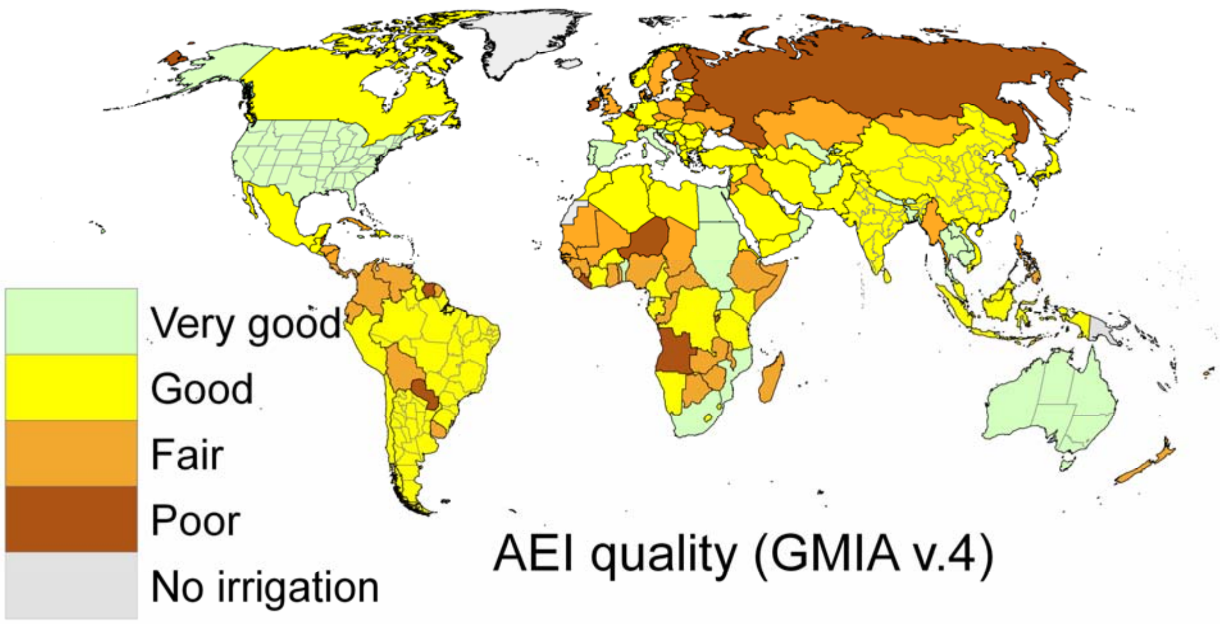

Figure 13. Quality parameter Q3_3_AEI of the area equipped for irrigation AEI of the input data set of the Global Map of Irrigation Areas (GMIA) version 4.0.1, as drawn from published country values [*Siebert et al.*, 2007]. Used classes range from very good (1), good (2), fair (3), to poor (4). The classes excellent (0) and very poor (5) are not filled.

The parameters of dispersion of irrigated harvested area (Q3_4_AHI) and that of rainfed harvested area (Q3_4_AHR) show different spatial patterns (Figure 14, Table D-1). On a global level, AHI is distributed in 33.7 million km^2 or 24.9% of the global land area that sums up to 135.5 million km^2 from the values of the individual units, excluding the units Antarctica and Small Islands that have no cropland. AHR, in contrast, is distributed on nearly double the number of grid cells with a cell area of 66.4 million km^2 or 49.0% of the global land area without Antarctica (see supplementary Table L-6).

Units with concentrated AHI as distributed in grid cells with up to 10% of the land area of the given unit (Q3_4_AHI $\leq$ 10%) globally account for 2.3 million km^2 grid cell area, which is 1.7% of the global land area without Antarctica and 6.8% of the global cell area with AHI. The concerned units are located especially in Africa, Canada, parts of southern America and Asia (Figure 14, top). This means that either the AHI is distributed in a concentrated manner like e.g. in Egypt where most of the relatively high percentage of AEI is located in the valley and the delta of the river Nile, or only a small AEI percentage in relatively few cells is present, like e.g. Canada, Alaska, and southern Argentina (Figure 4, center).

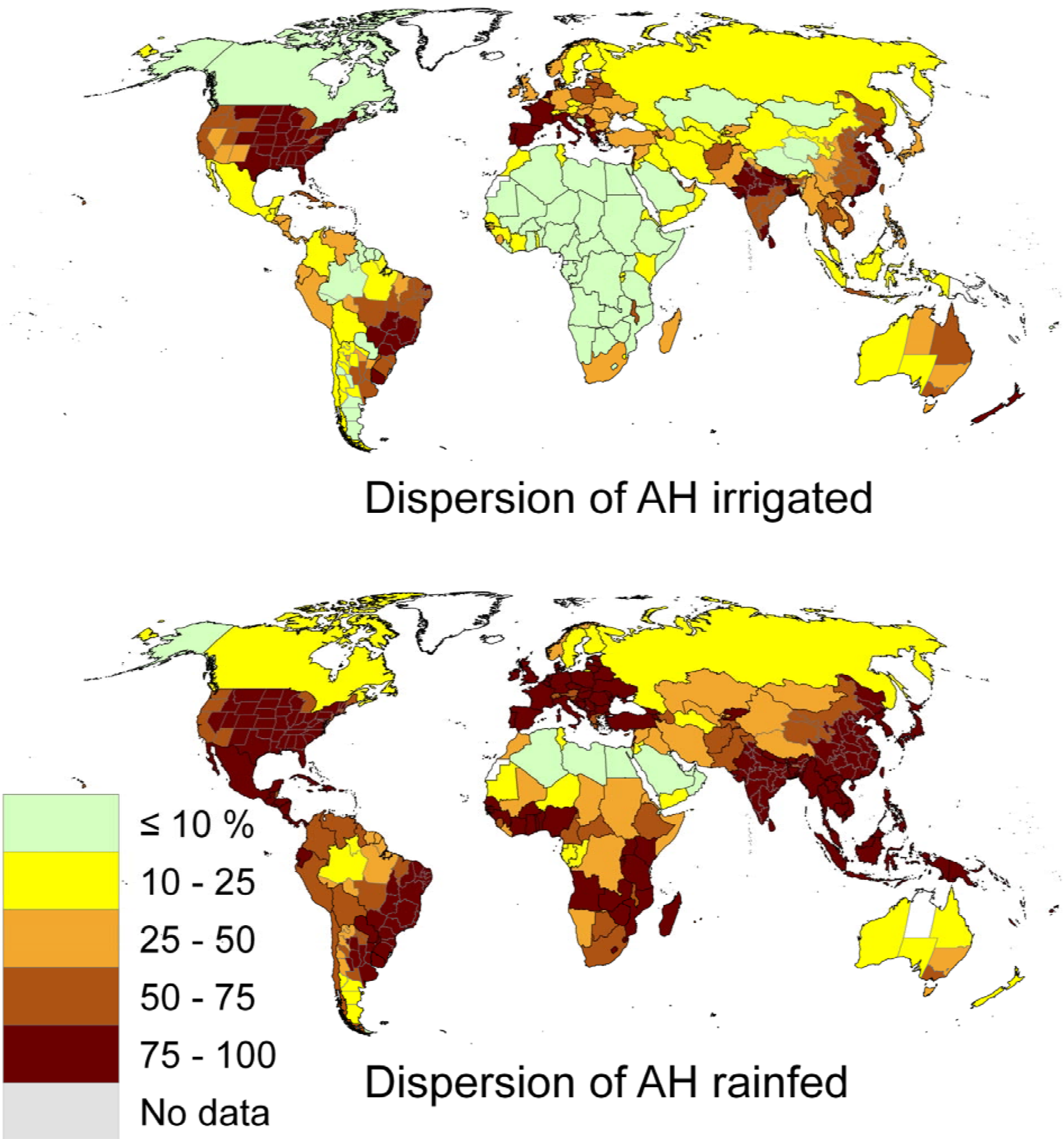

Figure 14. Quality parameters Q3_4_AHI and Q3_4_AHR of spatial dispersion of irrigated (top) and rainfed (bottom) harvested area, as a percentage of land area that is covered by grid cells with AHI (or AHR), per unit.

Units with disperse AHI as distributed in grid cells with more than 75% of the land area of the given unit (Q3_4_AHI > 75%) globally account for 11.0 million km^2 grid cell area, which is 8.1% of the global land area and 32.7% of the global cell area with AHI. The concerned units are especially located in northern India, the coastal provinces of China, and the central United States of America. These are generally also the units where the AEI percentage is very high (Figure 4, center). The same percentage class of Q3_4_AHI in Sri Lanka, New Zealand, in eastern United States of

America, central Brazil, Uruguay, the Iberian Peninsula, France, Greece, and Italy is associated with lower AEI percentage.

On the contrary, units with concentrated AHR as distributed up to 10% of the land area of the given unit (Q3_4_AHR $\leq$ 10%) globally account for only 0.3 million km^2 grid cell area, corresponding to 0.2% of the global land area and 0.4% of the global cell area with AHR. The concerned units are located especially in northern Africa, the Arabian Peninsula, and in Alaska (Figure 14, bottom). These are either units with arid climate with often erroneous AHR (e.g. Egypt) or generally concentrated rainfed agricultural area because of cold climate (Alaska).

Units with disperse AHR as distributed to more than 75% of the land area of the given unit (Q3_4_AHR > 75%) globally account for 38.4 million km^2 grid cell area, corresponding to 28.3% of the global land area and 57.9% of the global cell area with AHR. Clusters of such units are found in Asia in India, in China, and in all countries of tropical south-east Asia, and in Africa in West Africa, in the countries south or east of the Democratic Republic of the Congo, and in Madagascar. In North America, nearly all units besides Canada and Alaska are concerned, and in South America units along a broad band of the eastern and southeastern coasts. In Europe, almost all countries besides Scandinavian countries are found in this class, too.

The overall quality parameter Q_MC, that depicts the relative differences in overall deviation and dispersion, is available only at the level of countries, as determined by the spatial resolution of the Q3_3_AEI parameter (Figure 15, Table D-1, and supplementary Table L-1). Within a theoretical range of 0 (small deviation) to 100 (large deviation), it effectively ranged from about 30 to 85 (Table D-1). The class limits of the 4 classes in Figure 15 were selected so as to have as much as possible equally filled classes. Q_MC marks up to 42 were classified as good quality (relative to other countries), marks between 42 and 48 as medium quality, marks between 48 and 62 as fair quality, and marks above 62 as poor quality.

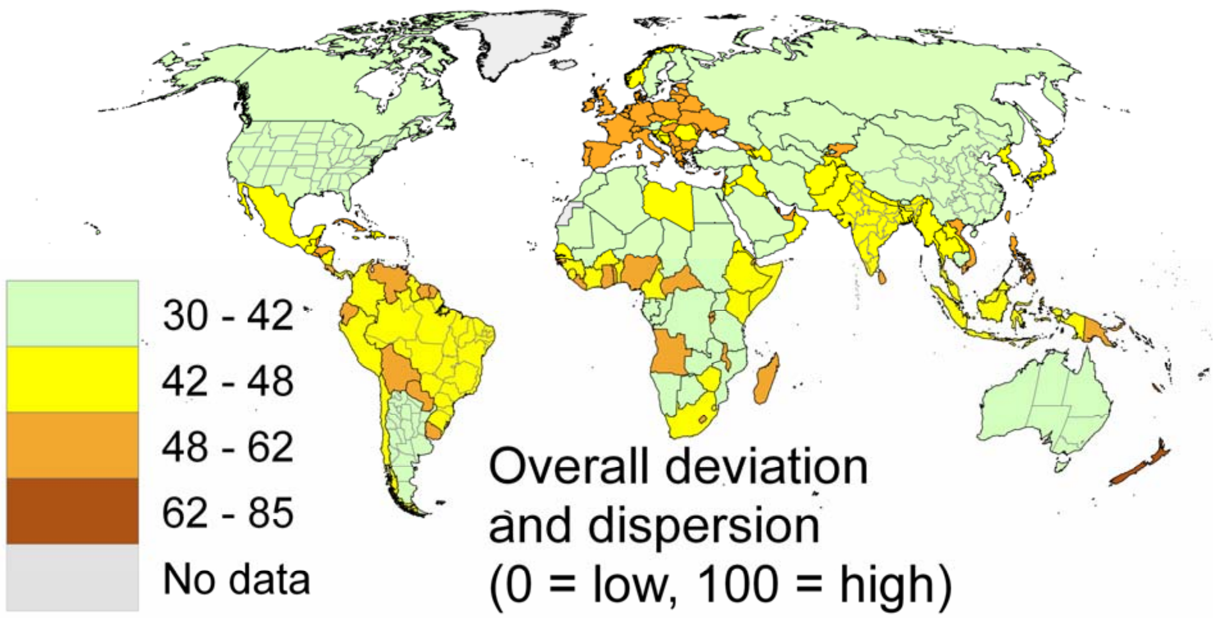

Figure 15. Overall quality parameter Q_MC of deviation and dispersion, calculated as arithmetic average from quality parameter of groups Q2 and Q3, with a range of 0 (small deviation or dispersion, excellent quality) to 100 (large deviation or dispersion, very poor quality), per country. The quality mark effectively ranges from 30 to 85.

The parameter shows good overall quality in the United States of America (Q_MC mark 40), where a good classification of irrigated crops in the census statistics (Q2_1_IR_mark 1.7, with important shares of "others" crop classes, especially fodder grasses) is available, the seasonal variability of precipitation and temperature is high (Q2_2_P = 2.3 mm d^{-1} and Q2_2_T = 27 °C), AEI quality is very good (Q3_3_AEI = 1), and the deviations of cropland extent and harvested area are mostly small (Q3_1_CE and Q3_2_AH ca. 3% each). Higher values of individual parameters are only found with the spatial dispersion of AHI and AHR, as agriculture is broadly present (Q3_4_AHI and Q3_4_AHR often more than 75% in sub-national units, and, on national level, 66 % and 73%, respectively).

In China the overall quality is good (Q_MC mark 37), with smaller area of irrigated "others" crop classes than in the United States of America (Q2_1_IR_mark =

1.1), but, on national level, much larger deviation of harvested area (Q3_2_AH = 25%), only somewhat larger in cropland extent (Q3_1_CE = 11%), and good AEI quality (Q3_3_AEI = 2).

Surprisingly, Australia has also good overall quality (Q_MC mark 38), due to a smaller dispersion of rainfed areas (16%), and small deviations of cropland extent (5%) and harvested area (15%), and a very good AEI quality (1).

India has medium overall quality (Q_MC mark 46), with similar quality in the units as the United States of America, and even very small deviation of classification of irrigated crops (Q2_1_IR_mark = 1.2, because of small shares of "other annual" or "other perennial" crop classes in relation to the AH of well-classified crops such as rice, wheat, and maize, and no irrigated fodder grasses). But in contrast to the USA, India has smaller seasonal variability of temperature (13.3 °C), and very high dispersion of irrigated and rainfed crops (72% and 96%, respectively).

Argentina (Q_MC mark 41.8) just falls into the same class as the USA, although with the same good AEI quality as India, and of stronger deviation of classification of irrigated crops (large share of "others" crop classes, Q2_1_IR_mark = 1.7). While other parameters have smaller differences between the two countries, the seasonal variability of precipitation is much smaller (3.1 mm d^{-1} as compared to 9 mm d^{-1}), and especially AHI and AHR are much more concentrated (dispersion 26% and 57%, respectively).

Brazil has nearly the same overall quality rating than India (Q_MC mark 46 when rounded). The AEI quality is good like in India, four other quality parameters are worse, while the three remaining are better than in India. Worse parameter values include stronger deviation of classification of irrigated crops (large share of "others" crop classes, Q2_1_IR_mark = 1.6), smaller seasonal variability of temperature (5.6° C) and precipitation (6.0 mm d^{-1}), and much larger deviation of cropland extent (14% as compared to 4%). Better parameters include smaller deviation of harvested area (6% as compared to 7%), much smaller dispersion of irrigated and rainfed crops (44% and 64%, respectively).

In Africa, Egypt has good overall quality (Q_MC mark 40) because of high concentration of AHI and AHR (dispersion ca. 8% each), even if deviations of cropland extent and harvested area are large (48% and 34%, respectively), and seasonal variability in precipitation is low (0.6 mm d^{-1}).

In Europe, the Russian Federation has good overall quality (Q_MC mark 38), because of small deviations of cropland extent and harvested area (1.2% and 1.6%, respectively), high seasonal variability in temperature (32.7 °C), and strong concentration of AHI and AHR (Q3_4_AHI = ca. 14% and Q3_4_AHR = 20%, respectively), even if AEI quality is poor (Q3_3_AEI = 4).

The rest of Europe has generally less quality than the Russian Federation, in most cases fair quality, with few exceptions. In the case of France with fair overall quality (Q_MC mark 53), very small deviations of cropland extent and harvested area (2% and 1%, respectively) are outnumbered by the strong dispersion of AHI and AHR

(97% and 89%, respectively), indicating presence of crops in nearly all grid cells. The case of Germany is similar to that of France (Q_MC mark 50, fair quality) with very small deviations of cropland extent and harvested area (2% and 3%, respectively), while the dispersion of AHI is less (33%) but more for AHR (96%), indicating rainfed crops in nearly all grid cells. Greece has a somewhat poorer overall quality rating than Germany and France (Q_MC mark 57, fair quality), as in addition to a strong dispersion of AHI and AHR (97% and 70%, respectively) the deviations of cropland extent and harvested area surpass 25% and 20%, respectively.

The poorest overall quality (Q_MC mark larger than 62) is observed in New Zealand and small islands all across the world, the latter of whose are not visible in the global maps at the presented scale. All these islands and also New Zealand (Q_MC mark 65) observe small or medium seasonal variability of precipitation and temperature, and typically a large deviation of classification of irrigated crops when these exist, because of large shares of “others” crop classes (New Zealand Q2_1_IR = 2.9, Saint Kitts and Nevis Q2_1_IR = 3). For many of these small islands no reference cropland extent (e.g. Saint Kitts and Nevis), sometimes additionally also no harvested area (e.g. Seychelles and United States Virgin Islands) exist, so that the Q3_1_CE and Q3_2_AH deviations are at their maximum of 100%, as compared to New Zealand with 48% for CE and 44% for AH, and the spatial dispersion of AHI and AHR is typically between 60% and 100% (New Zealand 79% and 23%, respectively).

Apart from this, some units, especially further, often smaller islands, do neither have irrigated nor rainfed harvested area in the current version of MIRCA2000, either because of lack of data (e.g. Iceland, Greenland, Saint Helena) or because of certainly non-existing crops (e.g. Svalbard and Jan Mayen Islands). Thus, the overall quality of these units cannot be evaluated, like that of the two units Antarctica and Small Islands which are generally excluded from the quality rating because no cropland was cited for these units.

5 Discussion

MIRCA2000 was compiled with the aim to provide maximum of confidence and usability, but like in other data sets there are uncertainties and shortcomings. First, it is discussed in which category MIRCA2000 falls with respect to the definition of the terms “land use” and “land cover”. Then the theoretical background of the downscaling methodology of MIRCA2000 with respect to the theory of scaling and observations in general is introduced, and practical consequences are discussed (Chapter 5.1). In the following Chapter, the major uncertainties and limitations of the MIRCA2000 data set are discussed also with the background of the “real” situation (Chapter 5.2), followed by a comparison of the methodology used to develop MIRCA2000 to other approaches and other types of data sets, together with an identification of major advantages and shortcomings (Chapter 5.3). Next, ideas for possible improvements of the data set (Chapter 5.4), and applications to estimate irrigated and rainfed crop yields, crop water use and virtual water content (Chapter 5.5) are presented.

MIRCA2000 as land use data set

As has been mentioned in the introduction, the terms land cover classes and land use classes are often mixed. While land cover can be observed (such as grass or building), land use is the actual use to which the land is put (such as grassland for livestock grazing or residential area) [*Koomen and Stillwell*, 2007]. Even a publication specifically dealing with land use change modeling is ambiguous in the use of the terms, using the term land use for convenience for both land cover and land use [*Koomen et al.*, 2007]. In the current text, however, both terms are distinguished. As MIRCA2000 distinguishes irrigated and rainfed growing areas, that can fall within the same land cover class (e.g. grassland), it is definitely a land use data set. Furthermore, the distinction of more than the classical single land cover / land use class for agriculture, which is typical for land cover data sets [e.g. *Cihlar and Jansen*, 2001], but of 26 different crop classes, also qualifies MIRCA2000 to be a land use data set. Though, it does not prescribe nor indicate any crop rotation on a specific field within the grid cell or within a calendar unit like some agricultural land use models do [e.g. *You and Wood*, 2006], but rather describes the shares of land covered with a given use within these spatial units. But still many land use models do not use a specific crop rotation pattern between crops, but percentage area coverage of different crops (equivalent to the absolute areas given in MIRCA2000) [e.g. *Rost et al.*, 2008a; *Criscuolo*, 2006; *Zuidema et al.*, 1994] or one crop class that is dominant in a given grid cell [e.g. *Heistermann*, 2006]. Finally, land use can always be transformed to land cover by a set of rules [*Brown and Duh*, 2004; *Heistermann*, 2006; *Zuidema et al.*, 1994; *Leemans and van den Born*, 1994].

5.1 Scaling and MIRCA2000

5.1.1 Theoretical aspects of scaling

The principle aim of any scientific study of the Earth, like that of the MIRCA2000 data set, is to get a picture of the real world. For this purpose, observations (or measurements) of the conditions (or processes) of the real world are made, which eventually are used as input data in a model. Conditions are often different in their space or time scale. The term “scale” refers to a characteristic length or time of a condition (process), observation or model. The “process scale” is the scale of natural phenomena, and is beyond direct control of the scientist. The “observation scale” can be chosen freely, within the constraints of measurement techniques and logistical possibilities. Finally, these observations are treated in representations of the natural phenomena at the “model scale” [*Blöschl and Sivapalan*, 1995; *Blöschl*, 1996]. “Scaling” is the respective transfer of information across scales, i.e. from one characteristic length to another or between process, observation and model scale, and the problems associated with it are called “scale issues” [*Blöschl and Sivapalan*, 1995]. Generally speaking, the natural phenomena can show elements of organization (e.g. drainage networks, soil catenas, irrigation schemes) or of randomness (stochastic character), or of both [*Blöschl and Sivapalan*, 1995].

It is obvious that with the degree of organization, the results of scaling and predictions also improve. At process scale, characteristic space scales can be defined either as (1) spatial extent, (2) period (or periodicity), or (3) integral scale, depending on the nature of the process. At observation scale, a finite number of samples is necessary that implies (1) the spatial extent (i.e. coverage) of the data set (or temporal extent in case of temporal downscaling); (2) the spacing (i.e. resolution) between samples; or (3) the integration volume (or time constant) of a sample. Under ideal circumstances, natural processes should be observed at the scale they occur, but this is of course not always possible or feasible [*Blöschl and Sivapalan*, 1995; *Blöschl*, 1996]. Finally, the working scale is the model scale, the specific scale of which is defined depending on the processes and on the applied models. In most cases, the model scale is much larger or much smaller than the observation scale. Scaling bridges that gap through the transfer of information across scales [*Blöschl and Sivapalan*, 1995]. Besides spatial scaling, also temporal scaling is possible. Generally, information is lost from process scale to model scales, and ambiguities of the observations with respect to the natural process (or condition) are common, such as temporal or spatial aliasing [*Blöschl and Sivapalan*, 1995]. When observation spacing is smaller than spacing at the model scale, sub-grid parameters (or representative values) of continuous variables for the model scale can be drawn through a methodological process called "upscaling", as e.g. in the case of soil moisture [*Kabat et al.*, 1997]. The transfer of information across scales in MIRCA2000, from regions (units) at national or sub-national level to local plots or grid cells, is a methodological process called (spatial) "downscaling".

In hydrology and similarly in meteorology, quantitative spatially continuous phenomena such as air temperature, air pressure, air humidity, precipitation, and soil moisture are subject to upscaling or downscaling during modeling efforts [*Wilby and Wigley*, 1997; *Blöschl and Sivapalan*, 1995]. Methods of scaling can be applied to state variables, parameters, inputs (conditions) or conceptualizations, the choice of which determines which methods of scaling can be used. Inputs and state variables can be treated independently of the model in many cases, while parameters often need to be scaled in the context of a particular model or theory [*Blöschl and Sivapalan*, 1995]. In hydrology and meteorology, both deterministic and stochastic approaches are used. Depending on the subject and whether spatial or temporal scaling is done, the scaling methods can be quite different [*Blöschl and Sivapalan*, 1995; *Wilby and Wigley*, 1997]. Typically, two steps are performed for downscaling and upscaling (at least in hydrology) at two levels: Upscaling engages, at level 1, the step of distributing (e.g. rainfall) single small-scale values (e.g. rain gage) to a spatial pattern (or probability density function) of many small-scale values. Then, at level 2, a further step of aggregating of the small-scale values to a single large-scale average value for the area (e.g. catchment) is made. Downscaling consists, at level 2, the step of disaggregating and at level 1 the step of singling out station-specific values (Figure 16) [*Blöschl and Sivapalan*, 1995]. Sometimes, both steps are performed in a single step (e.g. station weights for areal precipitation), and unfortunately, often the term "upscaling" is used in publications for distributing, aggregating or both [*Blöschl and Sivapalan*, 1995].

Downscaling and upscaling in hydrometeorology and also in the domain of land use modeling can be executed in a deterministic or stochastic framework, which means that the spatial (or temporal) pattern obtained through distributing (at upscaling) or disaggregating (at downscaling) is either described by a spatially explicit pattern in case of the deterministic framework, or by a probability density function (and covariance function, e.g. characterized by its moments) in case of the stochastic framework [*Blöschl and Sivapalan*, 1995].

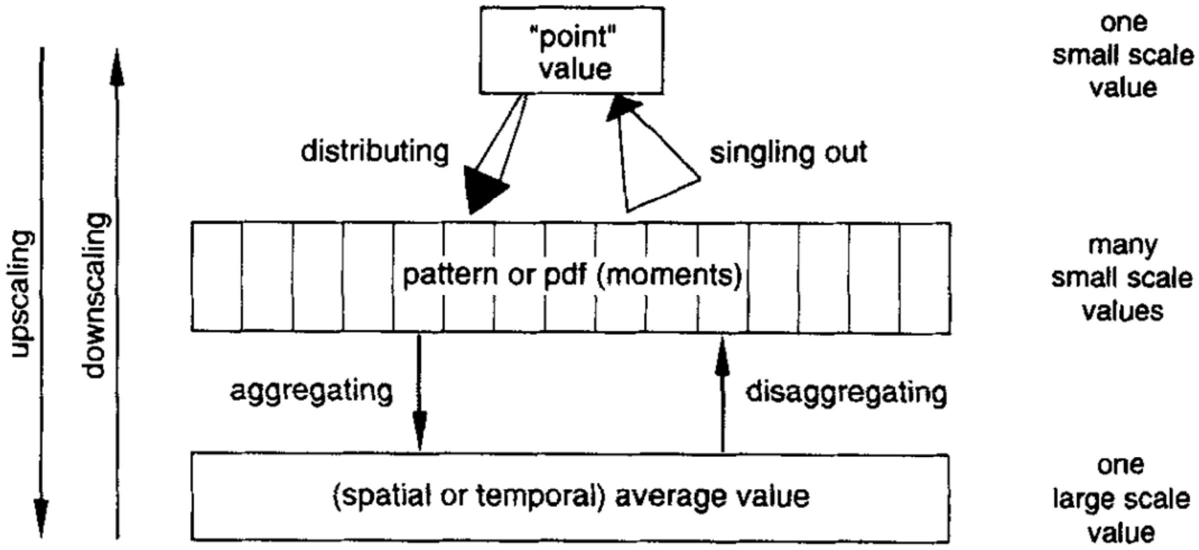

Figure 16. Downscaling and upscaling and the linkages across scales as a two-step procedure [*Blöschl and Sivapalan*, 1995].

In hydrology, the disaggregation at downscaling is often based on indices (e.g. wetness index), and one-step downscaling/upscaling methods are often based on empirical regression relationships [*Blöschl and Sivapalan*, 1995]. In hydrology, for the distribution of information across space (or time) during upscaling, usually some method of interpolation based on representative values (measurements) at point locations, the support, is applied. When the spacing of the supports and the spatial variability of the variable of interest are too large, then often the spatial distribution of the variable is often inferred from the spatial distribution of an auxiliary variable (covariate or surrogate) whose spatial distribution is better known [*Blöschl and Sivapalan*, 1995]. Such covariates are also used for downscaling meteorological fields such as Global Climate Model or regional climate model precipitation output via fields of finer spatial resolution, e.g. sea level pressure or other fields such as topography [*Trigo and Palutikof*, 2001; *Friederichs*, 2007; *Koßmann*, 2008].

Downscaling in meteorology uses as stochastic methods the so-called statistical downscaling, besides the already mentioned statistical regression methods which include non-linear Artificial Neuronal Networks, also further methods such as statistical weather (or circulation) pattern analysis with conditional probability distributions, or stochastic weather generators. Sometimes, statistical downscaling is understood and used only to transfer data from grids to reference stations [*Wilby and Wigley*, 1997; *Friederichs*, 2007; *Koßmann*, 2008; *Zorita and von Storch*, 1999; *von Storch*, 1999; *von Storch et al.*, 1993]. In general, the applied stochastic methods rely on the assumption that all variability in the small-scale variable is related to the variability in the large-scale relationships which is questionable [*von Storch*, 1999]. In the so-called dynamical downscaling as a further method, regional meteorological models are nested within the coarser Global Climate Models, from which they draw the boundary conditions [*Wilby and Wigley*, 1997; *Hübener et al.*, 2007; *Koßmann*, 2008; *Langer and Reimer*, 2007]. In Germany, the national meteorological service denotes any transfer of information to regular grids with the term “regionalization”, irrespective whether downscaling or upscaling methods as defined above are applied [*Koßmann*, 2008; *Blöschl and Sivapalan*, 1995].

Downscaling in land use modeling is often made in a different framework of constraints than in hydrology and meteorology at process, observation, and model scale. This implies that methods typical for these scales in hydrology cannot be readily applied. The most distinctive difference is that the spatial units at observation scale from which information is downscaled are not necessarily cells within a more or less regular grid, or hydrographic catchments of similar size, but can be administrative units with different orders of magnitudes in size, irregular shape, and possibly spatially disjunctive sub-units. The latter occurs frequently e.g. with islands and at coastlines, but definitely not with hydrographic catchments. The administrative units are the reference units whose values have to be exactly reproduced at model scale [*Monfreda et al.*, 2008; *Ramankutty et al.*, 2008; *Heistermann*, 2006]. Then, it is not uncommon to have multiple interdependencies at the model scale at the levels of the grid cells (or spatial units), e.g. irrigated crops can be grown only on areas equipped for irrigation that should be classified as cropland. This allows spatial downscaling following specific assumptions like e.g. for cropland extent in West Africa which under the (reasonable) assumption of being mostly subsistence farming is downscaled using the population distribution [*Ramankutty*, 2004]. But also sometimes because of lack of information, only uniform distribution within administrative units can be assumed, e.g. in the case of crop-specific yields [*Monfreda et al.*, 2008]. Furthermore, similar interdependencies exist also at sub-grid level at process scale like the previously mentioned for irrigated crops at model scale at grid cell level. But in the case of sub-grid variability, within the same administrative unit in one grid cell with AEI the situation can be totally different (e.g. only irrigated rice) from a neighboring grid cell without AEI (e.g. rainfed sorghum and maize). The large number of grid cells without crop areas for specific crops makes a numerical solution via linear equations difficult.

A special case of land use modeling is the land cover and land use classification based on remote sensing data. There for the pixels which are the spatially distributed support for subsequent aggregation, in general only one dominant (majority) land use or land cover class for each pixel is classified from the original data and used in subsequent aggregations [*Boston University*, 2008; *DeFries et al.*, 2000; *DeFries et al.*, 1998; *Cihlar and Jansen*, 2001; *JRC*, 2008; *Loveland et al.*, 2000; *Pekkarinen et al.*, 2009; *Ramankutty*, 2004; *Thenkabail et al.*, 2006]. This so-called majority rule is often used in landscape ecological studies and species atlases, but also in crop land use [*Araújo et al.*, 2005; *He et al.*, 2002; *Heistermann*, 2006]. Ignoring sub-pixel variability of the process scale in the final model can lead to significant over- or underestimation of total areas of specific classes. The majority rule lets dominant classes increase in abundance. Minor classes decrease in abundance or even disappear [*He et al.*, 2002]. As a solution for this effect, either the spatial resolution of the pixels is improved or adjustments are made to fit the distribution within reference units such as administrative units to external reference values such as census statistics [*Ramankutty et al.*, 2008; *Heistermann*, 2006]. When the majority rule is applied during aggregation, it also changes the spatial patterns [*He et al.*, 2002].

The degrees of spatial organization and randomness are often described via geostatistical methods that initially were developed to describe and predict the spatial variations of ore content in deposits [*Journel and Huijbregts*, 1997]. For data sets with rational numbers, these allow to make spatial (or temporal) estimations. With some methods the accuracy of the estimations can be specified, e.g. with Kriging [*Journel and Huijbregts*, 1997; *Hoffmann*, 2002; *Portmann*, 1992]. But stochastic methods also allow analyses and estimations at time scale, e.g. for meteorological data [*Gerstengarbe*, 2002; *von Storch and Zwiers*, 1999].

Large-scale land use models can be classified to be geographic, economic or integrated models [*Heistermann*, 2006]. Geographic models are centered around information on spatially explicit land use and its suitability. They can be statistical-empirical or rule (i.e. process) – based. In economic models, land is one of several economic factors and partial equilibrium models (with a subset of markets) are distinguished from computable general equilibrium models (all markets considered). In integrated models or approaches such as the Integrated Model to Assess the Greenhouse Effect (IMAGE), both economic drivers and spatially more or less explicit land use are considered [*Alcamo et al.*, 1994; *Zuidema et al.*, 1994; *Heistermann*, 2006; *You and Wood*, 2006].

Most of the land use models discussed here fall into the class of geographic models. The models or approaches with which the methodology of MIRCA2000 is compared are not always centered around land use with (economic) human activity influencing the actual land use, but rather focused on a subset like the vegetation distribution [*Rost et al.*, 2008a]. The downscaling of land use is made with different methods, depending on the aim of the study, the available data, and the conceptual model: For regularly spaced grids of bird species atlas Generalized Additive Models (similar to Generalized Linear Models such as Kriging) were used for downscaling in Europe [*Araújo et al.*, 2005]. Another approach uses administrative units with predefined crop-specific area. The area is distributed within these units on ranked grid cells, with the ranking of cells according to predefined covariates such as cropland, irrigated area, and suitability for crop [*Heistermann*, 2006]. In the case of the European Irrigation Map (EIM), irrigation intensity of GMIA together with a regression-based ranking of crop-specific irrigation probability on the level of administrative units is used [*Wriedt et al.*, 2009]. Others use a general maximum entropy approach [*Cai et al.*, 2007; *You and Wood*, 2006]. Deterministic approaches like in IMAGE may include climate, soil conditions and potential yield [*Leemans and van den Born*, 1994].

The distinction of irrigated crops during downscaling (or modeling) is often made in a very coarse way, e.g. by using cell-specific fraction of area equipped for irrigation without consideration of differences between crops [*Heistermann*, 2006; *Stehfest et al.*, 2007; *Liu*, 2009], by a general maximum entropy approach where irrigated cropland is treated as a separate land use class [*Cai et al.*, 2007; *You and Wood*, 2006], or by applying simple global assumptions on the importance of irrigation for different crop categories [*Bondeau et al.*, 2007; *Rost et al.*, 2008a] (see Chapter 1.1.3, Chapter 4.3, and Chapter 5.3).

Technically, the downscaling of MIRCA2000 is performed unit by unit, crop by crop, with a given prioritization on a set of constraints on unit-level or grid-level (Chapter 2.2.5). Similar nested and prioritized procedures are applied by other authors, even if the applied numerical methods and the constraints are different [*Heistermann*, 2006; *You and Wood*, 2006; *Araújo et al.*, 2005].

5.1.2 Practical scale issues relevant to MIRCA2000

At the observation scale of the land use data sets, census data and remote sensing have their specific inaccuracies:

The agricultural census data do not always reflect the true land use of the process scale, as the example of China shows: First, the official statistics for the 1990ies may underreport cropland area and crop-specific harvested area. Second, the definition of cropland is different. FAO includes fallow land and temporary meadows while Chinas State Statistical Bureau reports planted cropland [*Frolking et al.*, 1999]. Third, possibly census statistics report planted, but not harvested area [e.g. *Ministry of Internal Affairs and Communications - Statistics Bureau & Statistical Research and Training Institute*, 2006]. Likewise, often the cropland, i.e. the area of land already cultivated, is underreported, as governments sometimes do not recognize, or report, cultivation which is not supposed to exist: illegal incursion of forest reserves and other protected areas, and possibly also cultivation of steep slopes [*Young*, 1999: 12].

Remote sensing based estimations may underestimate cropland because of sub-pixel variability: When the majority rule is applied in classification, pixels classified as pure cropland can contain up to 10-40% of the area from non-cropland classes such as infrastructure, at least in the case of China. Estimations of this error are based on rough approximations or on data of a smaller scale, see *Frolking et al.* [1999]: “In the Jiangshan Plain, a flat region with widespread rice cultivation in southern Hubei

Province, ca. 10-20% of the landscape is agricultural infrastructure which would be identified as cropland by moderate to coarse resolution remote sensing analysis [*Fang*, 1998]". Therefore, for China reliable estimates on cropland extent are supposed to exist for northern and central China, while for the rest of China with paddy rice and irrigated land large uncertainties are assumed [*Frolking et al.*, 1999].

Similarly, also during the scaling, in the aggregation of small-scale information of cropland extent to national inventories similar errors like those in the classification in remote sensing with dominant (majority) classes occur:

Non-agricultural land (e.g. hills, scarps, rock outcrops, minor water bodies, and swamps), individually small but of large total extent, is often lost when detailed soil surveys are aggregated to large scales. Between 10% and 20% inclusions are common, and 30% not unknown, with a supposed average of 10-15% [*Young*, 1999: 11]. This leads to an overestimation of cultivable land, which is the land potentially available to agriculture [*Young*, 1999: 11]. The same type of error, but to a lesser degree, is probably also included when the census values of harvested areas are aggregated to larger reporting units: The planting (and harvesting) should in general take place on suited agricultural fields only, but could include marginal lands in specific cases.

It has to be held in mind that the definition of cultivable land used here is different from the use in studies where possible extensions of current cropland are discussed, e.g. leading to a large reserve of cultivable croplands mainly in tropical South America and Africa [*Ramankutty et al.*, 2002]. As stated there, much of this reserve is under valuable forests or in protected areas and the tropical soils could potentially lose fertility very rapidly once the forest cover is removed [*Ramankutty et al.*, 2002: 377].

The cropland extent used as input to MIRCA2000 is subject to both types of errors, originating from census and from remote sensing data. Derived with a combination of remote sensing and of census statistics, around the year 2000 about 15.1 million km^2 of cropland extent were the estimated [*Ramankutty et al.*, 2008]. With a similar methodology, about 18.0 million km^2 of cropland around the year 1992 were identified in an earlier effort [*Ramankutty and Foley*, 1998]. It is known that for this data set between these different versions corrections of the originally used classifications were applied, especially in West Africa [*Ramankutty*, 2004]. It appears to be reasonable that with a time span of 8 years between the reporting years no substantial net loss (or gain) of cropland occurred at global scale. If the value for the year 2000 is assumed to be correct at process scale and at observation scale, then the difference of 2.9 million km^2 can be attributed to methodological uncertainties. This means that from the observation scale, on a global level, for the cropland extent an uncertainty of about 20% with respect to the process scale is possible. This means, that at the level of grid cells, the error could be similarly large, especially in West Africa.

Concerning practical scale issues, it can finally be concluded that the uncertainties at the observation scale are either transferred to the model scale directly, or enhanced or mitigated through the specific scaling method. A further source of inaccuracy at the model scale is the selection of the input data sets. These can represent different reference years than the modeled period of time or older methodological status [e.g. *Liu*, 2009; *Tan and Shibasaki*, 2003]. As a consequence, the combination of the more or less inconsistent input data set deteriorates the quality of the modeled results.

5.2 Uncertainties and limitations of the MIRCA2000 data set

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 data bases 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 elsewhere [*Ramankutty et al.*, 2008; *Monfreda et al.*, 2008; *Siebert et al.*, 2005].

On a technical level, uncertainties arise from the necessary transformation of input data grids with different data representation between fractions of grid cell area, in which e.g. cropland extent and total harvested area are delivered, and absolute areas which are used e.g. on the level of the units in the Condensed Crop Calendars. The global difference in area for total harvested area, using two different geodetic transformations with locally different grid cell areas has been shown to be about 0.2% [*Santini et al.*, 2010]. To provide a maximum of transparency MIRCA2000 grid products are delivered in absolute areas, together with the used grid cell area grid, in order to re-establish grid cell fractions. Furthermore, during downscaling of crop-specific areas of the Condensed Crop Calendars, it was technically ensured that the original harvested areas, stored per unit with minimum areas of about 0.5ha and a precision of 0.01ha, were fully distributed to the considered grid cells.

To estimate the reliability and precision of the unit-level crop-specific irrigation statistics and the crop calendars used as additional input to the Condensed Crop Calendars for irrigated crops is very difficult. Most of the data was 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 necessary to estimate irrigated harvested areas for several crops and countries (Chapter 2.2.2, Chapter 4.4, and Appendix K). 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”.

The quality parameter Q1_IR tries to quantify this. It shows that from the globally dominant crops in terms of global harvested area only rice and wheat, both present in at least 195 of the 346 units with irrigated crops, are specifically mentioned in 81% and 86% of these units, respectively. Maize, present in 234 units, is specifically mentioned in only 75% of these units, while potatoes as a crop, secondary in terms of harvested area (Table 4) and present in 230 units, are specifically mentioned in 65% of these units. The presence of crops with smaller harvested area is much better represented, e.g. cocoa, present in 7 units, is specifically mentioned in 86% of these units, and cassava in 93% of the 28 units where it is present. This shows that in many cases information to disaggregate the crop 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, especially those with relatively small harvested areas, may be hidden in the crop classes "others annual" (specific crops in only 31% of 329 units) or "others perennial" (specific crops in 50% of 286 units). As a consequence, the parameter Q1_IR is somewhat biased for crops with small harvested area which are indicated to be extremely well specifically detected while they are probably often hidden in "others" crop classes.

Therefore, the MIRCA2000 harvested areas of the specific crops have to be considered as conservatively estimated minimum areas. As statistical records that cover all crops comprehensively and with a unique classification scheme are missing, a quality measure of misclassification of irrigated or rainfed crops, e.g. in form of the harvested area that was erroneously attributed to "other annual" crops, cannot be specified. The parameter Q1_IR remains a robust quantitative estimate of the classification accuracy for the given harvested areas, except for the "others" crop classes.

Fodder grasses on cropland, fodder crops on cropland and rangeland are often not clearly distinguished in the statistics on irrigation, leading to specifically mentioned crops in globally only 59% of the 142 concerned units. 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 of America. The quality parameter on the deviation of classification in the detailed crop calendars for irrigated crops (Q2_1_IR) clearly addresses this issue by assigning the maximum weight of 3 to the harvested area of these crops. As a result, the largest deviations per unit are generally associated with the largest share of unspecific "others" crop classes and fodder grasses, e.g. in New Zealand with a Q2_1_IR_mark of 2.9, reaching nearly the maximum of 3 (Figure 11, Table D-1 and Chapter 4.4).

The comparison to other data sets in Chapters 5.1 and 5.2 is designed like that of other authors, comparing total sums at the country level [e.g. *Liu*, 2009; *Heistermann*, 2006] or spatial patterns [e.g. *DeFries et al.*, 2000; *Araújo et al.*, 2005]. It shows 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 are reasonably reproduced by MIRCA2000, at least at the scale of the 402 calendar units, but not necessarily at sub-national level (Chapter 4.2). To quantify grid cell level deviations aggregated to the unit level, several quality parameters were developed (Chapter 4.4). These partly support the aforementioned finding for irrigated crops and add additional information for cropland extent, total harvested area, irrigated harvested area, and rainfed harvested area. The deviations for cropland extent are lower than for harvested area, and are only up to 10% in many units (Figure 12). The units with up to 10% deviation of cropland extent (parameter Q2_1_CE) are responsible for 36% of the global deviation area and account for only 2.3% of the global cropland extent. For total harvested area, with the reduced number of units in this class the respective area share is smaller, with 18% of global deviation area accounting for 2.0% of the global harvested area (parameter Q2_2_AH). This result seems to be quite good for cropland extent, while for AHT the correspondence is somewhat smaller, because the sources of uncertainty are various.

The quality parameters Q2_2 indicating the seasonal variability of precipitation and temperature per unit showed that only very few units have small variability and thus are prone to unclear definition of crop calendars for irrigated and rainfed crops (Chapter 4.4). This could be interpreted in the way that mean conditions for grid cells with cropland are quite well represented by the size of the units. However, there are important differences in the MIRCA2000 crop seasonality as compared to cropping periods simulated by a dynamic global vegetation model, especially associated with multi-cropping (Chapter 4.3). This shows first that sub-unit variability of biophysical constraints exists. If specific crops are grown only in parts of a concerned unit where the modeled periods coincide with those in the unit-level crop calendars, then the total size of the unit is irrelevant. Nevertheless, the variability should in general increase with the size of the unit. From this, it could be concluded that the MIRCA2000 dataset should be used with some caution in areas where local biophysical constraints differ considerably from average constraints in the calendar unit.

Many complex cultivation systems in which more than one crop is grown on the same field at the same time cannot be represented in the MIRCA2000 data model, neither in data sets with only one dominant crop class per grid cell [*Heistermann*, 2006]. Such systems are regionally important, e.g. agro-forestry in tropical regions, 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 multi-cropping is practiced. Field-scale crop rotation is not represented in MIRCA2000, as crop mapping at the field level is impossible at the macro-scale. However, monthly growing areas at the grid cell level represent the spatio-temporal average of crop rotations at the field scale.

The un-weighted overall quality mark for the different products Q_MC shows relative differences in quality between the countries based on the input data (Figure 15). However, it cannot fully include all sources of errors and establish a general absolute quality measure, because the quality of the input data cannot be fully expressed quantitatively. This is especially the case for China. There, large uncertainties concerning cropland extent and harvested area exist, as has been discussed before. But also the months of cultivation of specific crops are only broadly defined for three cultivation zones defined by FAO. Generally speaking, the aim is to establish consistent sub-national calendars for a complete set of crops for which harvested area is not always mentioned or aggregated, while often only scarce information on cultivation months is given that neither considers all crops nor distinguishes irrigated and rainfed cultivation. It is obvious that this task is more difficult for large heterogeneous countries with many crops than for small countries with a few main crops only (Chapter 2.2.2 and Appendix K).

5.3 Discussion of methodology in comparison to other approaches

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 sub-crops 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 multi-cropping 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 (Chapter 2.1) or estimates collected for the specific calendar units. Also, the maximization of consistency not only on unit level, but also on grid cell level is an advantage, as it considers quantitative and qualitative information of input data of cropland extent, area equipped for irrigation and total harvested area at its original high spatial resolution, in combination with monthly growing areas. This approach is far more sophisticated than the approaches of other data sets, and is of special relevance for spatially explicit global modeling. Shortcomings of MIRCA2000 are that, due to 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. Furthermore, the current dynamic modeling approach of e.g. LPJmL allows that, with the exception of double cropping of rice, only one sub-crop can be represented within the same grid cell, e.g. either winter or summer wheat, whereas MIRCA2000 allows both. This is especially critical for the currently prevailing grid cell resolution of 0.5 degrees in global models and consistency to census statistics. 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 macro-scale 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 in LPJmL [*Bondeau et al.*, 2007; *Rost et al.*, 2008a]. When MIRCA2000 was recently used as input in an adapted form, the advantage that MIRCA2000 represents wheat growing in the tropics clearly was shown, where LPJmL is currently not parameterized optimally and does not allow wheat growth e.g. in northern India, or tropical Africa [*Fader et al.*, 2010].

Some comparisons with other statistical downscaling approaches are possible. In contrast to MIRCA2000 with national statistics for European countries, the European Irrigation Map (EIM) (Chapter 4.2) is based on sub-national EUROSTAT statistics [*Wriedt et al.*, 2009]. It uses the sums of AEI of GMIA for administrative units for a regression on crop-specific irrigation probability, and distributes the results probabilistically with grid cell level anomalies respective to unit-level mean AEI of GMIA. While basic input data of EIM, on a different spatial scale, is comparable, the methodologies for disaggregation are different. Thus, the EIM using a probabilistic approach cannot be used to thoroughly validate MIRAC2000 with its deterministic approach. Approaches that result in only one dominant crop class in a grid cell are more likely to fail in correctly representing sub-national crop distribution for the same reference period as MIRCA2000 [*Heistermann*, 2006].

5.4 Possibilities for improving MIRCA2000

It is obvious that considering input data for an increased number of sub-national calendar units can improve the spatial pattern of irrigated and rainfed crop areas, as well as the related crop seasonality in MIRCA2000. The focus in 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. sub-national 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 in *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. But this would improve estimates in particular for Australia and the United States of America. In addition to that, the data base of irrigated harvested area for sub-national units in China could be improved at least for specific crops such as rice for which great uncertainty exist, as has been discussed before. The area was disaggregated for each province from the crop calendars for irrigated crops available for only 3 climate zones. In addition to that, the climate zones of the sub-national crop calendars for China and India possibly could be specified with better spatial resolution, when more detailed information is available on cropping periods with a separation of irrigated and rainfed crops.

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 expert knowledge. The global crop calendars recently produced by SAGE for 19 crops do not distinguish irrigated and rainfed crops and do not specify main and secondary cropping periods consistently [*Sacks et al.*, 2010]. Nevertheless, their evaluation of start and end of cropping periods including biophysical limitations by precipitation or temperature could be compared to respective calculations of LPJmL, as both approaches use Priestley-Taylor calculation of potential evapotranspiration [*Priestley and Taylor*, 1972]. This should be broadly possible, although with different Priestley-Taylor alpha coefficients parameterization; SAGE using the original standard value of 1.26 [*Sacks et al.*, 2010] and LPJmL using a value of 1.32 [*Rost et al.*, 2008a].

5.5 Applications of MIRCA2000 to estimate irrigated and rainfed crop yields, crop water use, virtual water content, and cropland use intensity

So far, the MIRCA2000 data set has been applied in several studies to estimate monthly crop water requirement (i.e. consumptive crop water use), crops yields and virtual water content (or crop water productivity), with a differentiation of irrigated and rainfed crops, i.e. blue and green water shares, and to estimate cropland use intensity.

In a companion paper of the co-authors of the author's publication in Global Biogeochemical Cycles [*Siebert and Döll*, 2010], the MIRCA2000 data set was used in a fully consistent way to model, for the period 1998-2002, crop water requirements and crop production in irrigated and rainfed agriculture. The latter differentiation is important as the productivity on irrigated land is usually higher, and thus the fraction of total harvested area that is irrigated is different from the fraction of total crop production on irrigated land. The list of globally important cereals in GCWM ("Global Crop Water Model") encompassed wheat, maize, rice, barley, rye, millet and sorghum. A separation of fodder cereals versus grain cereals was made for maize, rye and sorghum, because the productivity is much higher when cereals are harvested as fodder. The total yields were taken from the same source as the total harvested area in MIRCA2000 [*Monfreda et al.*, 2008], and the irrigated yield was derived from the total yield using, inter alia, the unit-specific average yield ratio defined as the yield of rainfed crops divided by the yield of irrigated crops and which was derived from the ratio of actual to potential evapotranspiration of rainfed crops and crop-specific parameters based on statistical data [*Siebert and Döll*, 2010]. It was found that 33% of global crop production and 44% of total cereal grain production stems 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, 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 [*Siebert and Döll*, 2010].

In a study on the yield gap of major cereals, i.e. the difference between potential and actual yields, the MIRCA2000 maximum monthly growing area of selected irrigated crops was used, together with MIRCA2000 growing periods for rice, with those for rainfed rice assumed to be the same for irrigated rice, and growing periods for maize and wheat according to LPJmL [*Neumann et al.*, 2010]. The maximum yield gaps were found to be 7.5 t/ha for wheat, 8.4 t/ha for maize and 6.4 t/ha for rice, or aggregated globally in total production, the yield gap equaled 43%, 60%, and 47% of the actual global production of wheat, maize and rice, respectively [*Neumann et al.*, 2010: 321]. The results of the applied statistical regression model indicate that regional efficiencies of the production of wheat, maize and rice can be explained by irrigation in five of the six selected world-wide regions. The respective coefficients are all positive, but the individual contributions vary between the regions [*Neumann et al.*, 2010: 321].

The intra-annual course of the monthly consumptive crop water use calculated by GCWM with consistent use of MIRCA2000 shows considerable differences between irrigated and rainfed crops [*Siebert and Döll*, 2010]. While rainfed (green) water globally peaks in July (780 km^3 $month^{-1}$), with somewhat lower values in August, irrigation (blue) water consumption has two peaks, a major in July to August (150 km^3 $month^{-1}$), and a minor in March (110 km^3 $month^{-1}$). Globally, rice follows this general pattern, cotton has always its peak water consumption in July and August, while wheat has its peak consumption in April to May as rainfed crop and March to April as irrigated crop [*Siebert and Döll*, 2010].

In an inventory of groundwater use for irrigation, with the author of this text as co-author, the total consumptive groundwater use for irrigation was estimated by GCWM with consistent use of MIRCA2000 to be 545 km^3 yr^{-1} or 43% of the calculated total consumptive irrigation water use of 1277 km^3 yr^{-1} [*Siebert et al.*, 2010a].

Other studies to calculate blue and green water consumption with further 6 different global models with the same cropland extent exist [*Hoff et al.*, 2010]. However, the land use applied either an adapted version of MIRCA2000 [*Liu and Yang*, 2010; *Fader et al.*, 2010], even older versions of the cropland extent and crop area input data [*Rost et al.*, 2008a], only the dominant crop per grid cell or aggregated harvested area of the input data with unspecific grid cell irrigation fractions derived from area equipped for irrigation [*Hanasaki et al.*, 2010; *Wisser et al.*, 2010], or totally different land use [*Calzadilla et al.*, 2010; *Menzel and Matovelle*, 2010]. This has to be considered when comparing GCWM results with the results of apparently the same variables in other studies. For example, the LPJmL model was formerly used with older data sets of cropland extent that exhibited larger extent than that used in MIRCA2000, and a smaller number of crops of *Leff et al.* [2004] and with crop fractions rather than harvested area [*Rost et al.*, 2008a]. In a newer study, MIRCA2000 crop-specific maximum monthly growing area was taken as the crop-specific annual harvested area for LPJmL crop functional types of temperate cereals and maize [*Fader et al.*, 2010], ensuring consistency with the cropland extent, but reducing the harvested area in case of multi-cropping, e.g. of cereals. For use with the GEPIC model ("GIS-based environmental policy integrated climate"), MIRCA2000 grids of harvested area of irrigated crops were directly subtracted from grids of total harvested area of *Monfreda et al.* [2008] without the unit-level homogenization made in MIRCA2000 [*Liu and Yang*, 2010]. As a result, rainfed harvested areas are regionally and globally different to that of MIRCA2000. This has consequences on the calculated crop water use, and hence, the virtual water content.

Furthermore, the method to calculate potential evapotranspiration has great influence on the volume of crop water use, too. In simulations with GCWM, the total crop water use as calculated with the Penman-Monteith (PM) method and two different formulations of the Priestley-Taylor method (PT_LPJ as used in LPJmL with uniform Priestley-Taylor alpha coefficient = 1.32, and traditional PT_SW with alpha = 1.74 for arid and 1.28 for humid land cells) ranged from globally 6685 (PM) to 7178 (PT_SW) km^3 yr^{-1} [*Siebert and Döll*, 2010], while GEPIC, using the Hargreaves method, calculates 7323 km^3 yr^{-1} [*Liu and Yang*, 2010], and LPJmL with larger cropland extent and older crop data results in 8600 km^3 yr^{-1} [*Rost et al.*, 2008a], all with unlimited irrigation water application. GCWM calculates global blue crop water use of 1145 (PT_LPJ), 1180 (PM), and 1448 (PT_SW) km^3 yr^{-1}, showing the tendency for much larger values with the PT_SW method.

Surprisingly, the shares of blue water and green water in crop water use are similar in GCWM and GEPIC for all crops together, while results for LPJmL are only available with different land use input and therefore not directly comparable [*Rost et al.*, 2008a]. GCWM with MIRCA2000 data and the PM method results in about 17% blue water of the global water use on cropland, and 83% green water, respectively [*Siebert and Döll*, 2010]. The shares calculated by the GEPIC model with adapted MIRCA2000 data and with the Hargreaves method are slightly different, with 13% stemming from blue water and 87% from green water, respectively [*Liu and Yang*, 2010]. The spatial pattern of blue water share with respect to total cropland in GCWM and GEPIC are highly similar, as a result of similar input data: High shares of more than 70% blue water use compared to total cropland water use occur always where irrigation dominates the cropland, like in the Sahara and the Arabian Peninsula, but also in Pakistan, and at least 30% blue water share exists in the central to western United States of America, northern and southern India and north-eastern China.

Comparing crop water use of crop functional types of temperate cereals (wheat) and maize in GEPIC and LPJmL with reference data showed that both models tend to underestimate the crop water productivity (CWP), i.e. the ratio of water use to production, for temperate cereals and LPJmL also for maize [*Fader et al.*, 2010]. Hence the inverse ratio, the virtual water content (VWC) tends to be overestimated. While CWP according to GCWM, for rainfed and irrigated conditions together, is 0.7 kg m^{-3} for wheat, and 0.9 kg m^{-3} for maize [*Siebert and Döll*, 2010], LPJmL gives (obviously somewhat underestimated) values under irrigation of 1 kg m^{-3} for temperate cereals (wheat), and 0.9 kg m^{-3} for maize, respectively [*Fader et al.*, 2010]. Concerning the VWC, LPJmL calculates a value of 1.4 m^3 kg^{-1} for temperate cereals, and 2.0 m^3 kg^{-1} for maize, while GCWM results in a value of 1.5 m^3 kg^{-1} for wheat (out of which 24% are blue water) and only 1.1 m^3 kg^{-1} for maize (out of which 11% are blue water), the latter being much nearer to previous estimates of other authors [*Fader et al.*, 2010; *Siebert and Döll*, 2010].

When the relative blue and green water share of absolute water consumption is of interest, the ratio of blue water to green water fraction of evapotranspiration (i.e. consumption), the Blue to Green Ratio (BTG), is an appropriate measure. Within the growth modeling framework of LPJmL, the BTG is only meaningful for irrigated crops [*Fader et al.*, 2010: 222]. Crops under LPJmL model runs with no irrigation that are performed to estimate isolated contributions of green water to yield, virtual water content and evapotranspiration, sometimes do not grow at all in many regions, equivalent to a green water fraction of zero, and, hence, the contribution of blue water to yield and virtual water content would be overestimated [*Fader et al.*, 2010: 222]. Under current climate conditions (1971-2000), BTG for irrigated maize according to LPJmL is much higher (value 4) than for temperate cereals (value 1.4). This indicates that globally more blue than green water is evapotranspirated during the growth of irrigated maize and that it is grown in many areas with low precipitation and high atmospheric demand [*Fader et al.*, 2010: 225–226]. For the future period 2041-2070 under the SRES A2 emissions scenario, and with climate models ECHAM5, CCSM3, and HadCM3, the BTG for maize is strongly increasing globally between 24% and 70%, with the increase being lower under dynamic CO_2 conditions than under constant CO_2 levels, because of the CO_2-induced lower irrigation requirements. However, for temperate cereals there is no clearly positive or negative sign of the future change in BTG between the three different climate models [*Fader et al.*, 2010: 226].

In a study on cropland use intensity, with the author of this text as co-author, which was performed with fully consistent MIRCA2000 data, the extent of fallow land, determined as the difference of cropland extent and maximum monthly growing area, was found to be 4.4 million km^2, or 28% of the MIRCA2000 cropland extent. Furthermore, global cropland duration ratios as ratios of grid cell average maximum monthly growing area (over all crops) divided by cropland extent (including fallow), or divided by maximum monthly growing area (excluding fallow land) was found to be 0.68 and 0.49, respectively. This indicates that on average only 50% of the cropland was covered with crops in the reference period [*Siebert et al.*, 2010b].

6 Conclusions

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-minutes. Twenty-six crop classes were selected to cover all major food and fodder crops as well as cotton, while establishment of the classes "others annual" and "others perennial" enables a holistic calculation of water fluxes on cropland. Also for the first time, crop calendars were consistently linked to annual values of harvested area at the 5 arc-minutes grid cell level, such that monthly growing areas could be computed that are representative for the time period 1998 to 2002. Finally, MIRCA2000 is the first global agricultural land use data set that includes multi-cropping and that covers both large and small countries and also islands all around the world.

The MIRCA2000 data set includes four core product subsets, each separately for 26 irrigated and 26 rainfed crops: 1) 5 arc-minute grid cell level Monthly Growing Area Grid (MGAG), 2) 5 arc-minute grid cell level Maximum Monthly Growing Area Grid (MMGAG), 3) 5 arc-minute grid 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). In addition to that, two more products were developed: 5) 5 arc-minute grid cell level Maximum Monthly Cropped Area Grids for the sum of all irrigated and rainfed crops (MMCAG), and 6) the annual harvested area (AH) for each of the 26 irrigated and 26 rainfed crops and their group-specific total (AHI & AHR).

To generate MIRCA2000, harvested area of irrigated crops was provided from agricultural census statistics at national and sub-national level. Crop calendars defining start and end of cropping periods were obtained from several inventories or national reports, and were available for 142 individual countries but mostly for selected crops only. Climatological data helped to validate and extend the crop calendars to further (especially rainfed) crops and countries. Grid-based input data included cultivable area in form of cropland extent, total harvested area, and area equipped for irrigation. During the spatial downscaling of the crop calendars of the final 402 spatial units, consistency between the monthly growing areas, the cultivable area in form of cropland extent and area equipped for irrigation has been maximized.

MIRCA2000 is the result of processing a large amount of different data at different spatial scales such that maximal consistency is achieved. The maximization of consistency on grid cell level considers quantitative and qualitative information of input data at its original high spatial resolution, in combination with monthly growing areas. This approach is far more sophisticated than those of other data sets, especially of those that represent only dominant crops rather than all 26 crop classes in a grid cell. It is of special relevance for spatially explicit global modeling, as the grid cell level sub-national spatial distribution is represented more realistically. Quality parameters on e.g. crop occurrence, crop classification accuracy, and grid cell level deviation from the input data are given and are discussed with respect to scaling issues. The spatial pattern of cropping intensity which results from the monthly growing areas is plausible. This supports the validity of the chosen approach. Comparison to a sub-national European data set showed that MIRCA2000 reflects rather well the differences in irrigated harvested area of maize and grapes among countries (calendar units) but not necessarily within countries. This is due to the application of only one crop calendar per country in Europe. Decreasing the size of the spatial units of the crop calendars should decrease the differences.

The comparison of growing periods between data-based MIRCA2000 and the dynamic global vegetation model LPJmL which simulates growing periods using biophysical constraints reveals different strengths and weaknesses of the approaches. While LPJmL allows that, with the exception of double cropping of rice, only one sub-crop can be represented within the same grid cell, e.g. either winter or summer wheat, MIRCA2000 allows more than one until a maximum of five, e.g. rainfed upland rice, deepwater rice, and three growing periods of paddy rice. The simplification is especially critical for the currently prevailing grid cell resolution of 0.5 degrees in global models and the resulting inconsistency to census statistics. Besides, human decisions on crop production and crop rotation are based on complex reasoning that cannot be captured by macro-scale modeling approaches. In MIRCA2000, such long-term average decisions can implicitly be included in the crop calendars. While MIRCA2000 represents wheat in tropical zones, LPJmL fails to model correctly wheat growth in tropical Africa and northern India. Nevertheless, future work should be invested in improving grid cell level data of harvested area that are an input to MIRCA2000. More 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.

MIRCA2000 has an unsurpassed level of detail covering large and small countries alike. Being based on reference data and distinguishing irrigated and rainfed crops, MIRCA2000 refers to present day conditions. While it is especially suited for global studies that require the differentiation of irrigated and rainfed crops, it is a valuable basis for many different applications. So far, it has been applied to estimate extent of fallow land and crop land use intensity, crop yield gap, blue and green shares of crop water use, crop water productivity, and virtual water content. Further applications could include the quantification of virtual water flows and water footprints, studies on food security and other relevant agricultural a good characterization of crop production, such as the area and seasonality of irrigated crops aspects. Further researchers are encouraged to work with the free data set and give feedback on errors or possible improvements.

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Appendices

Appendix A Glossary of terms

The glossary explains critical terms and acronyms that are not commonly known or that have specific meanings in this context. Terms with an asterisk (*) are cited according to an external reference *FAO* [2007a]. Extended version of *Portmann et al.* [2010].

Term	**Definition**
Annual crops (temporary crops)*	Annual or temporary crops are those which are both sown and harvested during the same agricultural year, sometimes more than once. The agricultural year can start in one calendar year and end in the following year as e.g. for winter wheat.
Area actually irrigated (AAI)	Part of the full or partial control irrigated land which is actually irrigated in a given year. Often, part of the equipped area is not irrigated for various reasons, such as lack of water, absence of farmers, land degradation, damage, organizational problems etc. It refers only to physically used cadastral areas. Irrigated land that is cultivated more than once (e.g. twice) a year is counted once. Therefore always AEI ≥ AAI.
Area equipped for irrigation (AEI)*	Area equipped to provide water to crops. It includes areas equipped for full control irrigation, equipped lowland areas, and areas equipped for spate irrigation. It does not include non-equipped cultivated wetlands and inland valley bottoms or non-equipped flood recession cropping areas. The area equipped for irrigation is larger than the area actually used for irrigation if parts of the existing infrastructure are not used (e.g. because of salinization, water shortage, crop rotation etc.).
Area harvested of irrigated crops (AHI)	Annual harvested area of crops under irrigation. Irrigated land that is cultivated twice a year is counted twice. Therefore always AHI ≥ AAI. AEI that is barren or managed as rainfed land is not counted as AHI. Therefore AHI is smaller than the AEI when only a small fraction of the AEI is actually irrigated and the cropping intensity of irrigated crops is low. The AHI is larger than the AEI if a large part of the AEI is actually used for irrigation and if additionally the cropping intensity on irrigated land is high.
Area harvested of rainfed crops (AHR)	Annual harvested area of rainfed crops. Rainfed land that is cultivated twice a year is counted twice. Annual rainfed crops can be cultivated on AEI in seasons where no irrigation is necessary, whereas permanent rainfed crops can only be cultivated on cropland that is not AEI. Always the AHR is equal or greater than the corresponding cropland extent (including AEI for annual crops). The AHR is larger than the cropland if a large part of the cropland is actually used for and if additionally the cropping intensity is high.

Term	Definition
Total area harvested of irrigated and rainfed crops*	The total harvested area excludes, like AHI, the area from which, although sown or planted, there was no harvest due to damage, failure, etc. In case of successive cultivation, i.e. when the same crop is sown or planted and cultivated more than once on the same field during the year, the area is counted as many times as harvested (twice, thrice, …). From permanent crops the area harvested will be recorded only once. The total harvested area includes irrigated and rainfed areas alike.
Crop area*	Crop area is a surface of land on which a crop is grown (see also growing area).
Condensed Crop Calendar (for irrigated crops) (CCC-I)	Crop calendar containing, for each crop class in a specific spatial unit, cropping periods with cultivation months and respective irrigated area, after the aggregation of crops of the detailed crop calendar belonging to the same crop class into a maximum of five sub-crops. The areas are valid for the whole spatial unit.
Detailed crop calendar (for irrigated crops)	Crop calendar with monthly areas from January to December for each irrigated crop class. The areas are valid for the whole spatial unit. It shows cropping period(s) with currently used growing area, the start month and the end month of the period when the crop is cultivated, and the total harvested area, for any identified irrigated crop together with its assignment to a specific crop class. Thus, also multiple entries for the same class are contained if distinct areas per spatial unit are found, e.g. lemons and oranges belonging to class "citrus".
Condensed Crop Calendar (for rainfed crops) (CCC-R)	Crop calendar containing, for each crop class in a specific spatial unit, cropping periods with cultivation months and respective rainfed area, for a maximum of five sub-crops. The areas are valid for the whole spatial unit. The areas are derived from the crop-specific balance between total harvested area and irrigated harvested area.
Cropland*	Arable land (including harvested cropland, crop failure, temporarily fallow or idle land, and cropland used temporarily for pasture) and land under permanent crops (such as cocoa, coffee, rubber, etc., including all tree crops except those grown for wood or timber).
Cropland extent	Area of grid cell that is covered by cropland. In this study, because of inconsistent coverage of the SAGE data set, a cropland extent synthesized from SAGE cropland extent, SAGE harvested area and from AEI is used. If the AEI is larger than the cropland extent, then area equipped for irrigation is the new hypothetic cropland area. When grid cells contain harvested area, but neither cropland extent nor AEI exist, the following rules apply: In case of total harvested area less than the cell area the harvested area is the new hypothetic cropland area. In case of values larger than the cell area, the cell area divided by the cropping intensity of the corresponding spatial unit is the new hypothetic cropland area, the maximum being the cell area, of course. Grid data are represented either as absolute area in hectare (ha) or as fraction or percentage of grid cell area.
Crop class	Individual crop or group of crops (like e.g. pulses, citrus) that are treated as a single class. They possibly include a broad variety of crops, as for the last 3 classes in Table 4.

Term	Definition
Cropping period	Coherent period of 1 to 12 months during which a specific crop class or crop is cultivated continuously, defined by the month of start (January for permanent crops), the month of end (month of harvest for temporary or annual crops, December for permanent crops). In case of the crop calendars for irrigated crops, the growing area of the crop is also specified.
Cropping intensity	Ratio of annual sum of harvested area divided by the cultivated area. Given for a specific crop class or crop. In case of sub-crops with equal growing area, the cropping intensity is equal to the number of cultivation periods.
CPL	Cropping Period Lists that provide harvested area, start and end of cropping periods for each 5 arc-minute grid cell.
Global Map of Irrigation Areas (GMIA)	Area equipped for irrigation as grid area with 5 arc-minutes resolution. Grid data are represented either as absolute area (in hectare) or as fraction or percentage of grid cell area.
Growing area	Actually cultivated area of a specific crop, i.e. the surface of land on which a crop is actually grown. May be irrigated or not irrigated at a specific point of time. For simplicity, for annual crops, the value refers not to the sown area, but to the area at the time of harvest.
MGAG-I	Monthly Growing Area Grids, irrigated crops
MGAG-R	Monthly Growing Area Grids, rainfed crops
MMCAG-I	Maximum Monthly Cropped Area Grids, irrigated crops, maximum of the monthly growing areas of all irrigated crops within the year
MMCAG-R	Maximum Monthly Cropped Area Grids, rainfed crops, maximum of the monthly growing areas of all rainfed crops within the year
MMGAG-I	Monthly Growing Area Grids, irrigated crops, maximum of the monthly growing areas within the year.
MMGAG-R	Monthly Growing Area Grids, rainfed crops, maximum of the monthly growing areas within the year.
Permanent crops	Permanent crops are sown or planted once and not replanted after each annual harvest.
Shapefile	GIS file with polygons or points
Spatial unit	Spatial unit (country or sub-national unit) to which tabular and grid data is associated. Sub-national units are on the level of states (Australia, Brazil, India, and the United States of America), provinces (Argentina, China) or geographically specified regions (Indonesia).

Term	Definition
(Spatial) Unit code	Unique number digits containing in the first 3 digits the United Nations country code (e.g. 4 for Afghanistan) and in latter 3 digits the number of the specific sub-national spatial unit. If only national level data exist, the last 3 digits are all zero. The formula is as follows: spatial unit code = UN * 1000 + sub-national number.
Sub-crop	Distinct cultivation period of the same crop class within the same spatial unit. Sub-crops of detailed crop calendars for irrigated crops represent cultivation periods of crops as specified in the original data source (e.g. agricultural census). Sub-crops of the Condensed Crop Calendar for irrigated crops have as area the sum of growing areas of irrigated crops that are listed in the detailed calendars, belong to the same crop class, and grow during the same months of the year.

Appendix B Country-level characteristics of MIRCA2000 irrigated and rainfed agriculture

Table B. Country-level characteristics of crop growing with hints at irrigated and rainfed agriculture. Cropland extent is compared to the value of the input data [*Ramankutty et al.*, 2008]. Variables are as follows: total cropland extent CE (km^2) [*Ramankutty et al.*, 2008], total cropland extent CE_{MIRCA} (km^2) (MIRCA2000), total area harvested AHT (km^2 yr^{-1}), total cropping intensity *CI_min* (as defined in Equation 1, in percent), area equipped for irrigation (as a percentage of CE_{MIRCA}), irrigated area harvested AHI (as a percentage of total area harvested), irrigated cropping intensity CI_irr (irrigation intensity computed as 100 * AHI / AEI). Countries that are not included in the official UN list are marked by an asterisk (*). The difference of the global sum of CE to the value mentioned in *Ramankutty et al.* [2008] can be caused by different geographic projections. Source *Portmann et al.* [2010], with naming of countries marked with an article sign (§) adapted to newest UN names according to *United Nations Statistics Division* [2010].

Country	CE	CE_{MIRCA}	AHT	CI_min [%]	AEI [%]	AHI [%]	CI_irr [%]
Afghanistan	80,829	94,809	33,407	35	34	57	60
Albania	7,037	8,011	4,442	55	42	41	53
Algeria	57,033	59,553	34,789	58	10	16	100
American Samoa	0	0	0	0	0	0	0
Andorra	11	11	2	13	15	100	91
Angola	33,664	36,713	21,654	59	2	2	53
Anguilla	0	0	0	0	0	0	0
Antigua and Barbuda	0	57	36	63	2	4	100
Argentina	330,304	347,789	303,768	87	5	4	76
Armenia	5,885	6,615	5,061	76	45	34	59
Aruba	0	0	0	0	0	0	0
Australia	291,722	306,151	236,039	77	8	10	103
Austria	14,578	14,709	13,723	93	7	3	41
Azerbaijan	20,333	25,188	14,645	58	57	50	50
Bahamas	0	125	117	94	0	0	0
Bahrain	52	82	36	44	49	86	77
Bangladesh	86,087	100,272	150,022	150	37	43	173
Barbados	0	173	142	82	6	7	100
Belarus	62,582	62,666	61,660	98	2	2	100
Belgium	8,791	8,813	4,268	48	4	2	27
Belize	1,073	1,172	853	73	4	4	58
Benin	26,874	28,523	17,901	63	< 0.5	< 0.5	22
Bermuda	0	0	0	0	0	0	0
Bhutan	1,488	1,666	1,213	73	23	36	112
Bolivia (Plurinational State of) §	31,542	32,308	23,280	72	4	5	99
Bosnia and Herzegovina	10,840	10,843	6,364	59	< 0.5	< 0.5	58
Botswana	8,686	8,701	1,675	19	1	< 0.5	14
Brazil	505,269	587,054	499,655	85	5	6	90
British Indian Ocean Territory*	0	0	0	0	0	0	0
British Virgin Islands	0	< 0.5	0	0	100	0	0

Country	CE	CE_{MIRCA}	AHT	CI_min [%]	AEI [%]	AHI [%]	CI_irr [%]
Brunei Darussalam	126	128	160	125	8	6	100
Bulgaria	36,620	36,757	32,153	87	15	2	9
Burkina Faso	42,888	43,369	35,039	81	1	1	81
Burundi	6,376	10,847	11,455	106	2	2	96
Cambodia	39,452	39,811	24,353	61	8	14	110
Cameroon	72,388	74,023	32,890	44	< 0.5	1	175
Canada	416,824	423,791	350,610	83	2	2	90
Cape Verde	0	601	495	82	5	5	93
Cayman Islands	0	4	4	100	0	0	0
Central African Republic	20,308	20,572	7,765	38	< 0.5	< 0.5	51
Chad	36,233	37,204	21,096	57	1	1	89
Chile	23,417	31,883	17,283	54	60	52	47
China	1,422,552	1,588,720	1,683,466	106	34	51	159
Christmas Island*	0	0	0	0	0	0	0
Cocos (Keeling) Islands*	0	0	0	0	0	0	0
Colombia	36,050	42,696	36,626	86	21	18	72
Comoros	0	798	758	95	< 0.5	< 0.5	65
Congo	5,581	5,818	2,134	37	< 0.5	1	100
Cook Islands	0	0	0	0	0	0	0
Costa Rica	5,299	5,589	4,724	85	18	26	119
Côte d'Ivoire	68,216	71,274	63,976	90	1	1	57
Croatia	15,868	15,949	11,430	72	< 0.5	< 0.5	80
Cuba	42,401	43,474	22,624	52	20	36	94
Cyprus	1,431	1,719	416	24	32	87	65
Czech Republic	31,538	31,543	26,100	83	2	1	33
Democratic People's Republic of Korea	28,040	30,567	28,352	93	47	45	89
Democratic Republic of the Congo	78,933	98,045	60,694	62	< 0.5	< 0.5	68
Denmark	23,466	26,039	26,550	102	18	8	43
Djibouti	11	20	11	54	47	35	40
Dominica	0	165	165	100	0	0	0
Dominican Republic	16,072	16,634	9,076	55	16	24	82
Ecuador	26,821	32,174	24,785	77	27	28	79
Egypt	23,494	45,099	72,271	160	76	83	176
El Salvador	9,120	9,832	7,889	80	5	6	112
Equatorial Guinea	1,993	2,165	1,272	59	0	0	0
Eritrea	5,474	5,581	5,070	91	4	1	28
Estonia	8,267	8,428	7,656	91	< 0.5	< 0.5	44
Ethiopia	108,319	110,936	82,212	74	3	5	141
Faeroe Islands	0	2	2	91	0	0	0
Falkland Islands (Malvinas)	0	0	0	0	0	0	0
Fiji	0	1,597	1,571	98	2	2	100
Finland	21,581	22,563	20,112	89	5	1	19
France	192,356	196,278	179,343	91	15	10	59
French Guiana	146	197	157	80	31	38	100
French Polynesia	0	0	0	0	0	0	0
Gabon	4,774	4,863	2,142	44	1	4	190
Gambia	2,703	2,977	2,531	85	1	1	100
Georgia	10,782	11,957	7,440	62	25	26	66
Germany	120,784	123,283	123,663	100	4	2	53
Ghana	60,786	65,769	51,580	78	< 0.5	< 0.5	55
Greece	28,468	38,140	32,989	86	40	38	80
Greenland	0	0	0	0	0	0	0

Country	CE	CE_{MIRCA}	AHT	CI_min [%]	AEI [%]	AHI [%]	CI_irr [%]
Grenada	0	147	157	106	1	1	100
Guadeloupe	0	289	258	89	28	22	70
Guam	0	141	140	100	2	2	93
Guatemala	19,997	20,386	16,192	79	6	9	106
Guinea	16,107	19,180	18,768	98	5	1	22
Guinea-Bissau	5,344	5,492	3,785	69	4	2	38
Guyana	5,140	5,640	2,318	41	27	77	118
Haiti	11,090	11,691	11,372	97	8	8	96
Honduras	16,273	16,628	9,524	57	4	10	136
Hungary	46,972	48,836	48,898	100	6	2	35
Iceland	0	0	0	0	0	0	0
India	1,701,241	1,773,976	1,844,434	104	32	37	120
Indonesia	537,816	557,559	315,336	57	8	23	160
Iran (Islamic Republic of) §	141,862	166,450	131,958	79	42	55	105
Iraq	57,864	66,471	24,760	37	53	99	69
Ireland	10,792	11,503	5,873	51	< 0.5	< 0.5	97
Israel	3,994	4,246	2,609	61	42	71	102
Italy	84,136	95,595	93,420	98	41	29	69
Jamaica	2,905	2,945	1,959	67	9	13	98
Japan	34,657	57,943	43,571	75	54	50	69
Jordan	3,841	4,061	1,426	35	18	70	137
Kazakhstan	219,373	231,022	158,899	69	9	11	91
Kenya	51,908	53,454	42,763	80	2	2	74
Kiribati	0	0	0	0	0	0	0
Kuwait	117	167	92	55	42	92	122
Kyrgyzstan	14,413	20,945	14,822	71	51	77	106
Lao People's Democratic Republic	9,845	11,075	9,924	90	26	36	122
Latvia	19,042	19,076	9,183	48	< 0.5	< 0.5	70
Lebanon	3,105	3,386	2,770	82	35	50	117
Lesotho	3,357	3,365	1,886	56	1	< 0.5	10
Liberia	3,405	4,611	4,019	87	< 0.5	1	100
Libyan Arab Jamahiriya	5,709	9,367	6,739	72	50	47	67
Liechtenstein	40	40	0	0	0	0	0
Lithuania	30,012	30,023	23,741	79	< 0.5	< 0.5	100
Luxembourg	617	617	342	56	< 0.5	< 0.5	11
Madagascar	35,206	43,421	23,930	55	25	46	102
Malawi	13,768	17,401	15,984	92	3	4	101
Malaysia	75,907	77,655	58,125	75	5	9	138
Maldives	0	0	0	0	0	0	0
Mali	46,722	48,443	26,049	54	5	7	76
Malta	0	286	159	55	8	22	154
Marshall Islands	0	0	0	0	0	0	0
Martinique	0	246	223	91	27	30	100
Mauritania	8,296	8,559	2,951	34	5	8	49
Mauritius	0	1,624	886	55	13	24	99
Mayotte	0	0	0	0	0	0	0
Mexico	363,338	376,743	172,048	46	17	35	92
Micronesia (Federated States of) §	0	0	0	0	0	0	0
Mongolia	19,214	19,614	3,097	16	3	19	99
Montenegro	3,807	3,810	3,497	92	1	1	80
Montserrat	0	6	6	92	0	0	0

Country	CE	CE_{MIRCA}	AHT	CI_min [%]	AEI [%]	AHI [%]	CI_irr [%]
Morocco	91,683	96,779	68,307	71	15	22	99
Mozambique	42,843	48,187	31,336	65	2	1	34
Myanmar	104,315	126,423	131,533	104	15	17	123
Namibia	8,133	8,209	1,947	24	1	5	94
Nauru	0	0	0	0	0	0	0
Nepal	25,032	34,217	42,082	123	34	30	110
Netherlands	9,301	10,408	8,911	86	45	17	33
Netherlands Antilles	0	0	0	0	0	0	0
New Caledonia	0	118	118	100	0	0	0
New Zealand	5,337	10,213	7,559	74	57	51	66
Nicaragua	22,486	22,875	9,431	41	3	8	123
Niger	144,675	145,256	103,343	71	< 0.5	1	135
Nigeria	363,867	386,228	370,168	96	1	< 0.5	56
Niue	0	0	0	0	0	0	0
Norfolk Island	0	0	0	0	0	0	0
Northern Mariana Islands	0	1	1	100	100	100	100
Norway	4,548	6,913	6,411	93	19	6	27
Occupied Palestinian Territory	2,572	2,615	1,265	48	8	23	136
Oman	703	1,264	756	60	59	96	98
Pakistan	234,422	251,604	228,167	91	57	85	135
Palau	0	0	0	0	0	0	0
Panama	7,045	7,273	3,098	43	5	10	89
Papua New Guinea	21,742	22,229	9,232	42	0	0	0
Paraguay	29,447	48,689	49,150	101	1	1	81
Peru	43,121	51,152	26,036	51	34	43	64
Philippines	90,449	121,930	133,106	109	13	16	133
Pitcairn	0	0	0	0	0	0	0
Poland	144,684	144,855	122,333	84	1	1	62
Portugal	24,321	27,040	23,666	88	29	27	81
Puerto Rico	851	1,088	674	62	34	26	47
Qatar	0	125	95	76	100	100	76
Republic of Korea	18,215	20,947	21,658	103	42	40	99
Republic of Moldova §	21,683	21,714	17,866	82	14	14	86
Réunion	0	577	541	94	23	14	58
Romania	100,195	101,636	98,267	97	21	4	20
Russian Federation	1,259,848	1,274,829	790,618	62	4	5	77
Rwanda	7,523	12,890	13,551	105	1	< 0.5	70
Saint Helena	0	0	0	0	0	0	0
Saint Kitts and Nevis	0	79	78	100	< 0.5	< 0.5	100
Saint Lucia	0	245	245	100	1	1	100
Saint Pierre and Miquelon	0	0	0	0	0	0	0
Saint Vincent and the Grenadines	0	173	173	100	0	0	0
Samoa	0	0	0	0	0	0	0
San Marino	20	20	20	100	5	0	0
Sao Tome and Principe	0	278	251	90	35	39	100
Saudi Arabia	21,561	32,605	14,028	43	53	91	74
Senegal	24,302	25,217	17,775	70	5	5	71
Serbia	34,348	34,349	31,600	92	5	2	37
Seychelles	0	3	2	86	100	100	86
Sierra Leone	5,622	6,749	5,080	75	4	6	102
Singapore	182	183	4	2	0	0	0
Slovakia	15,242	15,446	14,295	93	15	7	47

Country	CE	CE_{MIRCA}	AHT	CI_min [%]	AEI [%]	AHI [%]	CI_irr [%]
Slovenia	1,969	2,006	1,942	97	8	5	67
Solomon Islands	0	780	780	100	0	0	0
Somalia	10,715	12,115	5,468	45	17	38	103
South Africa	149,742	157,010	74,324	47	10	22	111
Spain	183,525	187,486	149,234	80	19	23	96
Sri Lanka	19,303	21,555	20,763	96	26	35	128
Sudan	172,861	184,027	114,534	62	10	11	65
Suriname	660	1,067	606	57	48	84	100
Svalbard and Jan Mayen Islands	0	0	0	0	0	0	0
Swaziland	1,958	2,390	1,800	75	21	25	91
Sweden	24,410	26,010	22,810	88	7	2	28
Switzerland	4,305	4,652	4,429	95	9	3	36
Syrian Arab Republic	44,149	47,415	46,680	98	27	32	119
Taiwan, Province of China*	4,195	8,086	9,525	118	65	62	112
Tajikistan	10,661	13,640	9,843	72	52	65	89
Thailand	167,995	183,185	177,020	97	27	35	124
The former Yugoslav Republic of Macedonia	6,318	6,468	4,026	62	20	11	33
Timor-Leste	4,424	4,513	1,864	41	4	4	39
Togo	25,909	26,284	13,790	52	< 0.5	< 0.5	35
Tokelau	0	0	0	0	0	0	0
Tonga	0	0	0	0	0	0	0
Trinidad and Tobago	1,213	1,244	609	49	3	6	100
Tunisia	23,311	25,139	20,571	82	16	18	93
Turkey	220,077	232,308	206,185	89	18	17	83
Turkmenistan	18,826	26,055	18,763	72	67	75	80
Turks and Caicos Islands	0	0	0	0	0	0	0
Tuvalu	0	0	0	0	0	0	0
Uganda	82,240	85,781	62,906	73	< 0.5	< 0.5	26
Ukraine	341,846	344,831	277,388	80	7	4	42
United Arab Emirates	1,643	3,948	2,244	57	71	91	74
United Kingdom of Great Britain and Northern Ireland	64,648	65,668	58,577	89	3	3	80
United Republic of Tanzania	51,549	56,728	58,685	103	3	4	123
United States of America	1,802,854	1,854,007	1,319,426	71	15	16	74
United States Virgin Islands	0	2	2	100	100	100	100
Uruguay	14,545	15,677	7,688	49	15	28	94
Uzbekistan	51,545	60,514	49,636	82	68	77	93
Vanuatu	0	1,025	1,025	100	0	0	0
Venezuela (Bolivarian Republic of)	34,427	37,665	17,427	46	15	28	86
Viet Nam	73,471	95,210	116,786	123	31	45	175
Wallis and Futuna Islands	0	0	0	0	0	0	0
Western Sahara	0	0	0	0	0	0	0
Yemen	14,936	16,552	10,610	64	24	38	102
Zambia	53,471	54,325	11,265	21	3	5	36
Zimbabwe	33,659	35,349	22,601	64	5	9	117
WORLD	14,955,553	16,000,368	13,053,334	82	17	24	112

Appendix C Global maps of harvested area for the 26 crop classes of MIRCA2000

Here for each of the 26 crop classes of MIRCA2000, global maps of rainfed and irrigated harvested area are shown, together with a complete list of MIRCA2000 crop classes and their corresponding names.

The colors of the legend have been optimized to a display on computer screens. Any printout of the figures will probably yield different colors.

Table C-1. MIRCA crop classes and their names.

Crop class	Crop name
1	Wheat
2	Maize
3	Rice
4	Barley
5	Rye
6	Millet
7	Sorghum
8	Soybeans
9	Sunflower
10	Potatoes
11	Cassava
12	Sugar cane
13	Sugar beet
14	Oil palm
15	Rape seed / canola
16	Groundnuts / peanuts
17	Pulses
18	Citrus
19	Date palm
20	Grapes / vine
21	Cotton
22	Cocoa
23	Coffee
24	Others perennial
25	Fodder grasses
26	Others annual

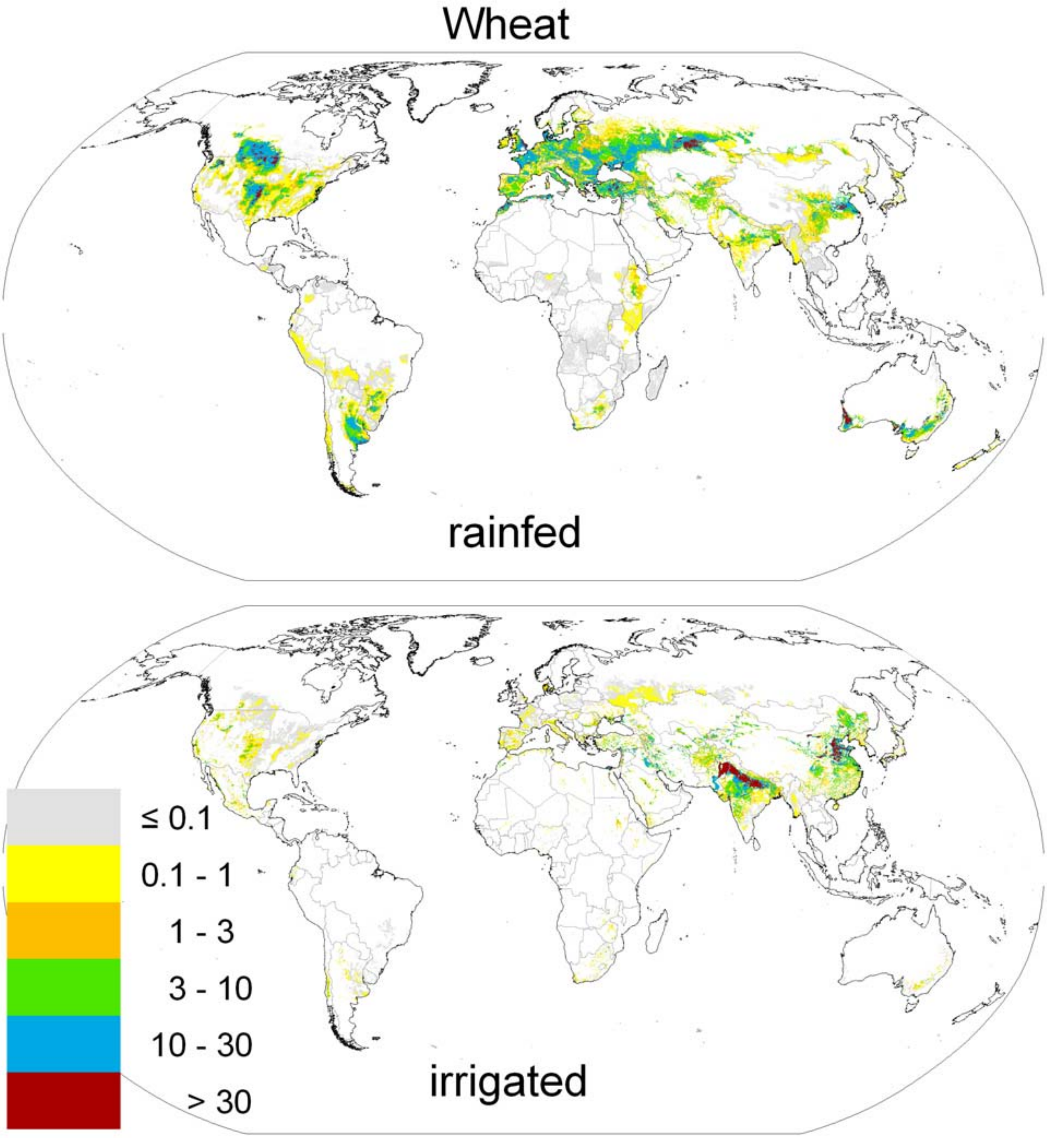

Figure C-1. Global distribution of harvested area of rainfed (top) and irrigated (bottom) wheat, as a percentage of grid cell area, for 1998-2002.

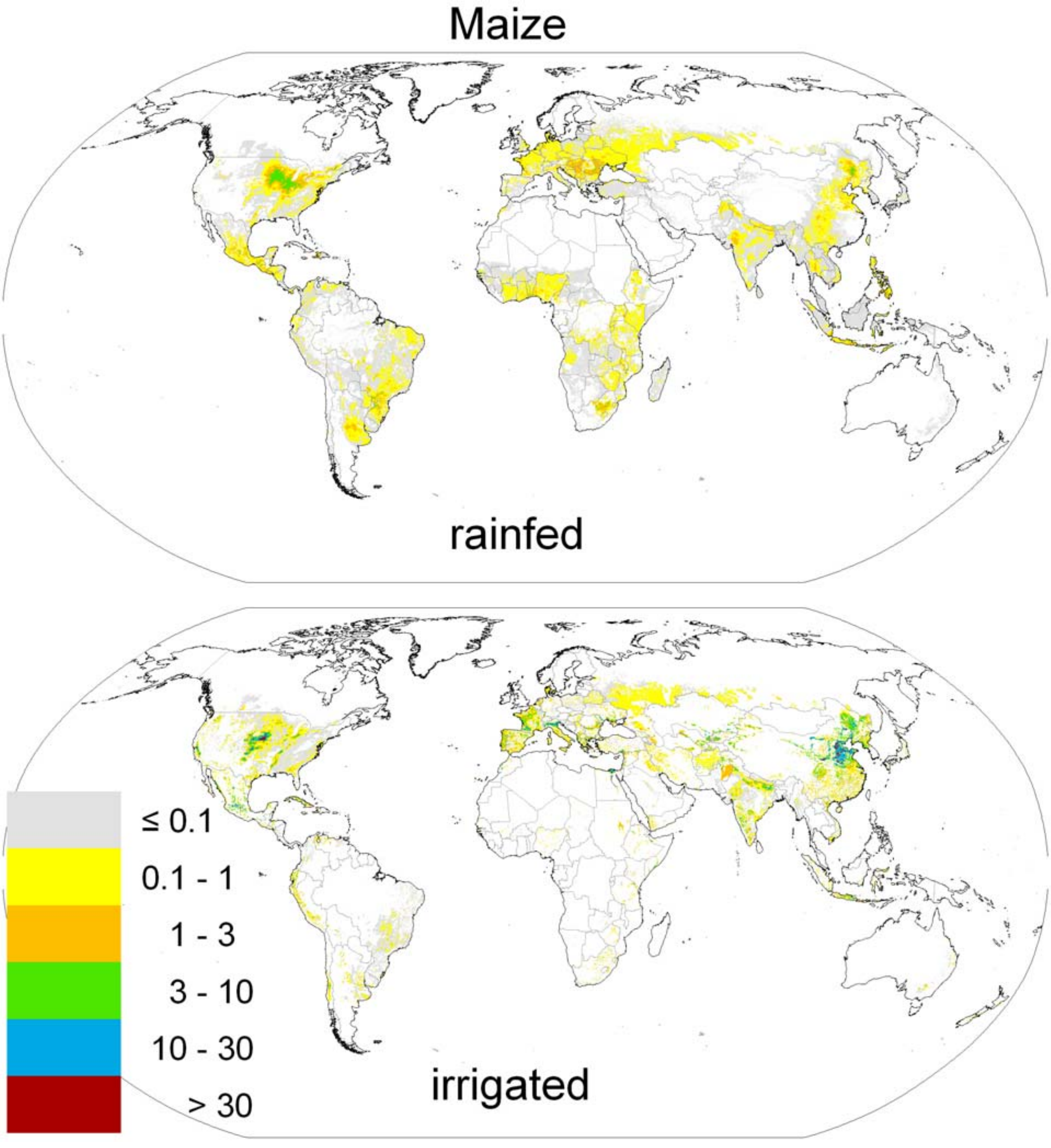

Figure C-2. Global distribution of harvested area of rainfed (top) and irrigated (bottom) maize, as a percentage of grid cell area, for 1998-2002.

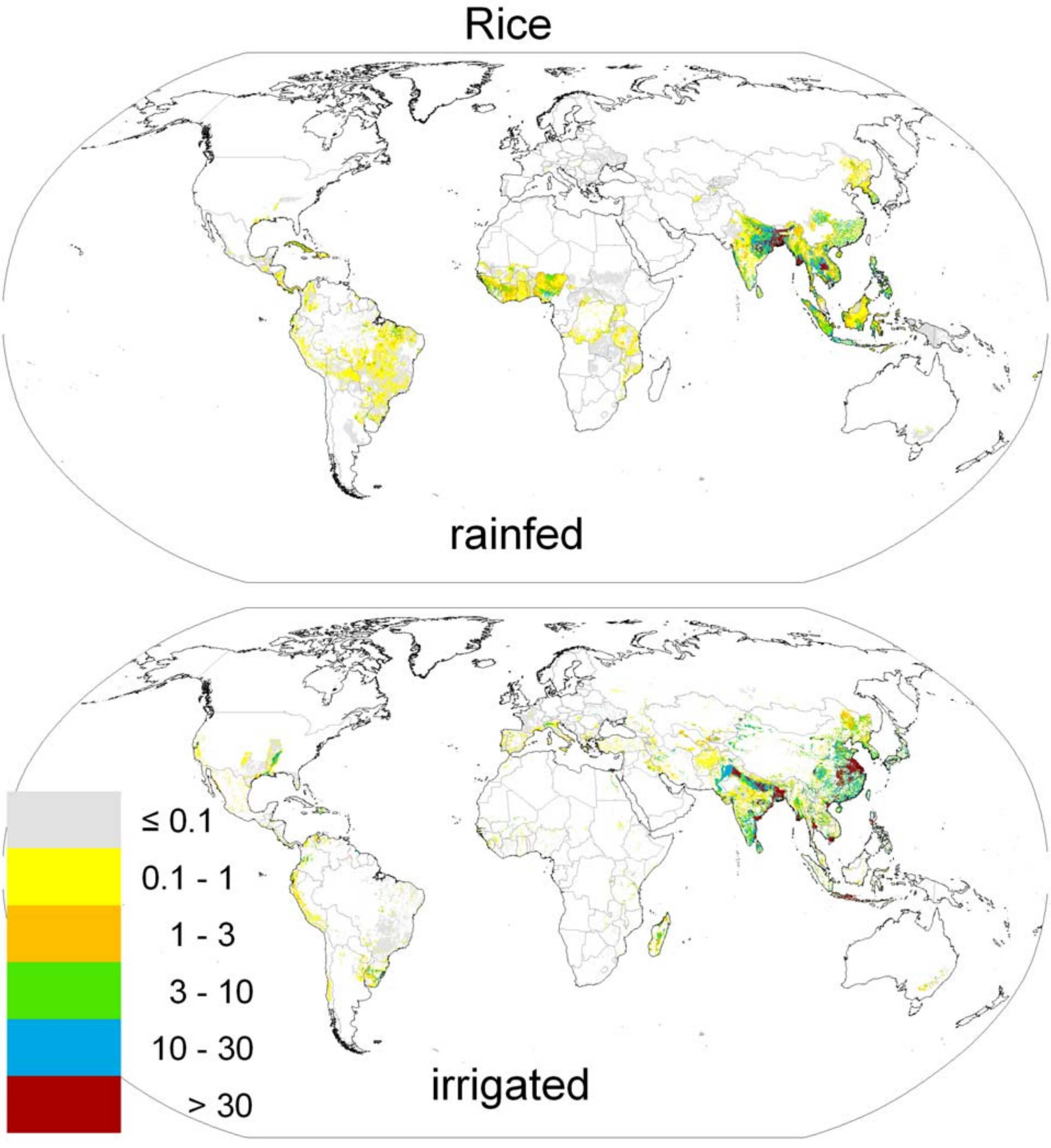

Figure C-3. Global distribution of harvested area of rainfed (top) and irrigated (bottom) rice, as a percentage of grid cell area, for 1998-2002.

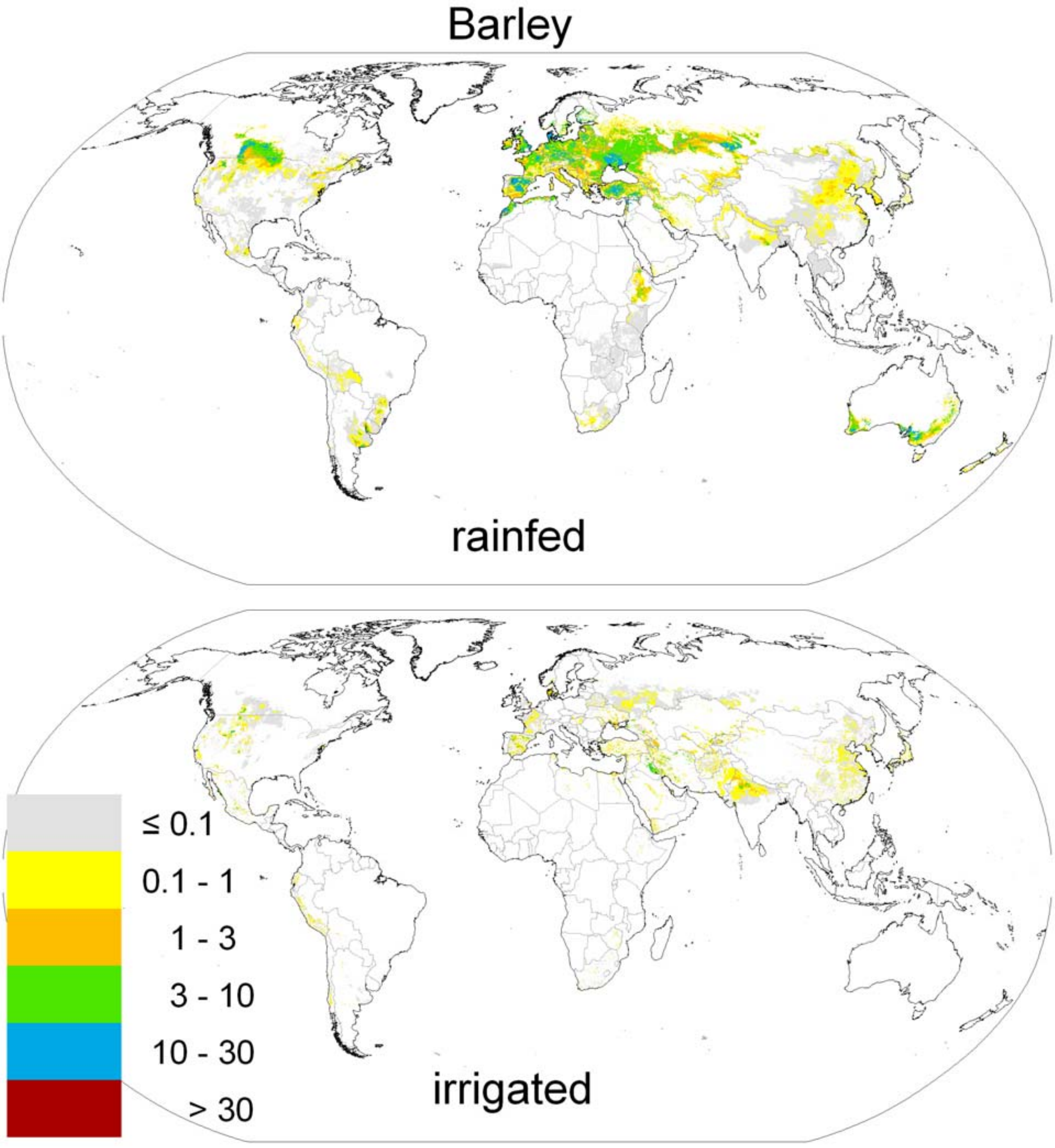

Figure C-4. Global distribution of harvested area of rainfed (top) and irrigated (bottom) barley, as a percentage of grid cell area, for 1998-2002.

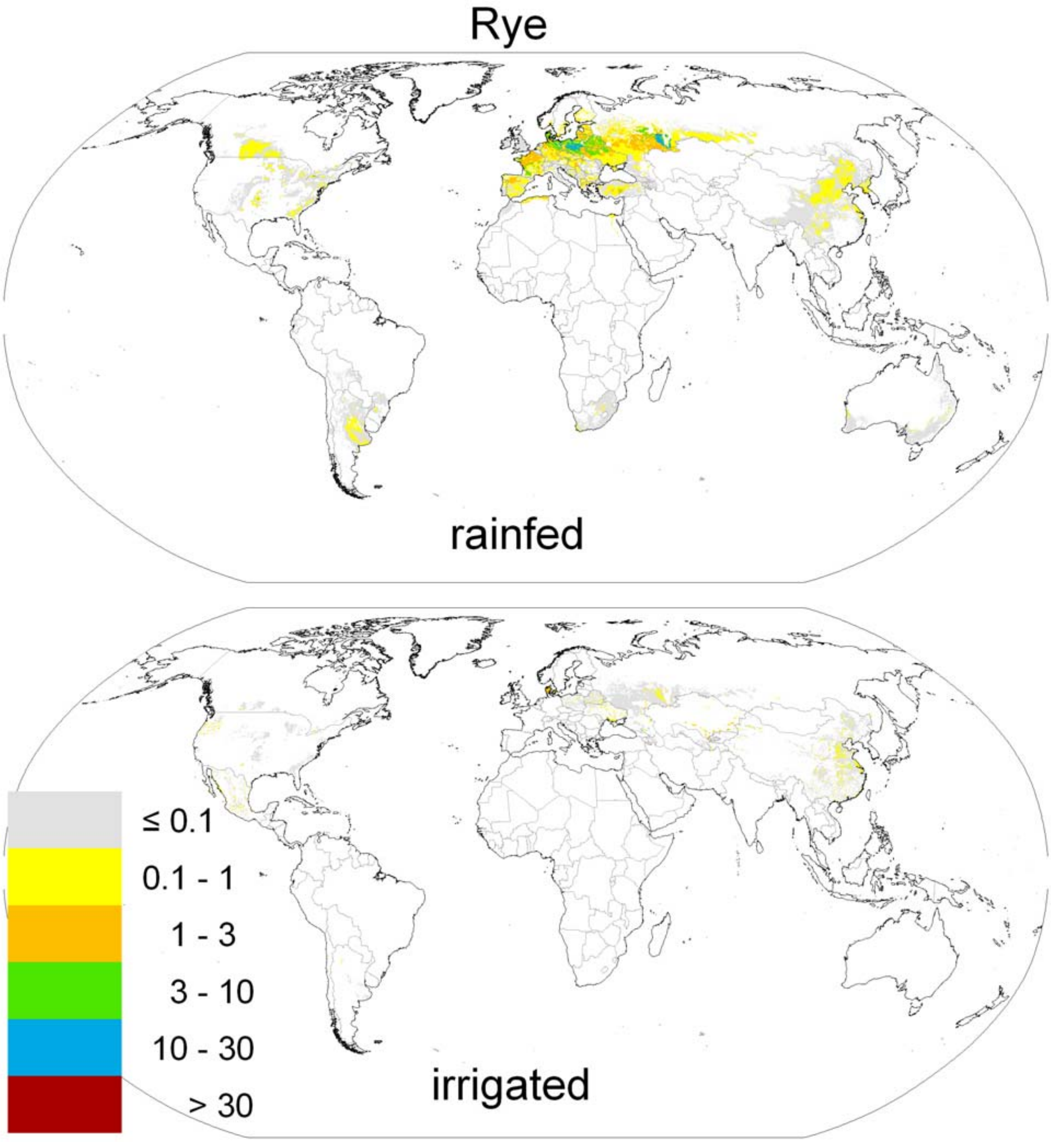

Figure C-5. Global distribution of harvested area of rainfed (top) and irrigated (bottom) rye, as a percentage of grid cell area, for 1998-2002.

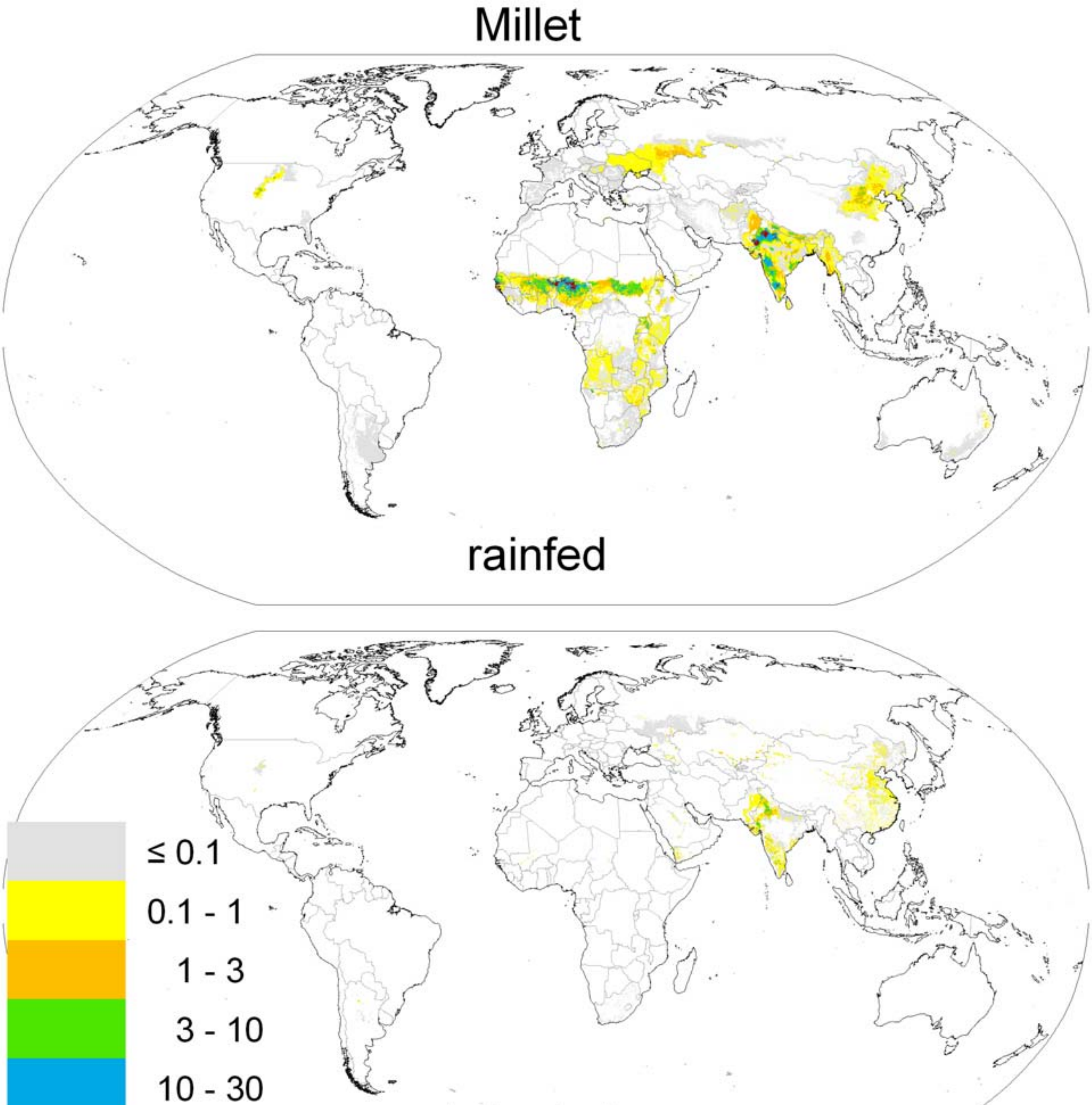

Figure C-6. Global distribution of harvested area of rainfed (top) and irrigated (bottom) millet, as a percentage of grid cell area, for 1998-2002.

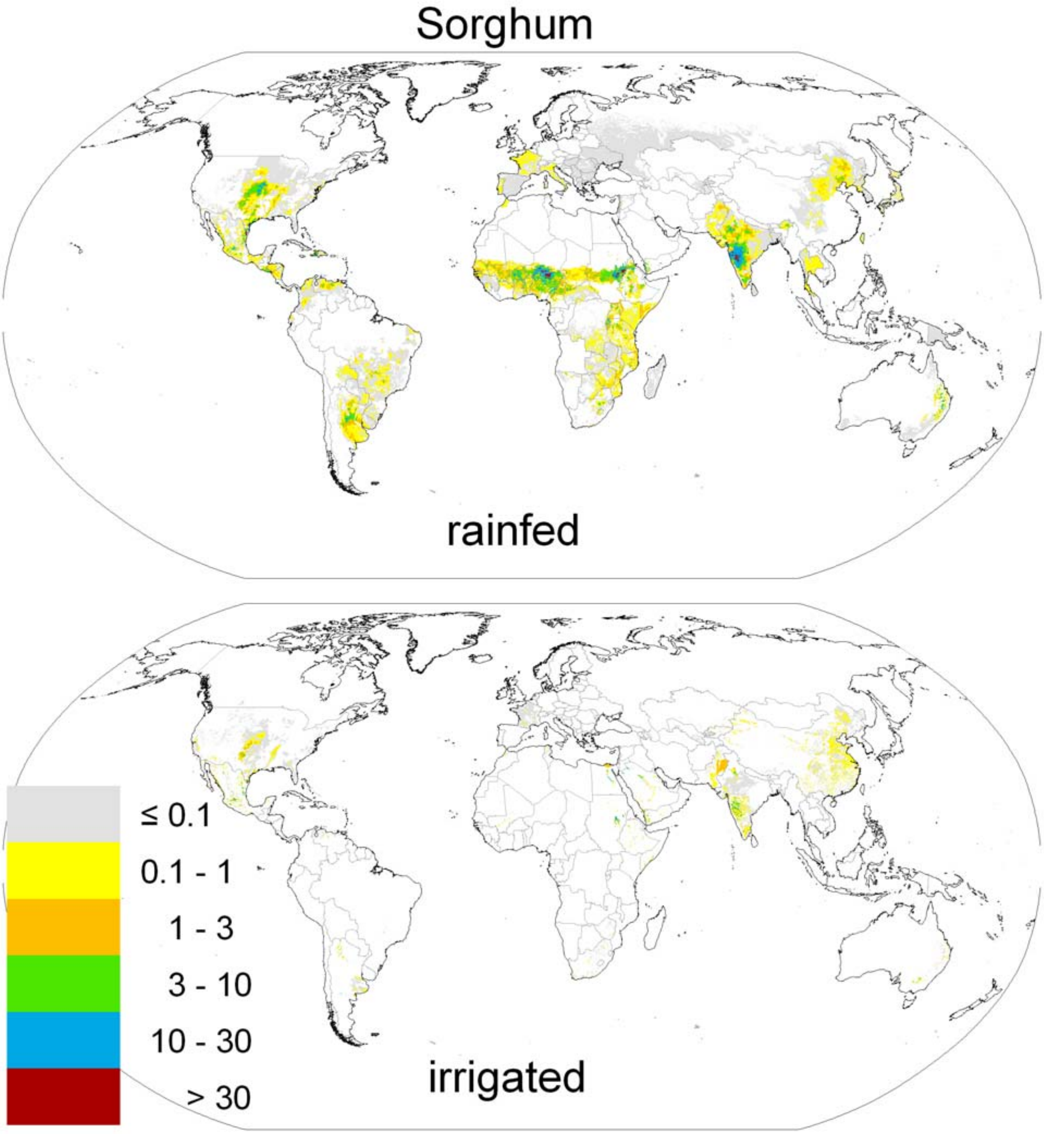

Figure C-7. Global distribution of harvested area of rainfed (top) and irrigated (bottom) sorghum, as a percentage of grid cell area, for 1998-2002.

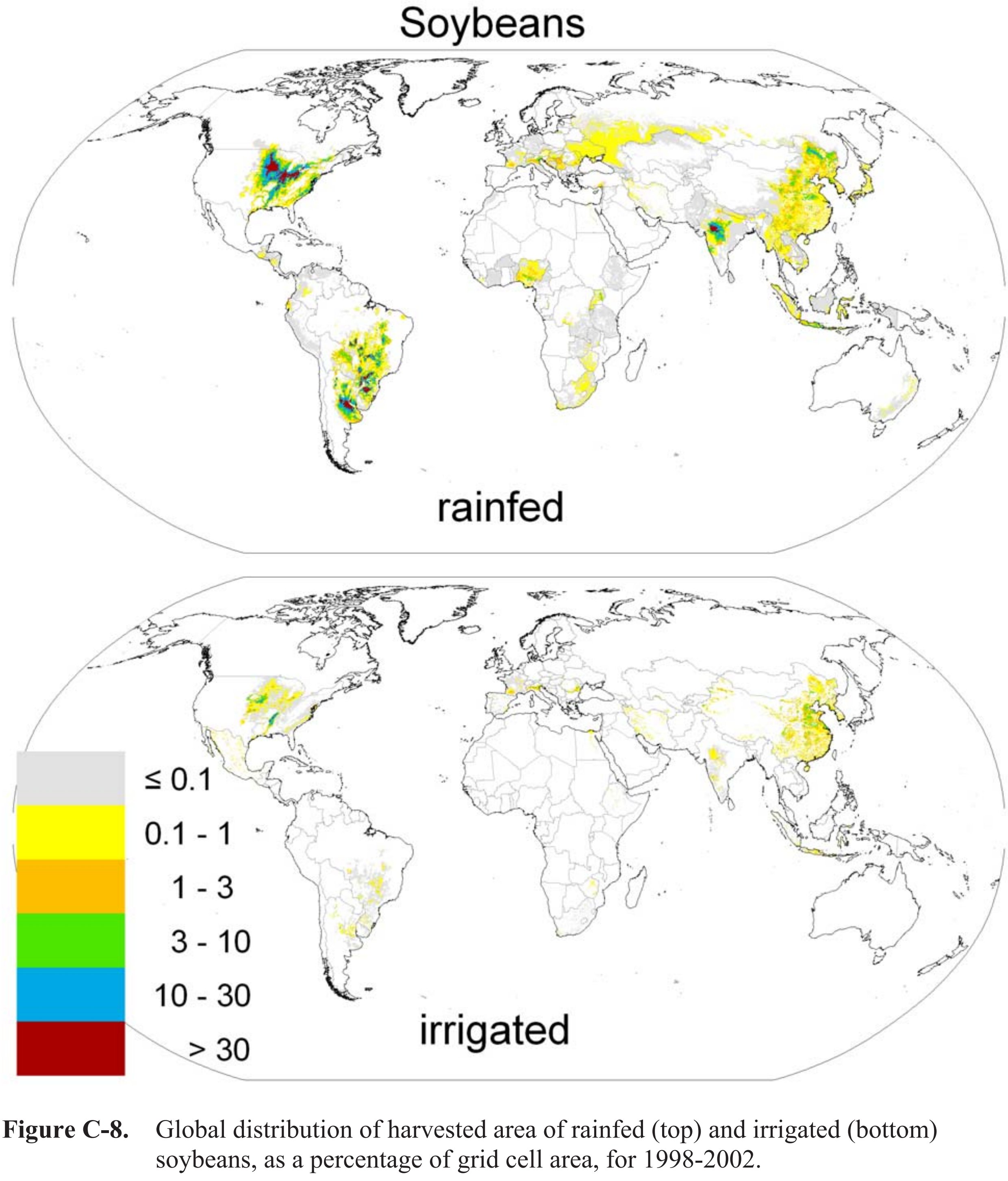

Figure C-8. Global distribution of harvested area of rainfed (top) and irrigated (bottom) soybeans, as a percentage of grid cell area, for 1998-2002.

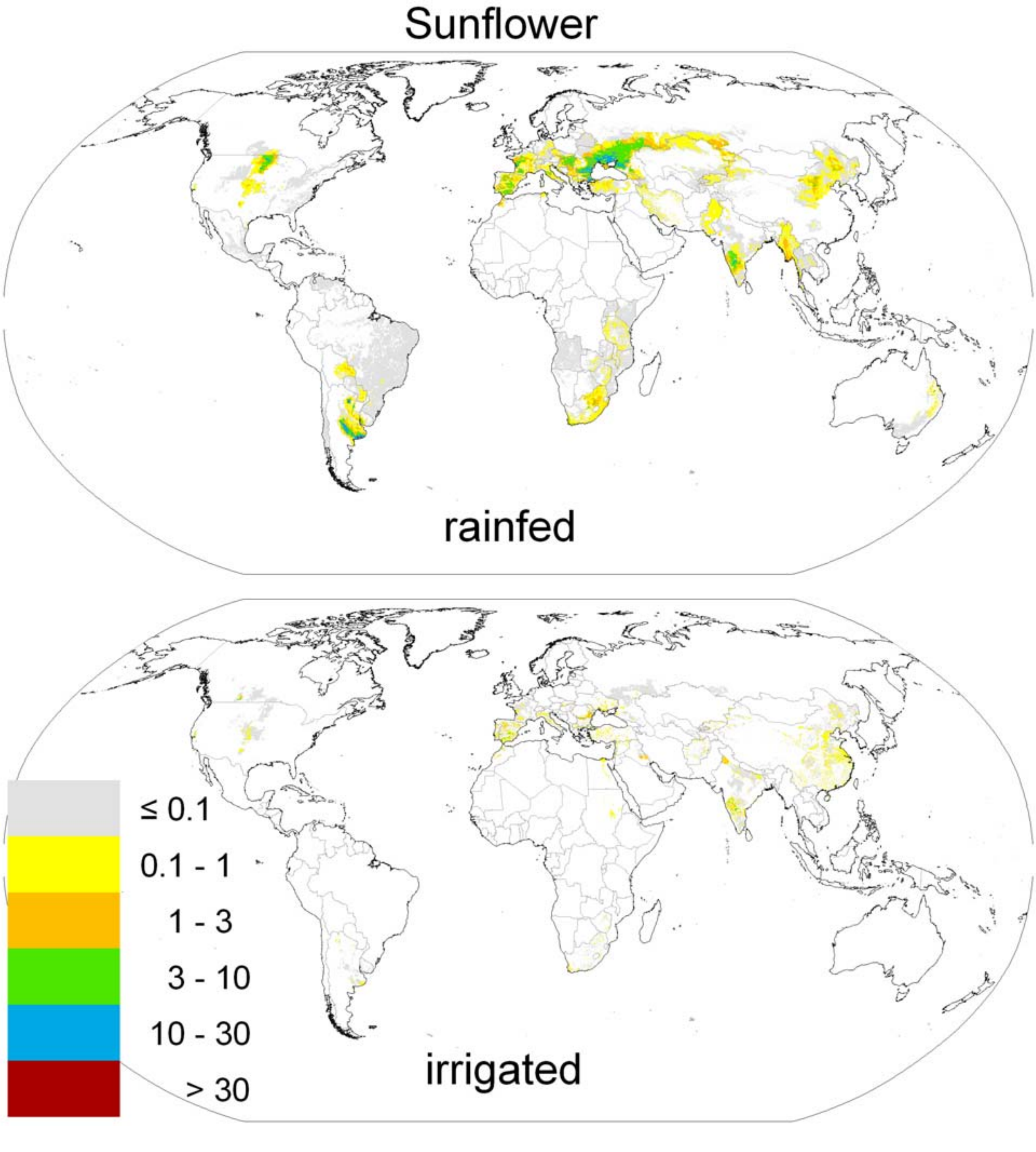

Figure C-9. Global distribution of harvested area of rainfed (top) and irrigated (bottom) sunflower, as a percentage of grid cell area, for 1998-2002.

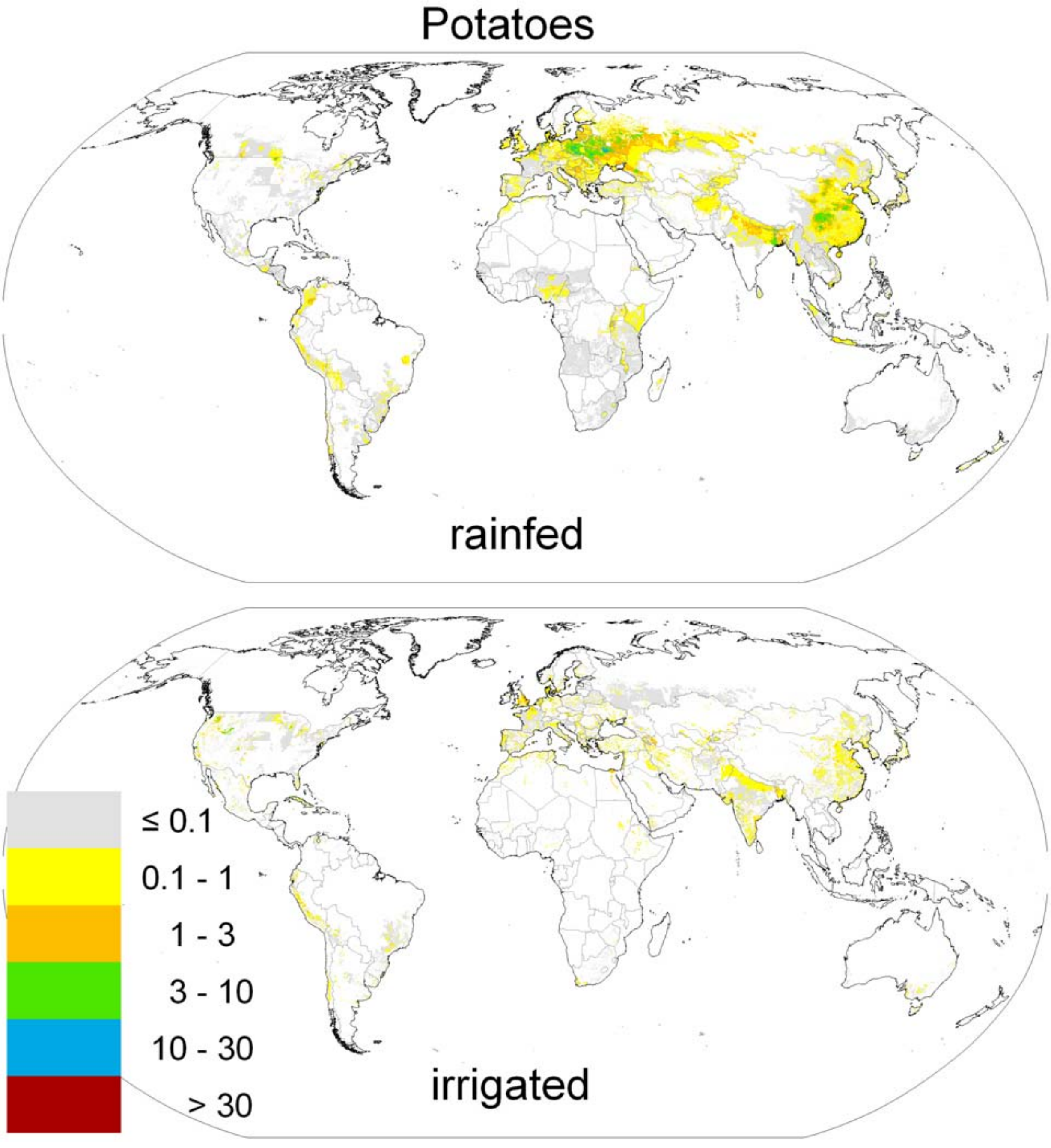

Figure C-10. Global distribution of harvested area of rainfed (top) and irrigated (bottom) potatoes, as a percentage of grid cell area, for 1998-2002.

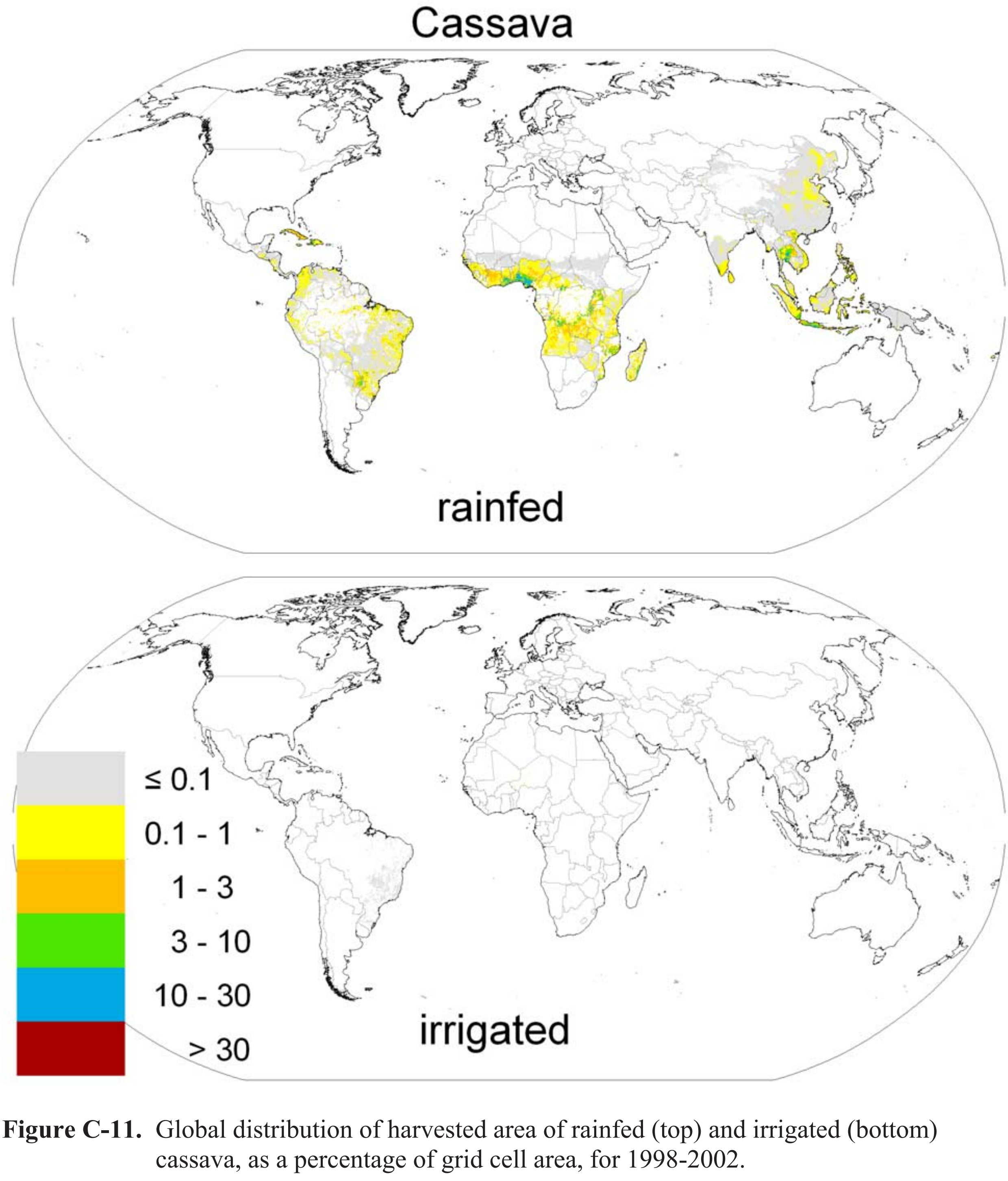

Figure C-11. Global distribution of harvested area of rainfed (top) and irrigated (bottom) cassava, as a percentage of grid cell area, for 1998-2002.

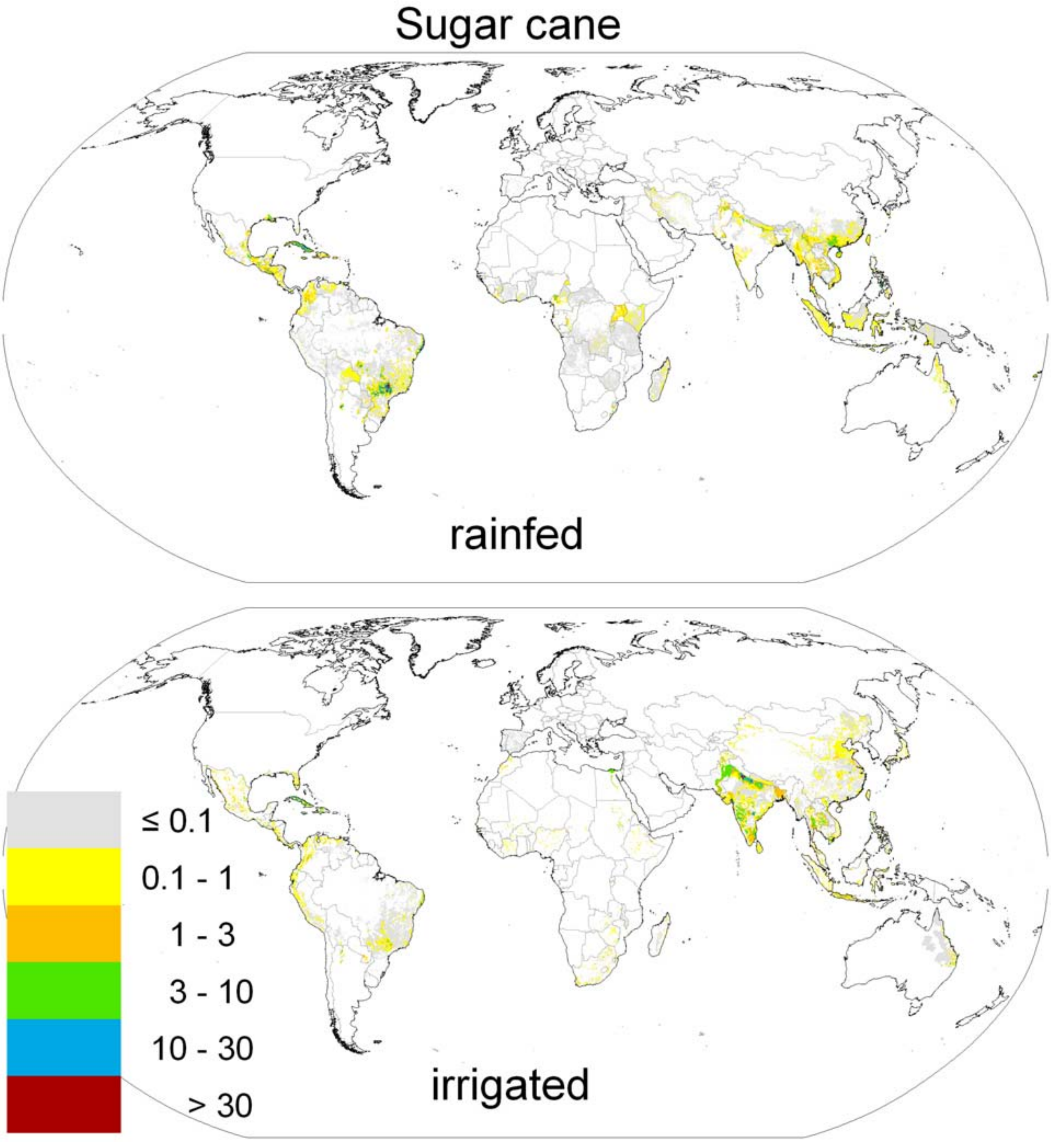

Figure C-12. Global distribution of harvested area of rainfed (top) and irrigated (bottom) sugar cane, as a percentage of grid cell area, for 1998-2002.

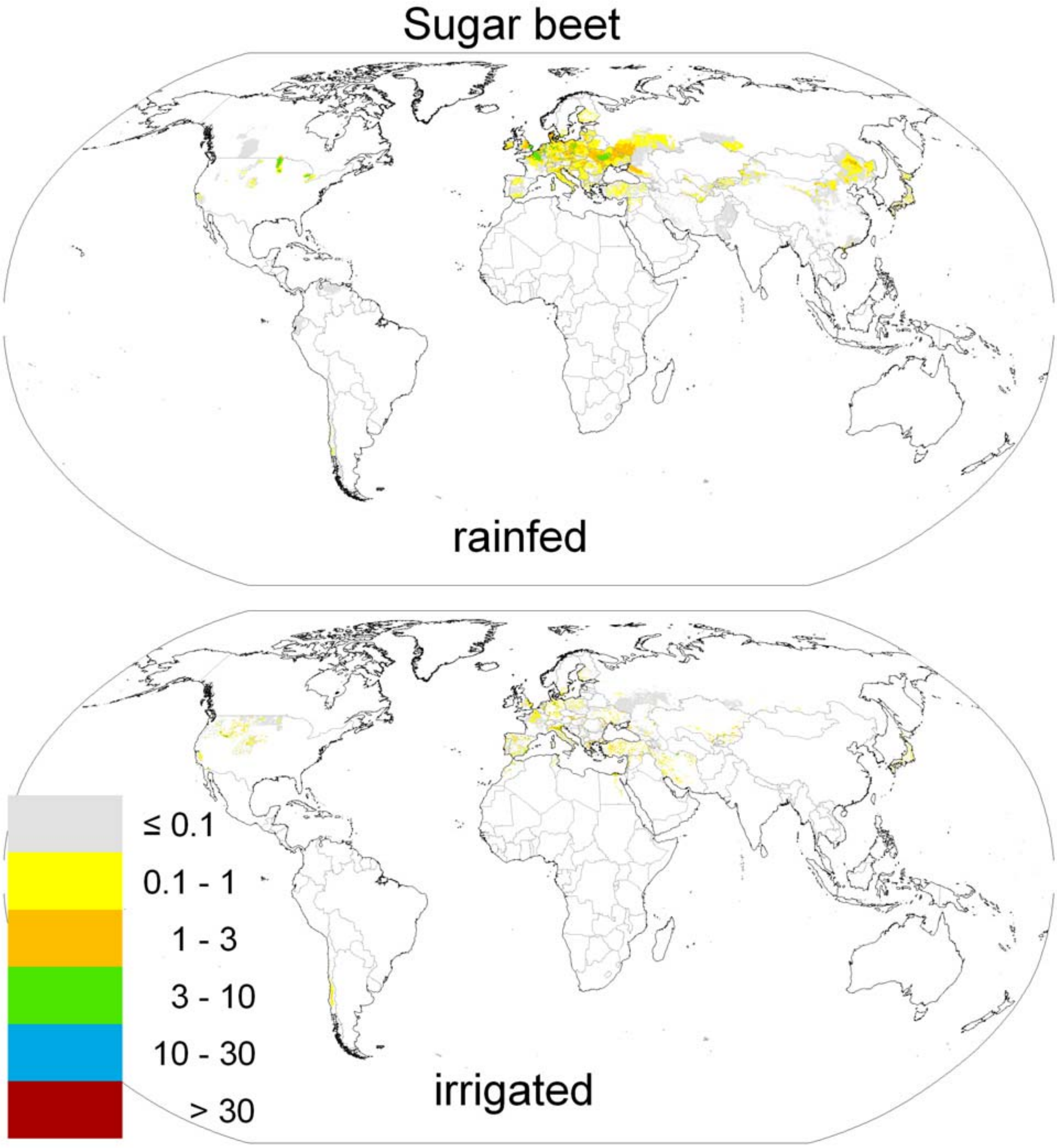

Figure C-13. Global distribution of harvested area of rainfed (top) and irrigated (bottom) sugar beet, as a percentage of grid cell area, for 1998-2002.

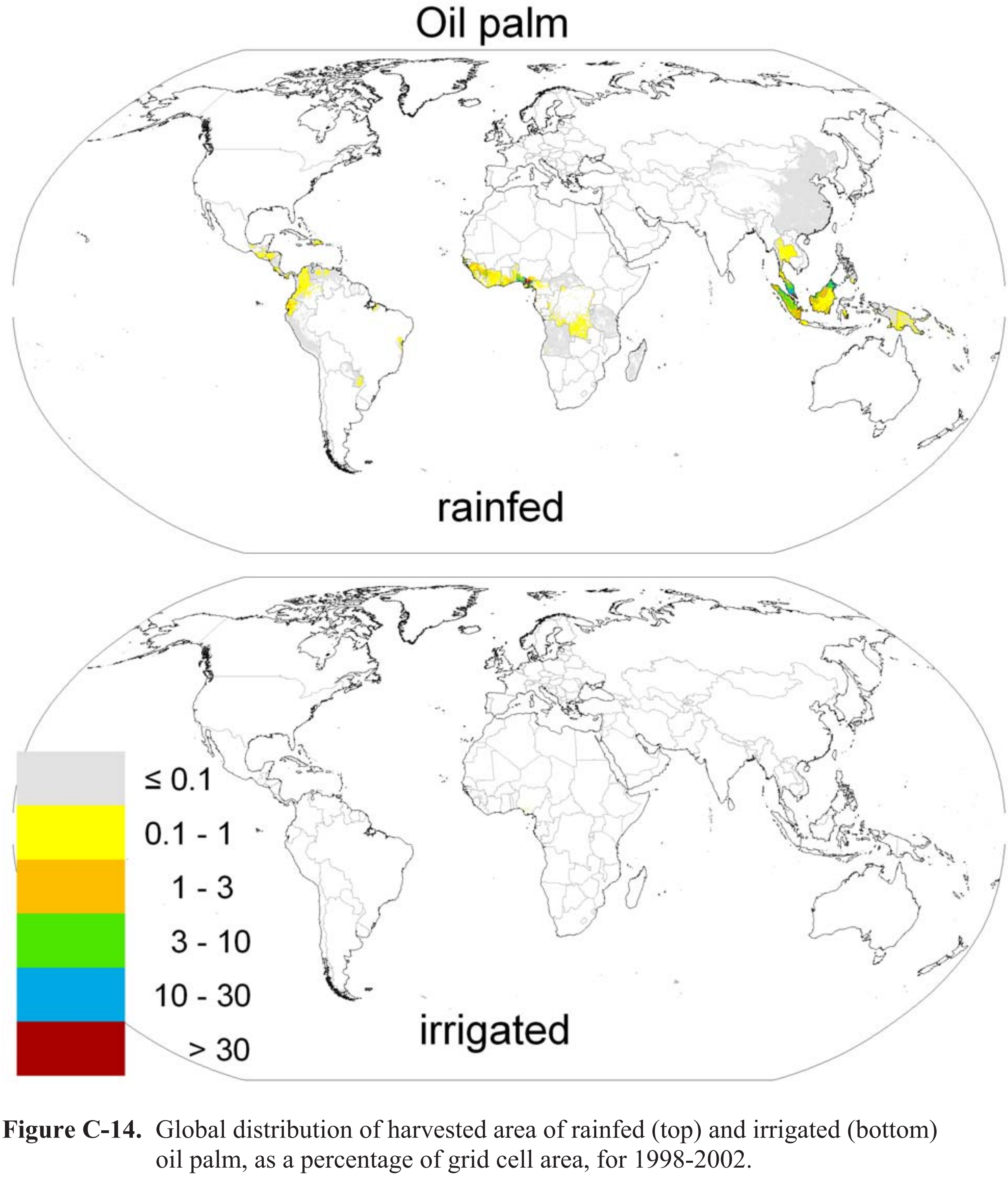

Figure C-14. Global distribution of harvested area of rainfed (top) and irrigated (bottom) oil palm, as a percentage of grid cell area, for 1998-2002.

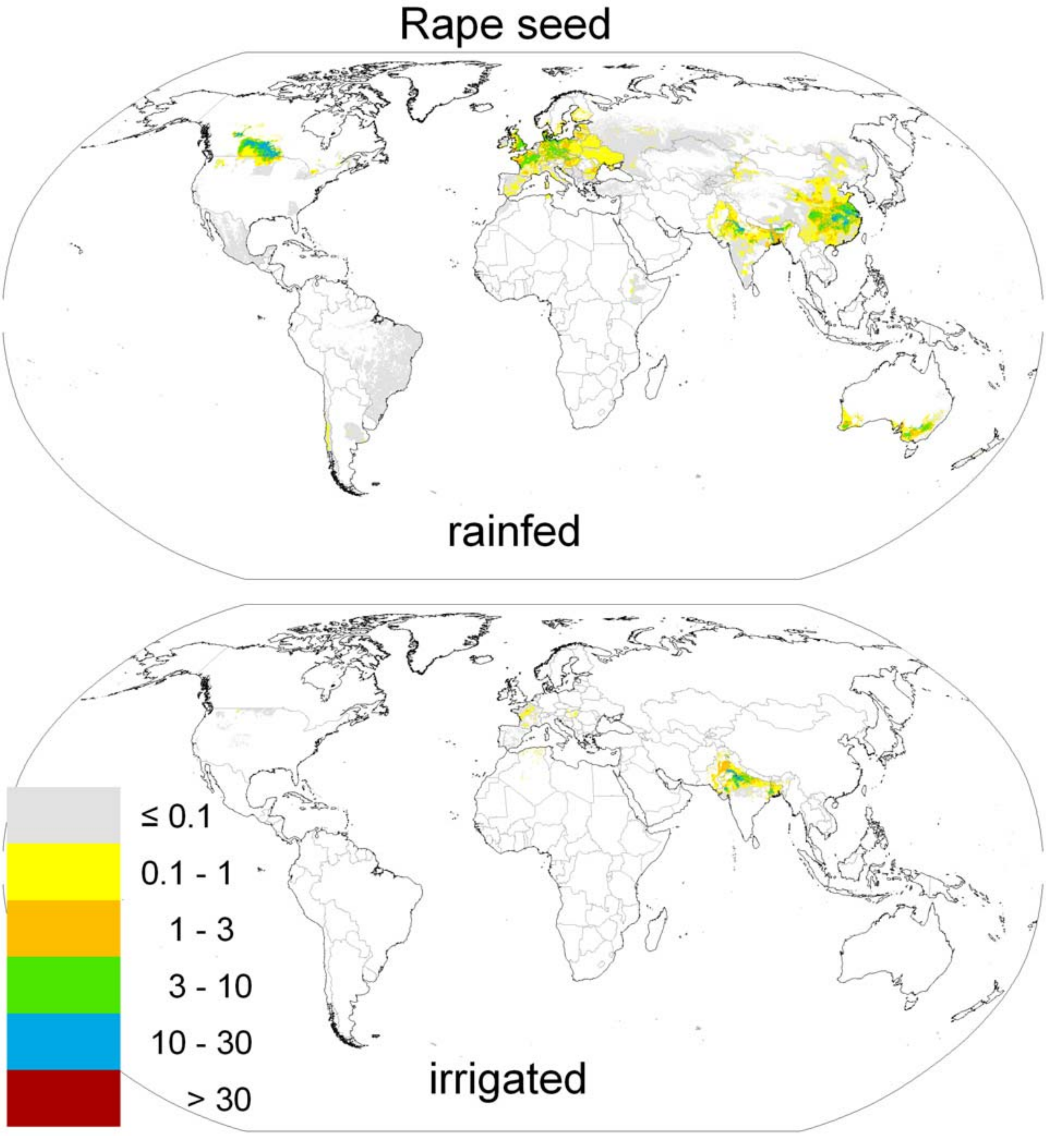

Figure C-15. Global distribution of harvested area of rainfed (top) and irrigated (bottom) rape seed, as a percentage of grid cell area, for 1998-2002.

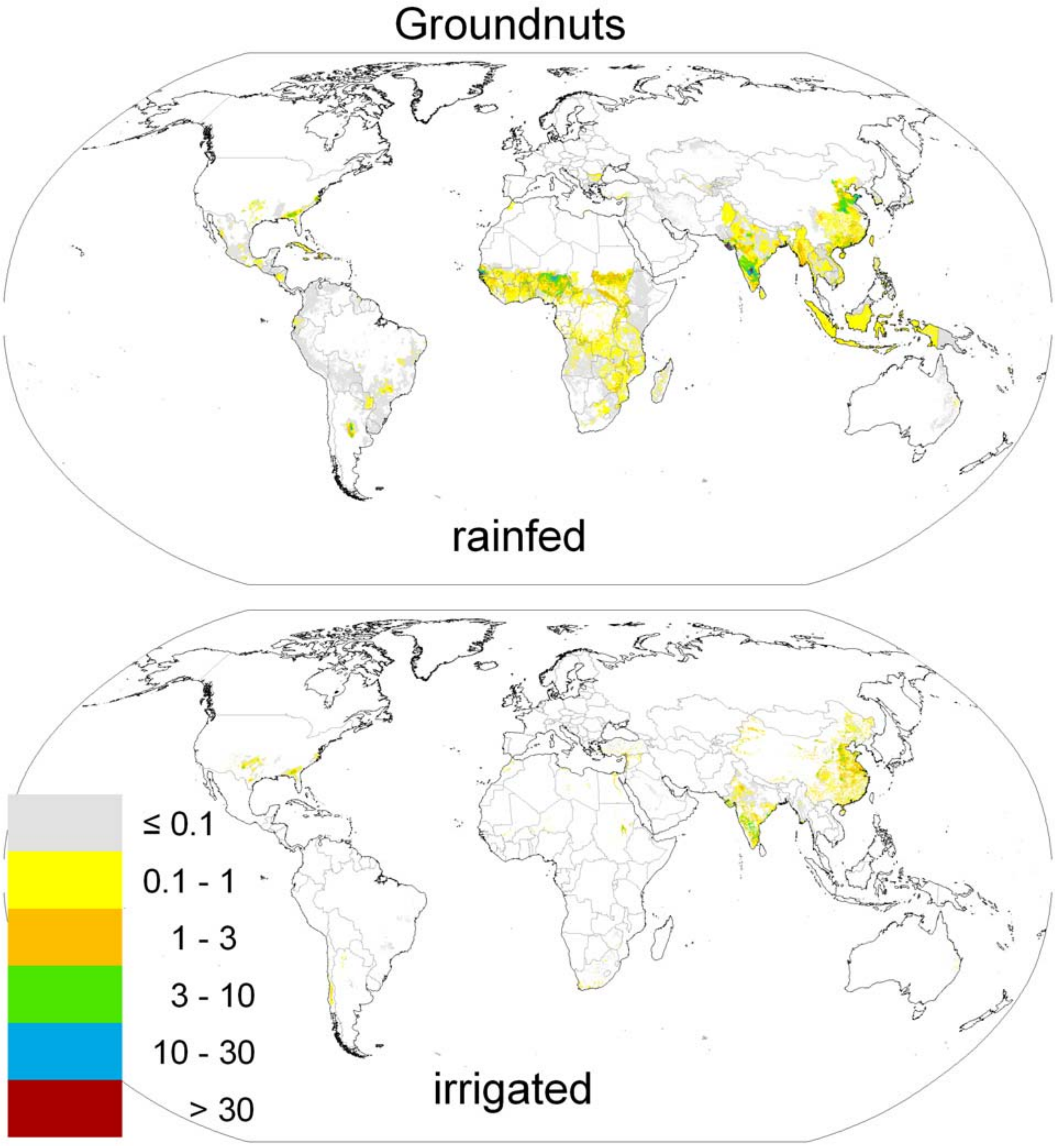

Figure C-16. Global distribution of harvested area of rainfed (top) and irrigated (bottom) groundnuts, as a percentage of grid cell area, for 1998-2002.

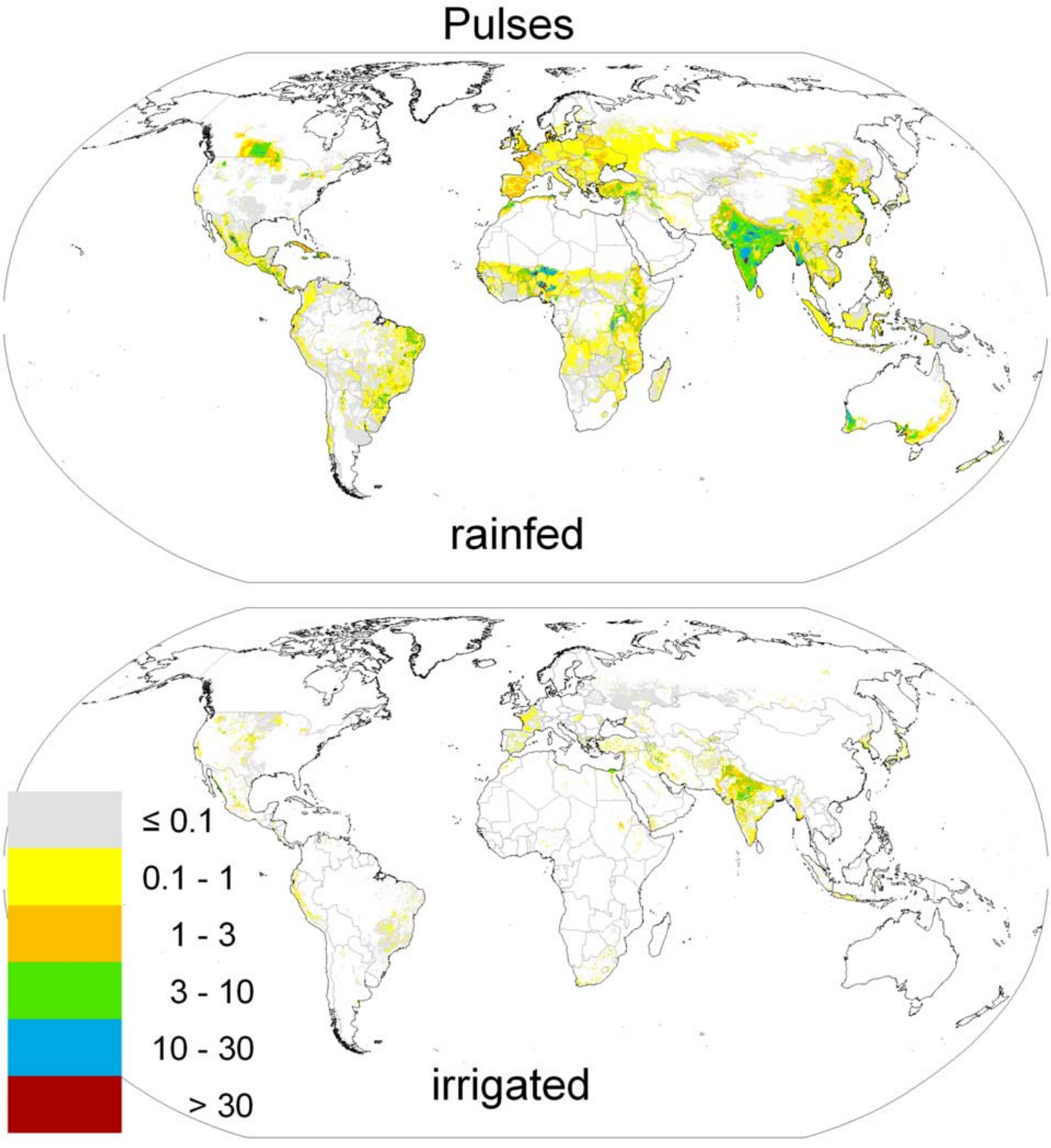

Figure C-17. Global distribution of harvested area of rainfed (top) and irrigated (bottom) pulses, as a percentage of grid cell area, for 1998-2002.

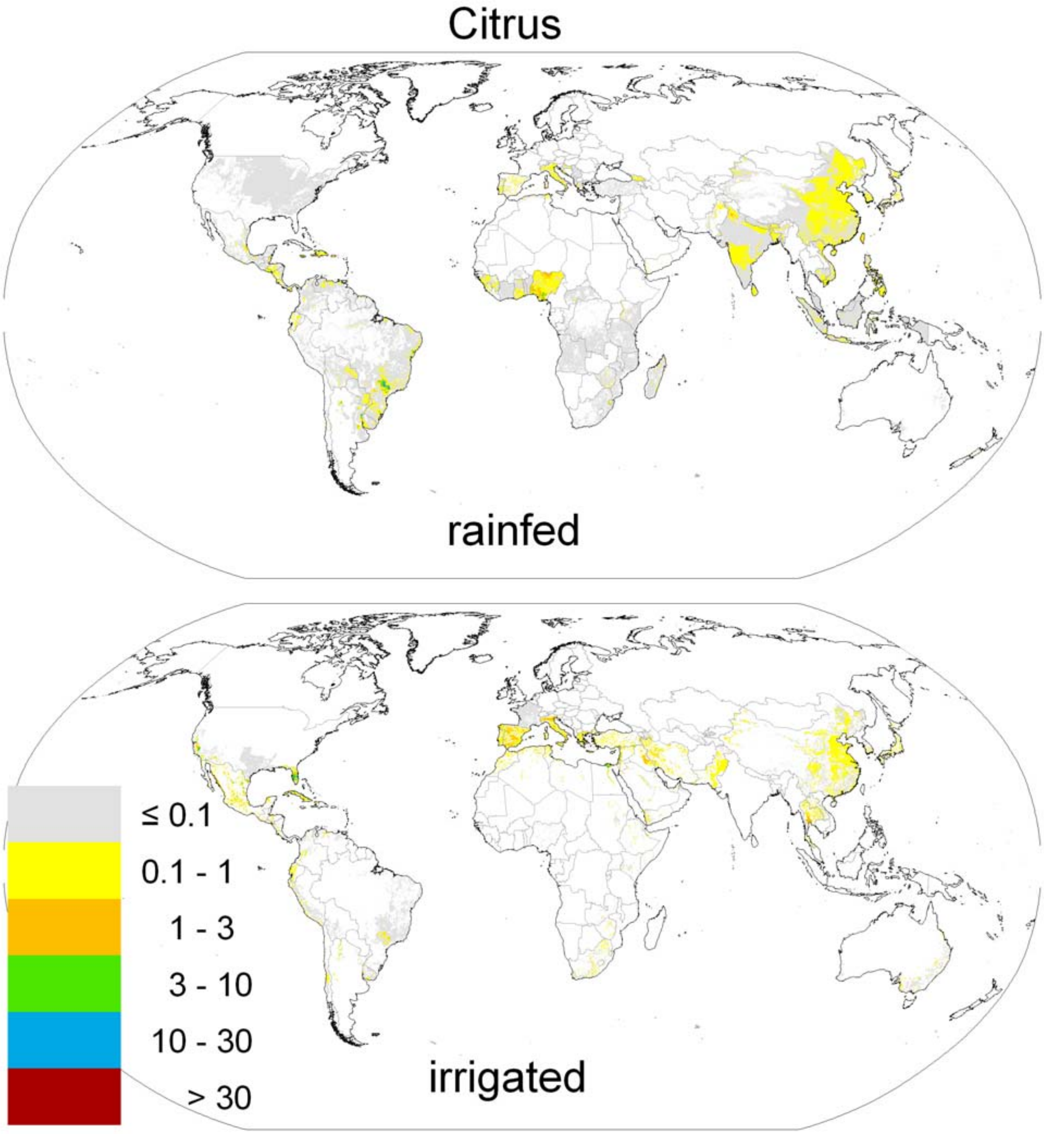

Figure C-18. Global distribution of harvested area of rainfed (top) and irrigated (bottom) citrus, as a percentage of grid cell area, for 1998-2002.

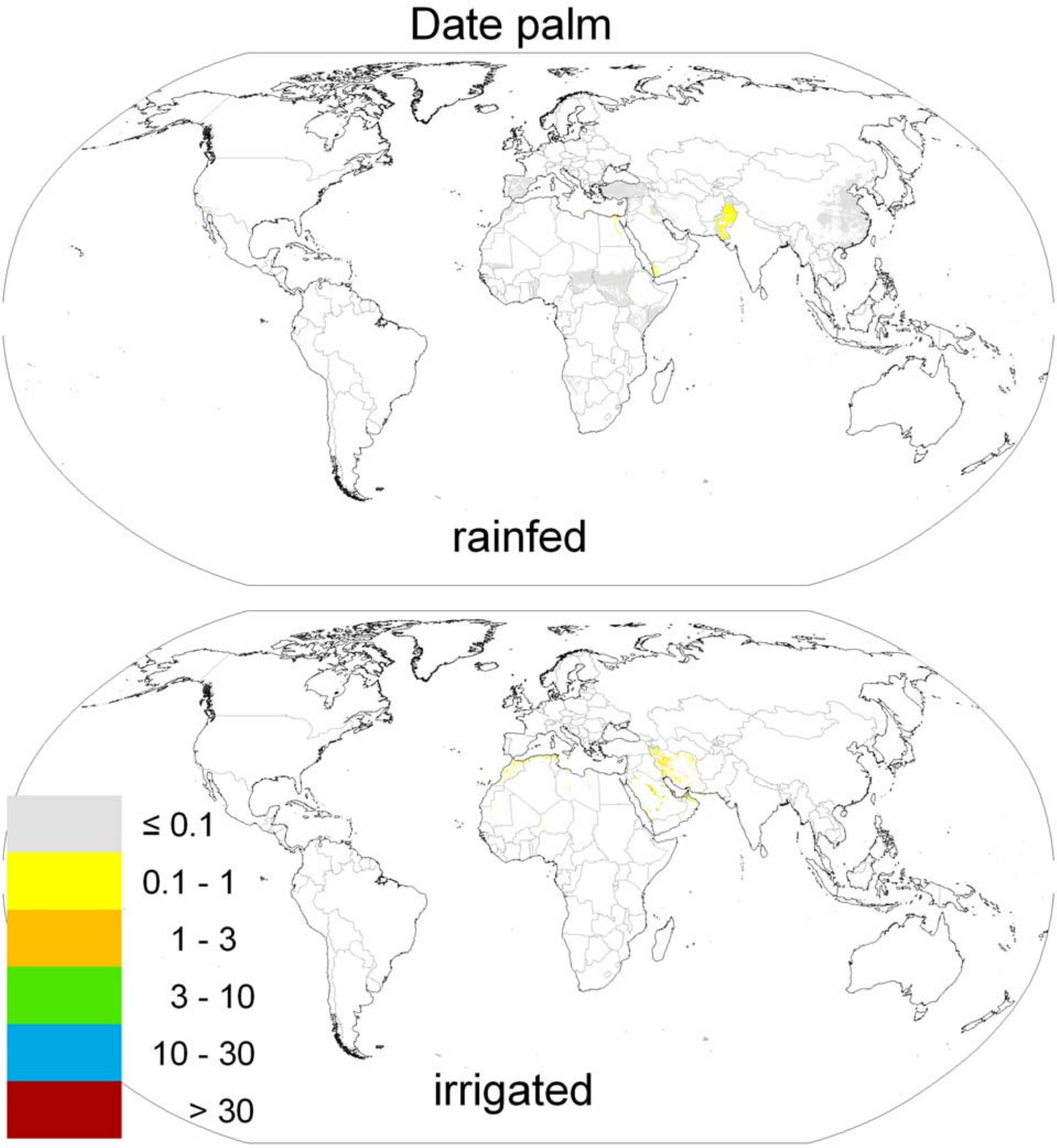

Figure C-19. Global distribution of harvested area of rainfed (top) and irrigated (bottom) date palm, as a percentage of grid cell area, for 1998-2002.

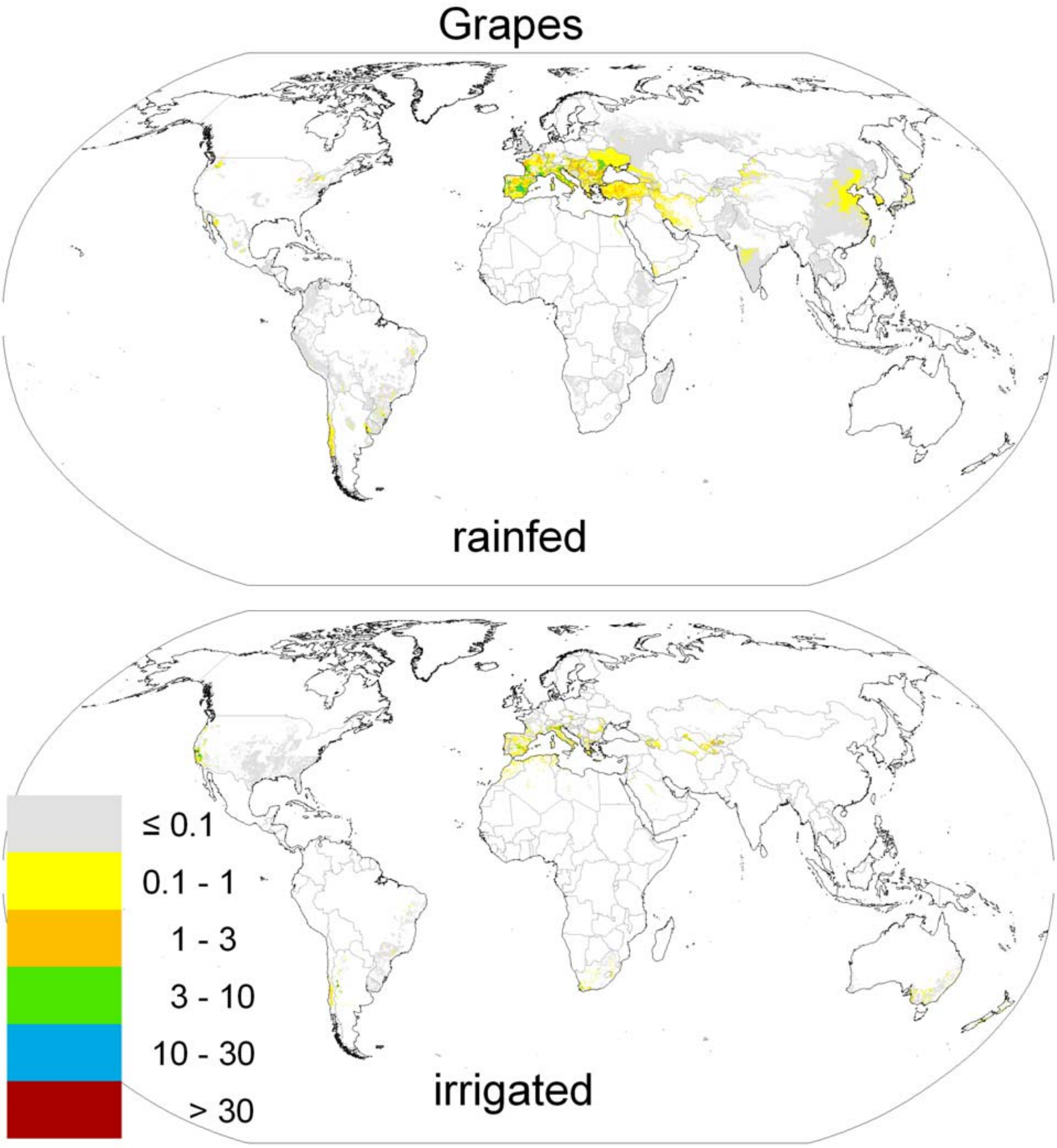

Figure C-20. Global distribution of harvested area of rainfed (top) and irrigated (bottom) grapes, as a percentage of grid cell area, for 1998-2002.

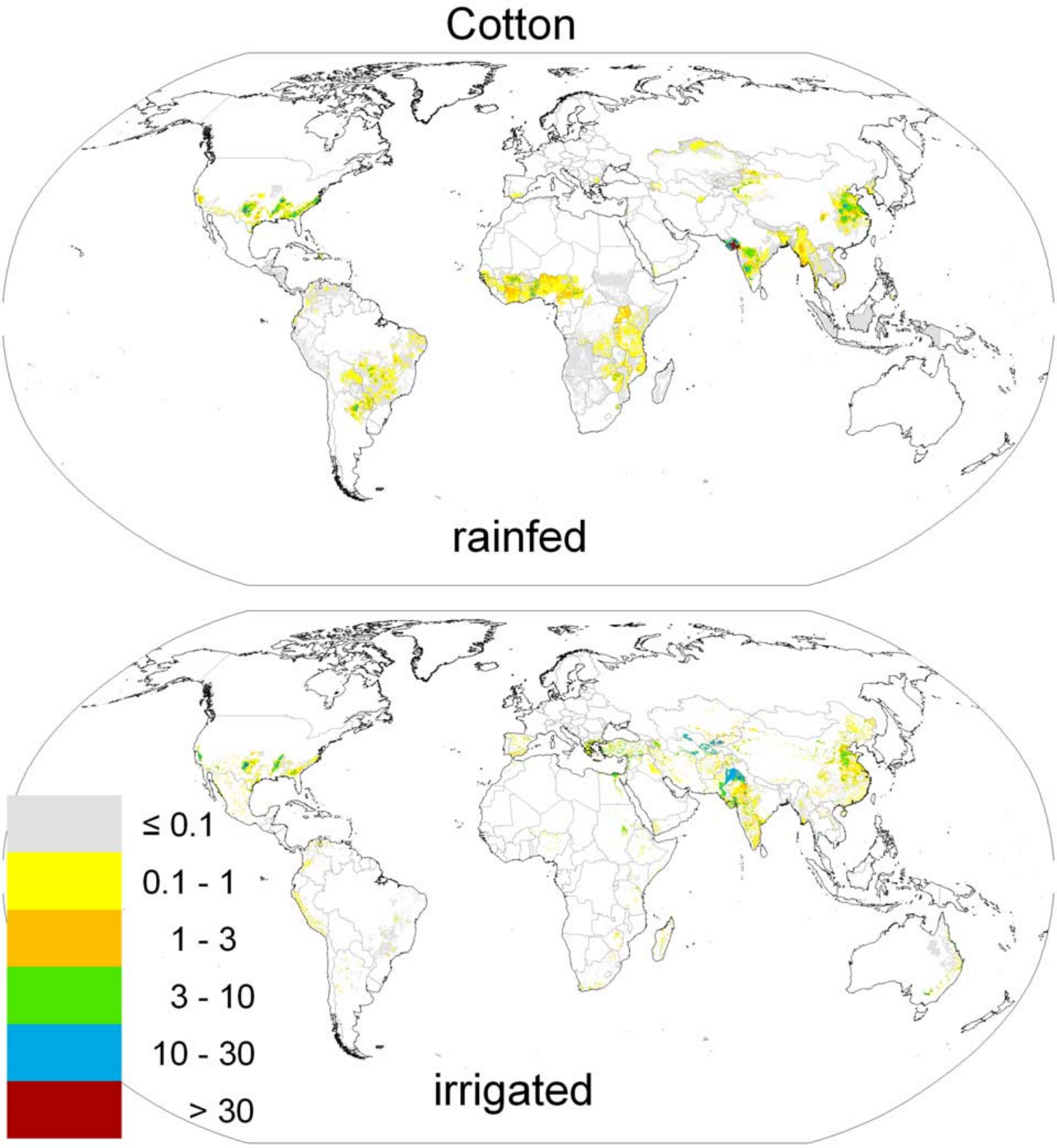

Figure C-21. Global distribution of harvested area of rainfed (top) and irrigated (bottom) cotton, as a percentage of grid cell area, for 1998-2002.

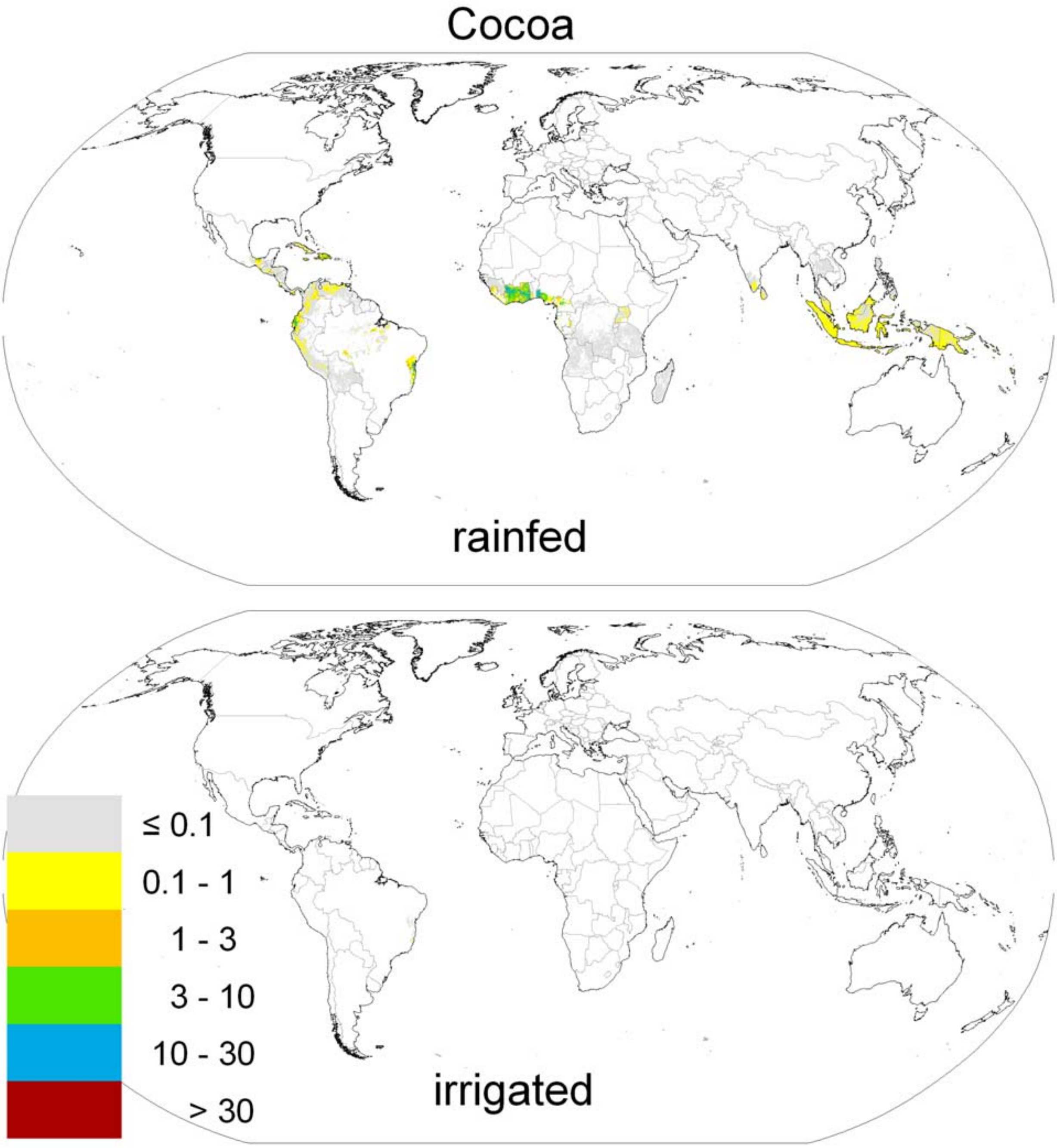

Figure C-22. Global distribution of harvested area of rainfed (top) and irrigated (bottom) cocoa, as a percentage of grid cell area, for 1998-2002.

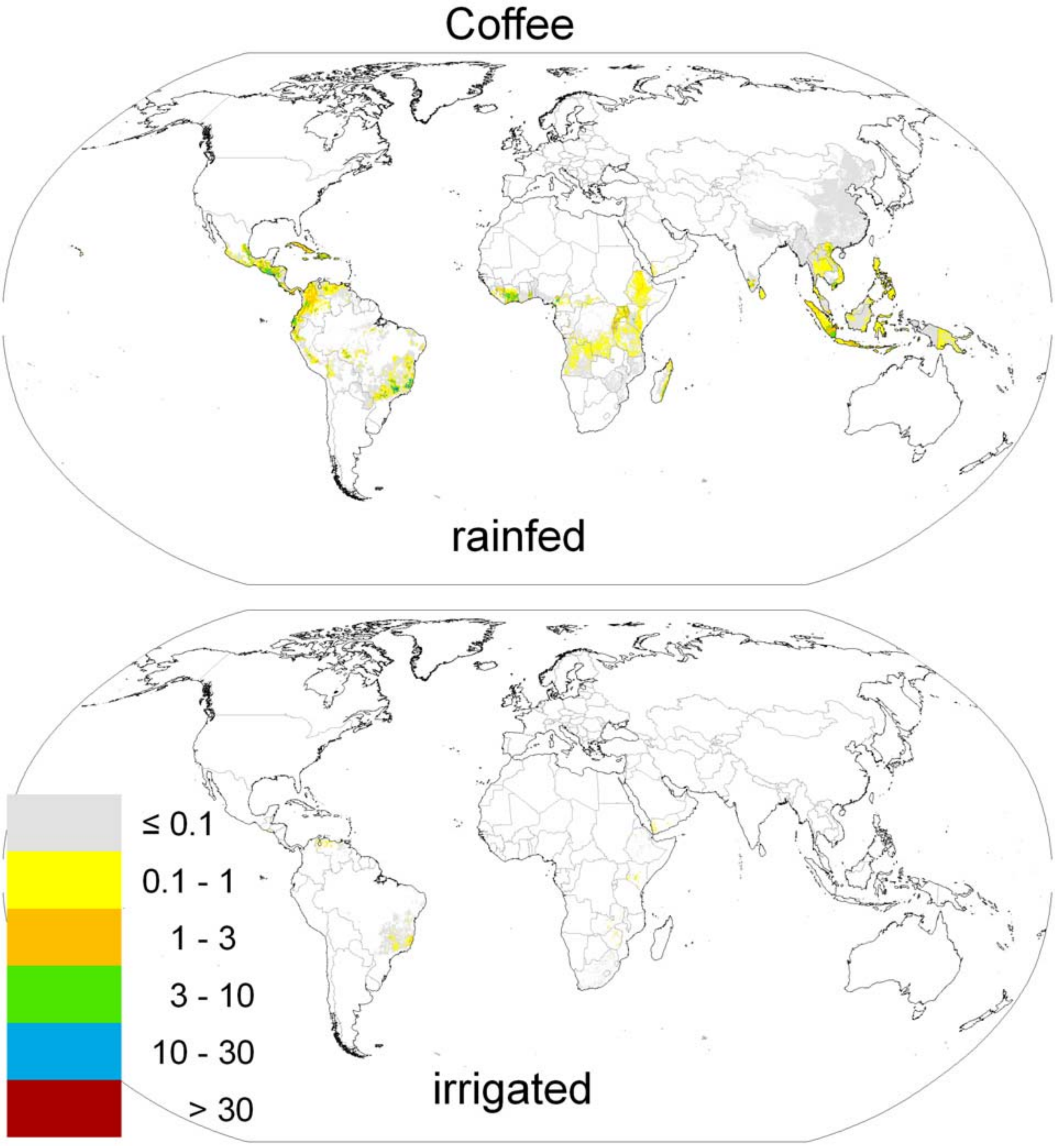

Figure C-23. Global distribution of harvested area of rainfed (top) and irrigated (bottom) coffee, as a percentage of grid cell area, for 1998-2002.

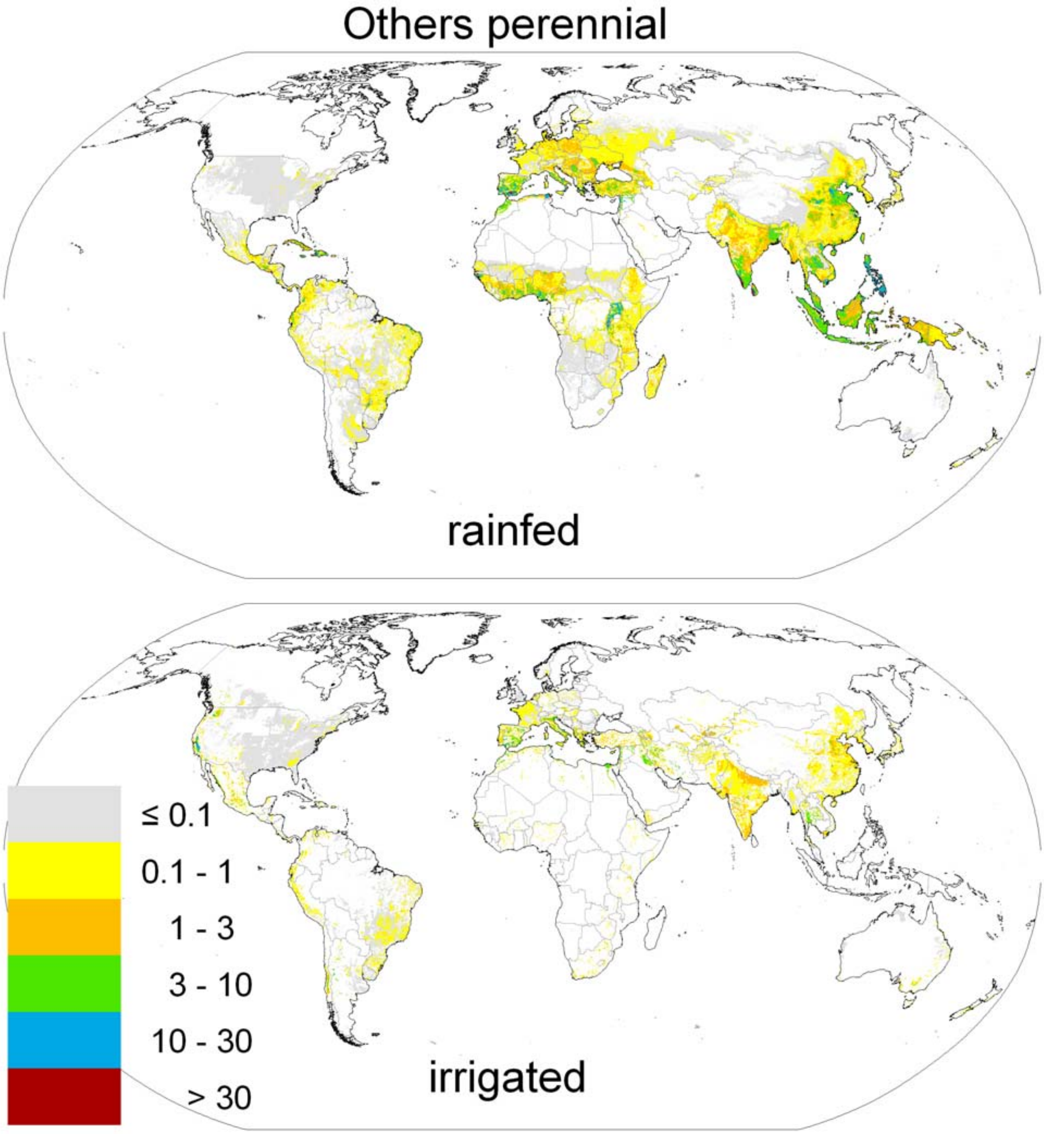

Figure C-24. Global distribution of harvested area of rainfed (top) and irrigated (bottom) other perennial crops, as a percentage of grid cell area, for 1998-2002.

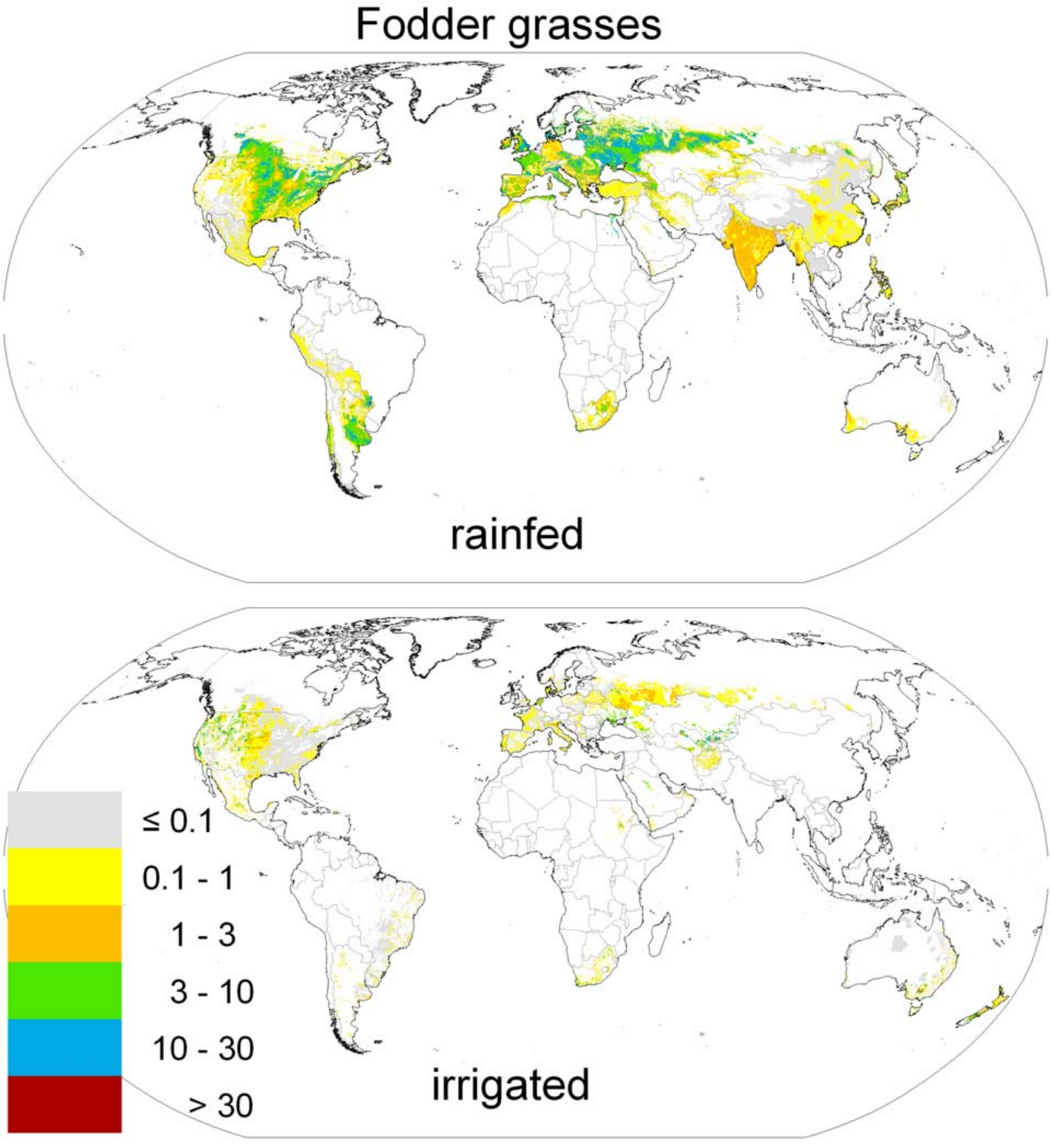

Figure C-25. Global distribution of harvested area of rainfed (top) and irrigated (bottom) fodder crops, as a percentage of grid cell area, for 1998-2002.

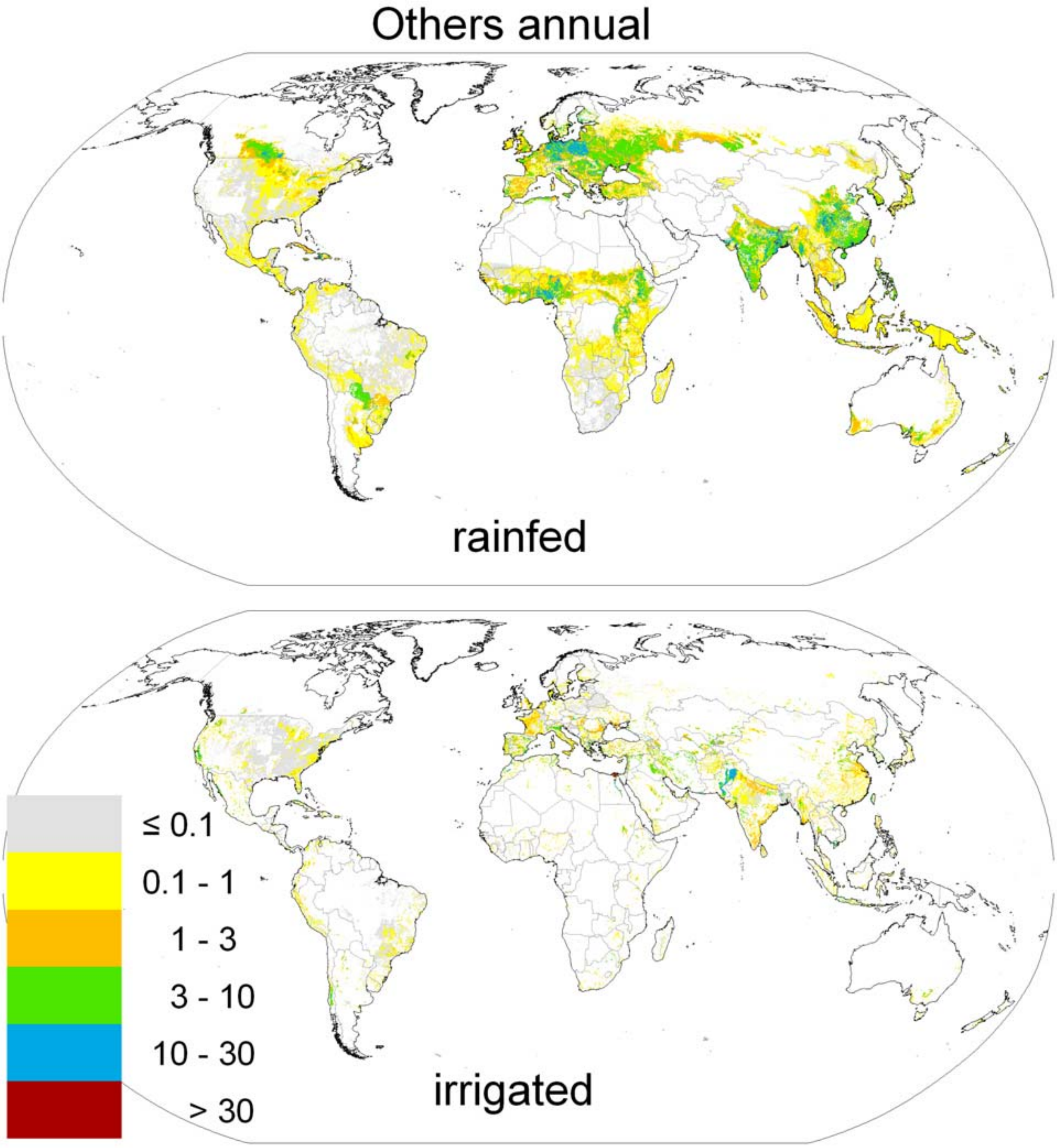

Figure C-26. Global distribution of harvested area of rainfed (top) and irrigated (bottom) other annual crops, as a percentage of grid cell area, for 1998-2002.

Appendix D MIRCA2000 quality parameters

This Appendix shows the detailed results of the quality parameters introduced in Chapter 4.4 on the level of countries (Table D-1), and for parameters Q2_2_P and Q2_2_T on the level of sub-national climate zones (as defined in Appendix K) (Table D-2) and sub-national units (Table D-3). The definition of the parameters is repeated here, in order to facilitate the interpretation of the results. In Appendix L, the unit-level (or country-level) input data used for calculations and for the generation of maps are provided together with a list of the unit codes and unit names as spreadsheets.

Quality parameters of crop calendars (Q2)

Area-weighted deviation of the classification of irrigated crops, per country (or unit), across crops (Q2_1_IR)

The area-weighted quality parameter of a detailed cropping calendar for irrigated crops for a specific unit (most often corresponding to the country) Q2_1_IR was calculated by classification-specific multiplication factors. The areas of specifically mentioned crops (crop-specific quality Q1_IR_mark = 1 in this unit) are multiplied by a factor of 1, the areas of disaggregated or less reliable crops (Q1_IR_mark = 2) are multiplied by 2, while the areas of unspecific crops (e.g. others annual, others perennial, fodder grasses) are multiplied by 3. Then the parameter Q2_1_IR equals the total accumulated multiplication sum of harvested area divided by the total harvested area of all crops, and has a range of 1 to 3. For countries with several sub-national units, the country level quality mark is calculated by adding the multiplication sums of all sub-national units and dividing the result by the respective overall total harvested area for the whole country. If all crop areas were within specific crop classes (all weight factors 1), then Q2_1_IR would be 1, if all areas would have been disaggregated (all weight factors 2), then Q2_1_IR would be 2, and if all areas would be within unspecific crop classes (all weight factors 3), then Q2_1_IR would be 3. Intermediate values indicate a combination of all of these three aspects.

Seasonal climatic variability for precipitation and air temperature, per country (or sub-national climate zone, or unit) (Q2_2_P, Q2_2_T)

As seasonal climatic variability the range between maximum and minimum of climatologic mean monthly precipitation (in mm d^{-1}) or monthly air temperature (° Celsius) of the grid cells belonging to the considered unit is calculated, using the 30 arc-minute mean climatologic values (1961-1990) of the Climate Research Unit (CRU). To calculate the mean variability for the country (Table D-1), sub-national climate zone (Table D-2), or unit (Table D-3), the grid cell level values are weighted with the MIRCA2000 cropland extent CE_{MIRCA}.

Quality parameters derived from grid-cell differences, per country or sub-national unit (Q3)

These quality parameters are calculated with grid cell level differences aggregated on the levels of countries or sub-national units.

Deviation of cropland extent (Q3_1_CE)

The parameter Q3_1_CE is calculated as unit-level (or country-level) sum of grid cell level (absolute) deviation of MIRCA2000 cropland extent CE_{MIRCA} from the CE of the input data set [*Ramankutty et al.*, 2008], divided by the respective sum of the grid cell level maximum of CE of either source, and multiplied by 100 to express percentage. A value of 0% would indicate a perfect fit, while larger values until a maximum of 100% indicate larger relative deviations.

Deviation of total harvested area (Q3_2_AH)

The parameter Q3_2_AH is calculated as unit-level (or country-level) sum of grid cell level (absolute) deviation of MIRCA2000 total harvested area AHT_{MIRCA} from the total harvested area of the input data set AHT_M [*Monfreda et al.*, 2008], divided by the respective sum of the grid cell level maximum of AHT of either source, and multiplied by 100 to express percentage. A value of 0% would indicate a perfect fit, while larger values until a maximum of 100% indicate larger relative deviations.

Quality of area equipped for irrigation, per country only (Q3_3_AEI)

The quality parameter for AEI Q3_3_AEI equals the country-level quality mark of the Global Map of Irrigation Area (GMIA), with values derived from two quantitative indicators, IND_A as the density of the used sub-national irrigation statistics, and IND_B as the fraction of irrigated area that could be assigned to specific grid cells by using geospatial records on the position and extent of known irrigation projects. The values range effectively from classes 1 (very good) to 4 (poor), while the classes 0 (excellent) and 5 (very poor) are not represented in GMIA version 4 [*Siebert et al.*, 2005; *Siebert et al.*, 2006; *Siebert et al.*, 2007].

Spatial dispersion of AHI and AHR (Q3_4_AHI, Q3_4_AHR)

The spatial dispersion of harvested area AH is calculated as the sum of the cell area of grid cells where AH is present divided by the land area of the respective unit or country, and expressed as a percentage of land (surface) area. The parameter Q3_4 is calculated for irrigated harvested area AHI and for rainfed harvested area AHR (Q3_4_AHI and Q3_4_AHR). A value near 0% indicates a very concentrated distribution, while a value near 100% indicates that in almost the whole of the respective country (or unit) used agricultural area exists.

Overall quality mark (Q_MC)

To provide a general quality mark that summarizes the unit-specific quality parameters in one single value, a simple overall quality mark Q_MC is calculated. For deriving its value, first the individual quality parameters are standardized to a relative range of 0 (best performance) to 100 (least performance), inverting direction of the seasonal variability parameters for which the largest variability should indicate the best performance and rescaling them within the effective minimum (new value: 100) and the maximum (new value: 0) of all considered countries. Then, the overall mark is calculated as the arithmetic mean of all individual quality parameters that exist for the given country, omitting Q2_1_IR, Q3_3_AEI, and Q3_4_AHI in case of only rainfed agriculture, and resulting in no quality mark for countries without harvested area. The resulting Q_MC mark can be interpreted in terms of relative differences between countries in the overall mean of deviation, dispersion, and quality. The parameter should be interpreted with some caution, because it is an un-weighted mean and multi-collinearity between the individual quality parameters cannot be fully excluded, and because the distribution process to grid cells is highly non-linear.

Table D-1. MIRCA2000 quality parameter sets Q2, Q3, and overall quality mark Q_CM, per country, with the measurement units and the considered minimum and maximum values. For description of the calculation of the meaning of the individual parameters Q2_1_IR, Q2_2_P, Q2_2_T, Q3_1_CE, Q3_2_AH, Q3_4_AEI, Q3_4_AHI, Q3_4_AHR, and Q_MC see previous short description. Invalid entries without data are marked as "n.a." (not applicable). For parameters Q2_2_P and Q2_2_T, the values of countries with small variability (< 2.5 mm d^{-1} precipitation, < 10 °C air temperature) and the names are marked in **bold**. The sequence is the same as in Table B.

	Q2_1_IR	Q2_2_P	Q2_2_T	Q3_1_CE	Q3_2_AH	Q3_4_AEI	Q3_4_AHI	Q3_4_AHR	Q_MC
	[-]	[mm d^{-1}]	[°C]	[% of ref. CE]	[% of ref. AH]	[-]	[% of area]	[% of area]	[-]
Minimum	1	0.6	0.8	0	0	0	0	0	0
Maximum	3	30.8	39.1	100	100	5	100	100	100
Country									
Afghanistan	2.1	2.3	25.2	14.7	29.4	1	56.1	68.6	46.6
Albania	2.6	3.6	18.4	12.2	12.7	1	93.1	93.3	56.9
Algeria	2.2	2.1	17.5	4.2	16.4	2	4.7	3.9	35.0
American Samoa	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Andorra	2.5	1.5	16.1	1.4	100.0	2	37.5	0.0	51.5
Angola	1.9	6.7	4.6	8.3	3.8	4	1.0	81.4	48.5
Anguilla	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Antigua and Barbuda	3.0	5.8	2.5	100.0	4.1	2	100.0	25.0	68.4
Argentina	1.9	3.1	14.0	5.0	5.1	2	25.9	57.0	41.8
Armenia	1.6	2.0	28.4	11.0	6.9	1	68.2	95.8	44.4
Aruba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Australia	2.1	1.7	13.7	4.7	14.5	1	30.8	16.4	38.3
Austria	2.5	2.0	20.2	0.9	0.3	2	14.9	54.5	41.2
Azerbaijan	2.2	1.4	24.9	19.3	18.2	2	28.8	51.3	43.7
Bahamas	n.a.	4.8	7.0	100.0	0.0	n.a.	n.a.	57.4	65.5
Bahrain	2.3	0.7	21.1	36.4	70.3	1	85.7	7.1	53.6
Bangladesh	1.0	16.5	10.3	14.1	6.2	1	85.4	97.2	43.3
Barbados	3.0	4.8	2.0	100.0	2.2	1	88.9	66.7	70.1
Belarus	2.6	1.7	24.5	0.1	0.3	4	73.0	97.1	57.8
Belgium	2.6	0.9	15.1	0.3	0.0	4	35.9	96.6	56.9
Belize	2.1	7.5	4.6	8.4	0.3	4	16.6	69.0	49.6
Benin	2.2	6.6	4.8	5.8	4.3	1	6.9	94.9	45.1
Bermuda	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Bhutan	1.0	16.5	13.0	10.7	33.5	1	34.7	98.1	39.1
Bolivia (Plurinational State of)	2.2	5.0	6.1	2.4	7.3	3	22.4	69.7	48.9
Bosnia and Herzegovina	2.5	1.8	19.8	0.0	0.0	2	8.1	94.6	45.2
Botswana	2.0	2.9	12.2	0.2	0.4	3	0.5	60.7	41.5
Brazil	1.6	6.0	5.6	13.9	5.8	2	43.7	64.2	46.2

	Q2_1 _IR	Q2_2 _P	Q2_2 _T	Q3_1 _CE	Q3_2 _AH	Q3_4 _AEI	Q3_4 _AHI	Q3_4 _AHR	Q_MC
	[-]	[mm d^{-1}]	[°C]	[% of ref. CE]	[% of ref. AH]	[-]	[% of area]	[% of area]	[-]
Minimum	1	0.6	0.8	0	0	0	0	0	0
Maximum	3	30.8	39.1	100	100	5	100	100	100
British Indian Ocean Territory*	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
British Virgin Islands	n.a.	5.5	3.1	100.0	0.0	n.a.	n.a.	0.0	55.5
Brunei Darussalam	2.3	5.3	1.2	1.6	1.9	3	35.6	94.9	55.0
Bulgaria	2.5	1.1	22.4	0.4	0.2	2	40.4	93.6	48.8
Burkina Faso	1.6	6.6	7.9	1.1	1.2	2	10.0	96.2	42.6
Burundi	1.1	6.3	1.7	41.2	7.7	4	21.4	91.0	53.0
Cambodia	1.0	10.3	4.0	0.9	0.7	1	30.3	96.9	38.6
Cameroon	2.5	9.2	4.3	2.2	4.8	2	1.4	53.9	42.3
Canada	2.6	1.8	32.9	1.6	1.0	2	8.6	14.7	32.3
Cape Verde	2.1	3.2	4.8	100.0	5.0	1	90.2	30.5	60.0
Cayman Islands	n.a.	5.4	3.7	100.0	0.0	n.a.	n.a.	100.0	75.3
Central African Republic	2.4	7.7	4.1	1.3	13.6	3	0.1	71.9	48.2
Chad	1.2	6.3	7.9	2.6	3.8	3	1.9	37.8	34.5
Chile	2.1	5.1	10.2	26.6	29.1	2	11.9	57.8	47.7
China	1.1	5.2	27.4	10.5	25.0	2	32.3	72.8	37.4
Christmas Island*	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cocos (Keeling) Islands*	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Colombia	1.4	7.4	1.4	15.6	13.0	3	22.5	63.2	46.1
Comoros	3.0	8.7	3.1	100.0	27.3	1	26.1	91.3	66.5
Congo	2.1	7.9	2.7	4.1	1.8	3	0.3	24.4	39.6
Cook Islands	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Costa Rica	1.6	12.5	2.4	5.2	19.7	3	49.3	79.8	50.1
Côte d'Ivoire	2.0	7.8	3.8	4.3	2.8	2	15.4	92.2	46.9
Croatia	2.4	2.1	20.3	0.5	0.0	1	64.7	81.8	47.6
Cuba	1.5	6.0	5.2	2.5	18.6	3	67.5	89.3	54.1
Cyprus	2.2	3.1	16.7	16.8	71.0	2	91.6	71.9	62.6
Czech Republic	2.8	1.6	20.0	0.0	0.1	3	15.3	94.2	50.7
Democratic People's Republic of Korea	1.3	8.2	31.7	8.3	7.7	3	90.3	88.9	45.6
Democratic Republic of the Congo	1.0	6.8	2.6	19.5	4.2	2	0.1	39.1	34.7
Denmark	2.0	1.4	16.1	9.9	7.5	3	72.6	99.0	56.8
Djibouti	2.9	**1.3**	**8.7**	46.7	51.4	1	9.8	4.7	50.4
Dominica	n.a.	8.4	2.6	100.0	37.8	n.a.	n.a.	20.0	65.5
Dominican Republic	1.0	5.6	3.9	3.4	17.0	2	45.3	95.9	47.4
Ecuador	1.4	7.1	1.6	16.6	20.2	3	34.2	87.1	51.7
Egypt	1.8	0.6	14.6	47.9	33.7	1	8.4	8.3	40.1

	Q2_1 _IR	Q2_2 _P	Q2_2 _T	Q3_1 _CE	Q3_2 _AH	Q3_4 _AEI	Q3_4 _AHI	Q3_4 _AHR	Q_MC
	[-]	[mm d^{-1}]	[°C]	[% of ref. CE]	[% of ref. AH]	[-]	[% of area]	[% of area]	[-]
Minimum	1	0.6	0.8	0	0	0	0	0	0
Maximum	3	30.8	39.1	100	100	5	100	100	100
El Salvador	2.2	11.3	2.9	7.2	7.7	2	30.3	99.2	50.6
Equatorial Guinea	n.a.	11.5	2.4	8.0	0.0	n.a.	n.a.	18.4	37.2
Eritrea	2.4	4.3	6.2	1.9	0.9	2	11.1	42.4	42.3
Estonia	2.8	1.7	23.2	1.9	0.0	2	28.8	87.4	48.5
Ethiopia	1.8	6.8	4.2	2.4	3.4	3	5.0	64.3	43.1
Faeroe Islands	n.a.	3.7	7.4	100.0	0.0	n.a.	n.a.	5.0	55.5
Falkland Islands (Malvinas)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fiji	3.0	10.6	3.6	100.0	3.5	3	7.4	92.6	65.4
Finland	2.5	1.6	25.0	4.4	0.0	4	19.2	21.9	41.7
France	1.6	1.2	15.1	2.0	1.0	2	96.9	88.5	52.6
French Guiana	2.1	13.8	1.6	25.7	44.9	3	1.6	47.3	48.7
French Polynesia	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Gabon	1.7	10.1	3.1	1.8	6.6	2	1.1	16.6	33.0
Gambia	2.0	9.8	5.7	9.2	1.2	1	5.3	98.5	42.6
Georgia	2.2	2.6	24.1	9.8	22.4	3	12.7	86.6	48.1
Germany	2.3	1.2	17.7	2.0	3.3	2	32.8	96.1	49.2
Ghana	2.4	6.8	4.1	7.6	11.4	3	7.7	94.2	52.6
Greece	2.1	2.8	18.3	25.4	20.0	2	97.2	70.0	56.7
Greenland	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Grenada	3.0	5.3	2.3	100.0	13.2	2	100.0	100.0	79.0
Guadeloupe	2.3	7.6	2.9	100.0	5.5	1	100.0	46.9	63.8
Guam	3.0	30.8	1.4	100.0	0.7	2	100.0	36.4	59.4
Guatemala	2.1	13.8	3.5	1.9	7.7	2	21.4	88.6	45.2
Guinea	1.5	12.9	4.3	16.0	12.4	3	23.4	87.2	47.0
Guinea-Bissau	2.7	14.7	5.4	2.7	0.7	3	48.0	84.5	52.5
Guyana	1.0	8.7	1.6	8.9	53.5	2	5.5	55.7	42.1
Haiti	1.5	6.5	3.6	5.1	5.0	2	31.3	92.1	46.5
Honduras	1.7	9.2	3.8	2.1	8.6	3	45.2	90.2	50.9
Hungary	2.6	1.5	22.1	3.8	4.0	2	38.0	98.5	50.6
Iceland	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
India	1.2	9.0	13.3	4.1	7.4	2	71.7	96.2	45.8
Indonesia	1.1	7.3	1.1	3.5	12.0	2	17.2	97.2	43.8
Iran (Islamic Republic of)	2.0	1.7	25.4	14.8	26.6	2	22.2	32.2	39.6
Iraq	1.5	1.5	25.1	12.9	87.3	3	24.3	38.4	47.4
Ireland	2.5	**1.9**	**10.0**	6.2	0.1	4	30.6	86.7	56.6
Israel	2.1	3.9	14.5	5.9	38.3	1	52.9	45.7	46.3
Italy	1.9	2.1	17.9	12.0	8.6	1	93.5	80.0	50.9
Jamaica	1.4	7.5	3.2	1.4	2.9	1	49.0	90.5	44.6

	Q2_1 _IR [-]	Q2_2 _P [mm d-1]	Q2_2 _T [°C]	Q3_1 _CE [% of ref. CE]	Q3_2 _AH [% of ref. AH]	Q3_4 _AEI [-]	Q3_4 _AHI [% of area]	Q3_4 _AHR [% of area]	Q_MC [-]
Minimum	1	0.6	0.8	0	0	0	0	0	0
Maximum	3	30.8	39.1	100	100	5	100	100	100
Japan	1.1	6.1	23.9	40.2	33.0	2	37.3	78.7	44.7
Jordan	2.5	2.7	16.5	5.4	59.4	3	14.7	13.0	47.6
Kazakhstan	2.0	1.1	36.2	5.0	15.3	3	3.9	36.9	34.3
Kenya	2.1	4.5	3.1	2.9	1.5	2	12.1	78.8	46.5
Kiribati	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Kuwait	2.2	0.7	23.7	29.8	77.5	1	10.4	3.9	42.7
Kyrgyzstan	2.2	1.8	28.8	31.2	64.4	2	26.8	88.1	53.9
Lao People's Democratic Republic	1.2	11.0	7.5	11.1	17.8	1	36.8	97.5	42.6
Latvia	2.3	1.6	22.4	0.2	0.0	2	64.1	91.3	50.1
Lebanon	2.4	4.7	16.9	8.3	28.6	1	76.0	89.6	54.5
Lesotho	3.0	3.6	12.0	0.2	0.0	2	8.2	84.8	49.2
Liberia	3.0	13.8	2.6	26.2	4.2	4	3.9	31.9	49.7
Libyan Arab Jamahiriya	2.3	1.6	15.1	39.1	43.5	2	4.0	0.8	43.6
Liechtenstein	n.a.	2.6	16.9	0.0	0.0	n.a.	n.a.	0.0	30.2
Lithuania	3.0	1.6	22.3	0.0	0.0	2	55.8	96.4	54.1
Luxembourg	3.0	1.0	16.9	0.0	0.0	2	43.2	97.0	54.6
Madagascar	1.0	9.0	5.2	18.9	46.1	3	40.4	76.3	50.4
Malawi	1.9	7.8	6.7	20.9	8.9	3	60.3	67.4	53.1
Malaysia	1.2	7.6	1.3	2.3	9.9	2	19.6	99.0	44.4
Maldives	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mali	1.1	5.8	9.7	3.6	10.1	3	2.0	37.0	34.9
Malta	2.5	2.4	14.0	100.0	0.8	1	100.0	63.6	64.6
Marshall Islands	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Martinique	2.5	7.6	2.4	100.0	18.5	2	38.9	77.8	65.4
Mauritania	1.2	3.8	11.1	3.1	10.5	3	1.2	13.6	32.8
Mauritius	1.1	7.8	5.3	100.0	9.4	1	85.3	67.6	56.6
Mayotte	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mexico	1.9	6.8	8.4	3.6	21.9	2	23.3	89.2	47.6
Micronesia (Federated States of)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mongolia	2.1	3.0	39.1	2.0	22.1	3	4.0	39.1	34.5
Montenegro	1.1	2.1	19.5	0.1	0.0	4	93.7	94.1	52.4
Montserrat	n.a.	6.2	2.7	100.0	0.0	n.a.	n.a.	100.0	75.3
Morocco	2.0	2.3	14.2	5.3	17.3	2	20.9	35.2	40.8
Mozambique	1.5	6.9	6.8	11.1	2.5	1	3.5	79.3	38.0
Myanmar	1.2	15.9	7.5	17.5	7.2	3	48.0	94.6	46.4
Namibia	1.9	3.2	9.4	0.9	7.0	2	1.2	43.7	38.5
Nauru	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

	Q2_1 _IR [-]	Q2_2 _P [mm d^{-1}]	Q2_2 _T [°C]	Q3_1 _CE [% of ref. CE]	Q3_2 _AH [% of ref. AH]	Q3_4 _AEI [-]	Q3_4 _AHI [% of area]	Q3_4 _AHR [% of area]	Q_MC [-]
Minimum	1	0.6	0.8	0	0	0	0	0	0
Maximum	3	30.8	39.1	100	100	5	100	100	100
Nepal	1.1	14.5	14.1	26.8	7.1	1	83.4	99.2	45.0
Netherlands	2.8	1.0	14.7	10.6	3.2	1	98.9	90.2	59.3
Netherlands Antilles	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
New Caledonia	n.a.	4.2	5.8	100.0	0.0	n.a.	n.a.	99.2	74.9
New Zealand	2.9	1.4	10.8	47.7	44.3	3	78.8	22.8	65.0
Nicaragua	1.5	10.7	2.8	1.7	5.8	3	30.6	88.4	46.8
Niger	2.3	5.0	10.8	0.4	1.4	4	1.9	24.4	41.3
Nigeria	1.9	8.0	6.0	5.8	11.3	3	9.8	95.5	48.9
Niue	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Norfolk Island	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Northern Mariana Islands	3.0	26.2	2.1	100.0	100.0	2	100.0	0.0	69.0
Norway	2.6	2.8	19.2	34.2	7.9	2	25.9	27.6	45.1
Occupied Palestinian Territory	2.5	4.1	14.9	1.6	22.7	1	57.5	83.9	51.8
Oman	1.9	0.9	13.6	44.4	80.6	1	11.8	2.2	46.3
Pakistan	1.3	3.0	20.9	6.8	37.0	2	40.3	68.5	43.5
Palau	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Panama	1.7	11.6	2.1	3.1	6.7	3	29.9	85.4	47.8
Papua New Guinea	n.a.	6.9	1.6	2.2	0.0	n.a.	n.a.	99.2	55.7
Paraguay	1.1	3.3	9.8	39.5	33.3	4	5.9	86.8	52.1
Peru	1.5	3.5	2.8	15.7	22.3	2	33.5	54.7	47.2
Philippines	1.1	8.4	2.4	25.8	8.6	3	35.8	93.8	49.8
Pitcairn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Poland	2.5	1.7	20.4	0.1	0.1	3	54.8	97.5	54.1
Portugal	1.9	3.6	13.6	10.1	10.8	1	97.0	79.2	52.1
Puerto Rico	2.9	5.8	3.4	21.8	12.9	1	94.7	86.4	63.6
Qatar	2.3	0.6	17.9	100.0	100.0	2	53.7	0.0	64.3
Republic of Korea	1.4	8.6	27.0	13.0	12.0	2	67.8	95.6	44.4
Republic of Moldova	2.3	1.6	24.3	0.1	5.5	2	41.5	99.8	48.5
Réunion	1.9	8.2	5.6	100.0	1.5	2	46.3	68.3	57.8
Romania	1.7	1.7	23.2	1.4	4.9	2	33.6	88.7	42.6
Russian Federation	2.4	1.5	32.7	1.2	1.6	4	13.7	20.4	37.7
Rwanda	1.7	5.1	0.8	41.6	12.9	2	12.9	90.4	52.4
Saint Helena	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Saint Kitts and Nevis	3.0	5.0	2.8	100.0	0.2	1	100.0	30.0	66.3
Saint Lucia	3.0	6.4	2.5	100.0	0.3	1	100.0	63.6	70.0
Saint Pierre and Miquelon	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Saint Vincent	n.a.	5.5	2.7	100.0	0.0	n.a.	n.a.	73.0	70.3

	Q2_1 _IR	Q2_2 _P	Q2_2 _T	Q3_1 _CE	Q3_2 _AH	Q3_4 _AEI	Q3_4 _AHI	Q3_4 _AHR	Q_MC
	[-]	[mm d^{-1}]	[°C]	[% of ref. CE]	[% of ref. AH]	[-]	[% of area]	[% of area]	[-]
Minimum	1	0.6	0.8	0	0	0	0	0	0
Maximum	3	30.8	39.1	100	100	5	100	100	100
and the Grenadines									
Samoa	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
San Marino	n.a.	1.6	17.6	0.0	0.0	n.a.	n.a.	100.0	50.5
Sao Tome and Principe	1.0	9.1	3.1	100.0	39.6	1	64.3	42.9	54.3
Saudi Arabia	1.7	0.6	17.7	33.9	59.9	2	7.4	3.0	41.8
Senegal	1.4	7.1	6.7	3.6	6.7	3	10.6	92.3	44.5
Serbia	2.5	1.5	21.9	0.0	0.0	2	75.9	96.5	53.8
Seychelles	3.0	7.9	2.3	100.0	100.0	1	93.4	0.0	73.0
Sierra Leone	2.2	17.0	3.2	16.7	4.0	3	27.2	66.8	47.0
Singapore	n.a.	4.0	1.5	0.1	0.0	n.a.	n.a.	100.0	57.4
Slovakia	2.0	1.7	21.3	1.3	2.5	2	32.8	83.5	44.4
Slovenia	2.7	2.3	19.9	1.9	2.0	1	31.2	70.7	44.1
Solomon Islands	n.a.	5.7	1.7	100.0	0.0	n.a.	n.a.	95.0	75.1
Somalia	1.5	3.1	3.9	11.6	47.3	3	4.9	31.4	45.3
South Africa	1.9	3.0	11.6	4.6	27.3	1	26.6	73.2	45.3
Spain	2.2	1.8	17.1	2.1	10.2	1	81.5	88.6	51.7
Sri Lanka	1.1	8.4	2.7	10.4	15.2	2	80.6	95.4	52.2
Sudan	1.5	4.8	7.0	6.1	9.6	1	2.9	43.8	34.4
Suriname	1.1	8.0	1.7	38.2	54.0	4	1.3	37.6	48.5
Svalbard and Jan Mayen Islands	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Swaziland	1.0	4.4	8.4	18.1	36.2	2	22.1	92.1	47.2
Sweden	2.4	1.3	19.0	6.2	3.2	3	19.3	19.9	41.3
Switzerland	2.8	1.9	17.2	7.4	2.6	3	13.5	67.9	49.0
Syrian Arab Republic	1.5	2.5	22.2	6.9	18.2	2	27.1	36.2	36.4
Taiwan, Province of China*	1.4	9.0	11.1	48.1	33.9	1	67.6	92.1	53.5
Tajikistan	1.8	2.8	25.8	21.8	47.5	2	18.1	58.6	44.3
Thailand	1.3	9.6	6.0	8.3	17.1	1	55.3	97.6	46.1
The former Yugoslav Republic of Macedonia	2.6	1.1	20.9	2.3	0.0	2	44.1	97.2	50.9
Timor-Leste	1.0	6.7	2.1	2.0	2.4	3	31.4	96.2	46.0
Togo	2.0	6.8	4.3	1.4	2.4	3	10.1	97.8	49.2
Tokelau	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tonga	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Trinidad and Tobago	2.1	6.6	1.9	2.5	1.6	3	67.1	75.4	54.8
Tunisia	2.3	2.4	17.3	7.3	14.4	2	24.8	19.2	39.9
Turkey	1.4	2.4	22.0	5.3	7.6	2	31.7	91.8	41.9

	Q2_1 _IR	Q2_2 _P	Q2_2 _T	Q3_1 _CE	Q3_2 _AH	Q3_4 _AEI	Q3_4 _AHI	Q3_4 _AHR	Q_MC
	[-]	[mm d^{-1}]	[°C]	[% of ref. CE]	[% of ref. AH]	[-]	[% of area]	[% of area]	[-]
Minimum	1	0.6	0.8	0	0	0	0	0	0
Maximum	3	30.8	39.1	100	100	5	100	100	100
Turkmenistan	1.8	1.2	27.7	27.7	33.6	2	12.8	21.8	37.9
Turks and Caicos Islands	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tuvalu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Uganda	1.5	4.4	2.3	4.1	8.8	1	3.3	78.0	40.2
Ukraine	2.5	1.4	25.3	0.9	0.1	3	30.3	97.0	49.4
United Arab Emirates	1.4	0.9	16.1	58.4	80.5	2	36.6	3.7	50.1
United Kingdom of Great Britain and Northern Ireland	1.8	1.2	12.1	1.6	0.6	3	48.3	80.3	49.7
United Republic of Tanzania	1.5	6.7	3.8	9.1	4.5	2	7.3	76.0	41.7
United States of America	1.7	2.3	27.0	2.8	3.0	1	66.1	72.8	40.4
United States Virgin Islands	3.0	5.6	3.1	100.0	100.0	2	100.0	0.0	77.2
Uruguay	1.2	1.8	12.4	7.2	28.0	3	81.8	87.6	55.3
Uzbekistan	1.9	1.6	28.1	14.8	26.2	1	23.0	36.1	36.2
Vanuatu	n.a.	6.7	2.8	100.0	0.0	n.a.	n.a.	75.3	70.0
Venezuela (Bolivarian Republic of)	1.3	7.2	2.3	8.6	31.4	3	32.0	65.6	48.6
Viet Nam	1.2	10.2	7.5	22.8	9.9	2	60.3	95.9	48.5
Wallis and Futuna Islands	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Western Sahara	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Yemen	1.7	**1.0**	**8.5**	9.8	22.8	2	18.7	10.9	39.3
Zambia	1.3	7.9	7.2	1.6	7.8	3	8.5	85.3	42.0
Zimbabwe	1.4	4.8	9.0	4.8	10.0	3	9.7	84.5	44.3
WORLD	1.4	4.7	18.0	6.5	11.4	1.88	25.0	48.7	36.1

Table D-2. MIRCA2000 quality parameters on seasonal climatic variability of precipitation (Q2_2_P) and air temperature (Q2_2_T) of Argentina, Australia, Brazil, China, India, Indonesia, and the United States of America, per sub-national climate zone. For the definition of the zones and the included sub-national units see Appendix K.

Sub-national climate zone name	Q2_2_P (mm d^{-1})	Q2_2_T (°C)
Southern_Patagonia_and_Fireland	0.9	13.2
Northern Patagonia	0.6	16.1
Semidesertic_Andes__Precordillera__Pediments	2.3	15.5
Dry_Pampa	3.4	14.4
Wet_Pampa	2.9	13.8
Tropical_Dry_North	4.4	11.7
Argentina	**3.1**	**14.0**
Australian_Capital_Territory	0.8	14.6
New_South_Wales	1.3	15.6
Northern_Territories	8.7	9.0
Queensland	3.4	13.0
South_Australia	1.3	11.9
Tasmania	1.9	9.5
Victoria	0.9	13.4
Western_Australia	2.2	13.3
Australia	**1.7**	**13.7**
South	2.6	9.3
Southeast	7.0	5.9
Centre-West	8.5	4.2
North	9.8	1.9
Northeast	6.1	3.2
Brazil	**6.0**	**5.6**
Northeast	4.6	32.4
Southeast	6.5	20.7
West	4.2	24.1
China	**5.2**	**27.4**
East	12.3	12.5
North	8.9	18.3
South	7.6	7.9
West	8.5	14.5
India	**9.0**	**13.3**
Java	10.6	1.3
OutsideJava	6.7	1.1
Indonesia	**7.3**	**1.1**
Northwest	1.9	29.2
California	2.7	16.8
Southwest	1.6	25.0
Great_Plains_North	2.7	30.0
Great_Plains_South_and_Southeast	2.4	21.2
Northeast	1.6	25.9
Alaska	2.1	24.6
Hawaii	5.8	3.7
United States of America	**2.3**	**27.0**

Table D-3. MIRCA2000 quality parameters on climatic variability of precipitation (Q2_2_P) and air temperature (Q2_2_T) of Argentina, Australia, Brazil, China, India, Indonesia, and the United States of America (USA), per sub-national unit. The values of units with small variability (< 2.5 mm d^{-1} precipitation, < 10 °C air temperature) and the namesare marked in **bold**.

Unit name	**Q2_2_P mm d^{-1}**	**Q2_2_T °C**
Argentina_Buenos Aires	2.4	14.3
Argentina_Catamarca	3.3	14.3
Argentina_Chaco	4.0	11.9
Argentina_Chubut	1.0	13.5
Argentina_Cordoba	3.6	14.0
Argentina_Corrientes	3.2	11.9
Argentina_Entre Rios	3.2	13.2
Argentina_Formosa	3.6	10.6
Argentina_Jujuy	5.8	11.1
Argentina_La Pampa	2.3	16.3
Argentina_La Rioja	2.3	14.9
Argentina_Mendoza	1.2	15.7
Argentina_Misiones	2.3	10.2
Argentina_Neuquen	0.9	15.8
Argentina_Rio Negro	0.6	16.1
Argentina_Salta	4.9	11.7
Argentina_San Juan	1.1	16.3
Argentina_San Luis	2.8	15.5
Argentina_Santa Cruz	0.5	12.1
Argentina_Santa Fe	3.8	13.4
Argentina_Santiago del Estero	3.8	13.1
Argentina_Tierra del Fuego	**0.6**	**8.2**
Argentina_Tucuman	4.9	12.8
Argentina_Distrito Federal	2.0	13.1
Australia_Australian Capital Territory	0.8	14.6
Australia_New South Wales	1.3	15.6
Australia_Northern Territories	8.7	9.0
Australia_Queensland	3.4	13.0
Australia_South Australia	1.3	11.9
Australia_Tasmania	**1.9**	**9.5**
Australia_Victoria	0.9	13.4
Australia_Western Australia	2.2	13.3
Brazil_Acre	8.3	2.2
Brazil_Alagoas	5.9	3.8
Brazil_Amapa	12.8	1.7
Brazil_Amazonas	7.8	1.4
Brazil_Bahia	4.2	3.7
Brazil_Ceara	7.4	2.7
Brazil_Distrito Federal	8.6	3.6
Brazil_Espirito Santo	5.2	5.6
Brazil_Goias	9.1	3.9
Brazil_Maranhao	9.5	2.1
Brazil_Mato Grosso	9.4	3.5
Brazil_Mato Grosso do Sul	5.5	6.3
Brazil_Minas Gerais	8.0	5.3
Brazil_Para	10.8	1.4
Brazil_Paraiba	6.3	3.5
Brazil_Parana	3.3	8.5
Brazil_Pernambuco	5.7	3.6
Brazil_Piaui	7.1	2.8
Brazil_Rio de Janeiro	5.2	6.2
Brazil_Rio Grande do Norte	6.1	2.7
Brazil_Rio Grande do Sul	1.8	10.3
Brazil_Rondonia	8.9	3.0
Brazil_Roraima	9.6	1.9

Unit name	Q2_2_P mm d^{-1}	Q2_2_T °C
Brazil_Santa Catarina	**2.3**	**9.1**
Brazil_Sao Paulo	6.6	6.5
Brazil_Sergipe	4.7	3.7
Brazil_Tocantins	9.1	2.4
China_Anhui	5.8	25.5
China_Beijing & Tianjin	5.2	30.6
China_Chongqing	5.4	21.1
China_Fujian	7.7	17.7
China_Gansu	2.7	25.0
China_Guangdong	9.2	14.9
China_Guangxi	7.3	16.4
China_Guizhou	6.2	18.7
China_Hainan	10.2	9.8
China_Hebei	5.0	30.4
China_Heilongjiang	4.5	41.9
China_Henan	5.2	26.2
China_Hubei	5.0	24.1
China_Hunan	5.5	23.1
China_Nei Monggol	3.5	35.8
China_Jiangsu	5.9	25.6
China_Jiangxi	7.2	22.9
China_Jilin	5.3	39.0
China_Liaoning	5.7	34.1
China_Ningxia	2.4	27.5
China_Qinghai	2.0	23.8
China_Shaanxi	3.8	26.4
China_Shangdong	6.4	28.0
China_Shanghai	4.6	23.9
China_Shanxi	3.9	29.1
China_Sichuan	6.1	19.5
China_Tibet_(Xizang)	6.6	18.2
China_Xinjiang	0.7	33.4
China_Yunnan	7.0	12.4
China_Zhejiang	5.7	23.1
China_Hong_Kong	11.4	13.5
India_Andra Pradesh	6.4	10.1
India_Arunachal Pradesh	11.5	13.0
India_Assam	16.0	11.5
India_Bihar	11.7	14.6
India_Chandigarh	8.4	19.4
India_Chhatisgarh	11.7	14.5
India_D & N Haveli	18.5	8.6
India_Daman & Diu	21.6	7.9
India_Dehli	7.9	19.3
India_Goa	24.0	4.6
India_Gujarat	7.8	12.5
India_Haryana	6.5	19.6
India_Himachal_Pradesh	7.7	17.7
India_Jammu & Kashmir	4.8	20.1
India_Jharkhand	10.5	14.2
India_Karnataka	7.3	7.5
India_Kerala	17.1	3.5
India_Madhya Pradesh	11.1	15.9
India_Maharastra	8.7	10.9
India_Manipur	13.5	9.5
India_Meghalaya	25.9	10.2
India_Mizoram	19.6	8.6
India_Nagaland	12.4	10.8
India_Orissa	10.8	11.4
India_Pondicherry	12.7	6.8
India_Punjab	6.3	20.7
India_Rajastan	5.5	18.2

Unit name	Q2_2_P mm d^{-1}	Q2_2_T °C
India_Sikkim	16.7	13.3
India_Tamil Nadu	7.0	5.7
India_Tripura	17.9	9.7
India_Uttaranchal	10.1	16.2
India_Uttar Pradesh	10.2	17.6
India_West Bengal	12.5	11.7
India_Andaman and Nicobar	15.9	2.3
India_Lakshadweep	11.2	2.4
Indonesia_Java	10.6	1.3
Indonesia_Outside Java	6.7	1.1
USA_Alabama	2.8	20.5
USA_Alaska	2.1	24.6
USA_Arizona	1.3	21.5
USA_Arkansas	2.0	24.0
USA_California	2.7	16.8
USA_Colorado	1.7	26.1
USA_Conneticut	0.8	25.6
USA_Delaware	1.0	24.0
USA_Florida	4.9	12.3
USA_Georgia	2.6	19.3
USA_Hawaii	5.8	3.7
USA_Idaho	1.0	24.2
USA_Illinois	2.2	28.8
USA_Indiana	1.9	27.4
USA_Iowa	3.0	31.6
USA_Kansas	2.9	28.3
USA_Kentucky	1.7	25.1
USA_Louisiana	2.2	19.0
USA_Maine	1.4	28.6
USA_Maryland	1.0	24.4
USA_Massachusetts	0.9	26.2
USA_Michigan	1.8	27.5
USA_Minnesota	2.8	34.6
USA_Mississippi	2.5	22.0
USA_Missouri	2.6	27.9
USA_Montana	1.8	29.1
USA_Nebraska	2.9	29.9
USA_Nevada	0.9	23.0
USA_New Hampshire	1.2	27.4
USA_New Jersey	1.2	25.1
USA_New Mexico	2.0	22.6
USA_New York	1.4	26.9
USA_North Carolina	1.8	21.4
USA_North Dakota	2.2	35.0
USA_Ohio	1.7	26.6
USA_Oklahoma	3.0	25.9
USA_Oregon	2.7	19.7
USA_Pennsylvania	1.4	25.6
USA_Rhode Island	1.2	24.3
USA_South Carolina	2.3	20.3
USA_South Dakota	2.5	32.9
USA_Tennessee	1.9	23.6
USA_Texas	2.4	21.6
USA_Utah	0.8	25.6
USA_Vermont	1.6	28.7
USA_Virginia	1.2	23.1
USA_Washington	1.5	22.0
USA_West Virginia	1.4	24.0
USA_Wisconsin	2.5	31.5
USA_Wyoming	1.3	25.7
USA_District_of_Columbia	0.9	24.9

Appendix E Reclassification of FAO crop classes to MIRCA2000 crop classes

This table shows how the original 175 FAO crop classes [*Monfreda et al.*, 2008] where reclassified to the 26 MIRCA2000 crop classes. In general, harvested areas of FAO classes crops were completely assigned to one MIRCA crop class. Only the FAO class “Forage products, other” that was assigned to two MIRCA crops, each sharing 50% of the original harvested area [*Portmann et al.*, 2010].

	MIRCA2000 crop class*																									
FAO crop class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Abaca (Manila Hemp)																										X
Agave Fibers, other																										X
Alfalfa																									X	
Almonds																								X		
Anise, Badian and Fennel																										X
Apples																								X		
Apricots																								X		
Areca Nuts (Betel)																								X		
Artichokes																										X
Asparagus																										X
Avocados																								X		
Bambara Beans																	X									
Bananas																								X		
Barley				X																						
Beans, Dry																	X									
Beans, Green																										X
Beets for Fodder																										X
Berries, other																										X
Blueberries																								X		
Brazil Nuts																								X		
Broad Beans, Dry																	X									
Broad Beans, Green																										X
Buckwheat																										X
Cabbage for Fodder																										X
Cabbages																										X
Canary Seed																										X
Cantaloupes & other Melons																										X
Carobs																								X		
Carrots																										X
Carrots for Fodder																										X
Cashew Nuts																								X		
Cashewapple																								X		
Cassava											X															
Castor Beans																										X
Cauliflower																										X
Cereals, other																										X
Cherries																								X		
Chestnuts																								X		
Chick-Peas																	X									
Chicory Roots																										X
Chillies & Peppers, Green																										X
Cinnamon (Canella)																								X		
Citrus Fruit, other																		X								
Clover																									X	
Cloves																								X		
Cocoa Beans																						X				
Coconuts																								X		
Coffee, Green																							X			
Coir																								X		
Cotton																					X					
Cow Peas, Dry																	X									
Cranberries																								X		

	MIRCA2000 crop class*																									
FAO crop class	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cucumbers and Gherkins																										X
Currants																								X		
Dates																			X							
Eggplants																										X
Fiber Crops, other																										X
Figs																								X		
Flax Fiber and Tow																										X
Fonio																										X
Forage Products, other																									X	X
Fruit Fresh, other																								X		
Fruit Tropical Fresh, other																								X		
Garlic																										X
Ginger																								X		
Gooseberries																								X		
Grapefruit and Pomelos																		X								
Grapes																				X						
Grasses, other																									X	
Green Corn (Maize)																										X
Green Oilseeds for Fodder																										X
Groundnuts in Shell																X										
Hazelnuts (Filberts)																								X		
Hemp Fiber and Tow																										X
Hempseed																										X
Hops																								X		
Jute																										X
Jute-Like Fibers																										X
Kapok Fiber																								X		
Kapokseed in Shell																								X		
Karite Nuts (Sheanuts)																								X		
Kiwi Fruit																								X		
Kolanuts																								X		
Legumes, other																										X
Lemons and Limes																		X								
Lentils																	X									
Lettuce																										X
Linseed																										X
Lupins																	X									
Maize		X																								
Maize for Forage and Silage		X																								
Mangoes																								X		
Mate																								X		
Melonseed																										X
Millet						X																				
Mixed Grain																										X
Mixed Grasses & Legumes																									X	
Mushrooms																										X
Mustard Seed																										X
Natural Gums																								X		
Natural Rubber																								X		
Nutmeg, Mace and Cardamons																								X		
Nuts, other																								X		
Oats																										X
Oil Palm Fruit														X												
Oilseeds, other																										X
Okra																										X
Olives																								X		
Onions & Shallots, Green																										X
Onions, Dry																										X
Oranges																		X								
Papayas																								X		
Peaches and Nectarines																								X		
Pears																								X		
Peas, Dry																	X									

FAO crop class	MIRCA2000 crop class*																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Peas, Green																										X
Pepper																								X		
Peppermint																										X
Persimmons																								X		
Pigeon Peas																	X									
Pimento																								X		
Pineapples																								X		
Pistachios																								X		
Plantains																								X		
Plums																								X		
Pop Corn		X																								
Poppy Seed																										X
Potatoes										X																
Pulses, other																	X									
Pumpkins, Squash, Gourds																										X
Pyrethrum, Dried Flowers																										X
Quinces																								X		
Quinoa																										X
Ramie																										X
Rape seed															X											
Raspberries																								X		
Rice			X																							
Roots and Tubers, other																										X
Rye					X																					
Rye Grass for Forage and Silage					X																					
Safflower Seed																										X
Sesame Seed																										X
Sisal																										X
Sorghum							X																			
Sorghum for Forage and Silage							X																			
Sour Cherries																								X		
Soybeans								X																		
Spices, other																										X
Spinach																										X
Stone Fruit other																								X		
Strawberries																								X		
String Beans																										X
Sugar Beets													X													
Sugar Cane												X														
Sugar Crops, other																										X
Sunflower Seed									X																	
Swedes for Fodder																										X
Sweet Potatoes																										X
Tangerines and Mandarins																		X								
Taro																										X
Tea																								X		
Tobacco Leaves																										X
Tomatoes																										X
Triticale																										X
Tung Nuts																								X		
Turnips for Fodder																										X
Vanilla																								X		
Vegetables & Roots for Fodder																										X
Vegetables Fresh, other																										X
Vetches																	X									
Walnuts																								X		
Watermelons																										X
Wheat	X																									
Yams																										X
Yautia																										X

*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: sugar cane, 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: others perennial, 25: fodder grasses, 26: others annual.

Appendix F Definition of United Nations (UN) regions and countries belonging to them

In this list, United Nations continental regions (Africa, America, Asia, Europe, and Oceania) and their sub-continental regions with the countries belonging to them are listed in alphabetical order. Countries that are not included in the official UN list are marked by an asterisk (*) [*United Nations Statistics Division*, 2010].

AFRICA

Eastern Africa
Burundi; Comoros; Djibouti; Eritrea; Ethiopia; Kenya; Madagascar; Malawi; Mauritius; Mayotte; Mozambique; Réunion; Rwanda; Seychelles; Somalia; Uganda; United Republic of Tanzania; Zambia; Zimbabwe

Middle Africa
Angola; Cameroon; Central African Republic; Chad; Congo; Democratic Republic of the Congo; Equatorial Guinea; Gabon; Sao Tome and Principe

Northern Africa
Algeria; Egypt; Libyan Arab Jamahiriya; Morocco; Sudan; Tunisia; Western Sahara

Southern Africa
Botswana; Lesotho; Namibia; South Africa; Swaziland

Western Africa
Benin; Burkina Faso; Cape Verde; Côte d'Ivoire; Gambia; Ghana; Guinea; Guinea-Bissau; Liberia; Mali; Mauritania; Niger; Nigeria; Saint Helena; Senegal; Sierra Leone; Togo

AMERICA

Caribbean
Anguilla; Antigua and Barbuda; Aruba; Bahamas; Barbados; British Virgin Islands; Cayman Islands; Cuba; Dominica; Dominican Republic; Grenada; Guadeloupe (until 2007 including Saint-Barthélemy and Saint Martin (French part)); Haiti; Jamaica; Martinique; Montserrat; Netherlands Antilles; Puerto Rico; Saint Kitts and Nevis; Saint Lucia; Saint Vincent and the Grenadines; Trinidad and Tobago; Turks and Caicos Islands; United States Virgin Islands

Central America
Belize; Costa Rica; El Salvador; Guatemala; Honduras; Mexico; Nicaragua; Panama

Northern America
Bermuda; Canada; Greenland; Saint Pierre and Miquelon; USA

South America
Argentina; Bolivia (Plurinational State of); Brazil; Chile; Colombia; Ecuador; Falkland Islands (Malvinas); French Guiana; Guyana; Paraguay; Peru; Suriname; Uruguay; Venezuela (Bolivarian Republic of)

ASIA

Central Asia
Kazakhstan; Kyrgyzstan; Tajikistan; Turkmenistan; Uzbekistan

Eastern Asia
China; Democratic People's Republic of Korea; Japan; Mongolia; Republic of Korea; Taiwan, Province of China*

South-Eastern Asia
Brunei Darussalam; Cambodia; Christmas Island*; Cocos (Keeling) Islands*; Indonesia; Lao People's Democratic Republic; Malaysia; Myanmar; Philippines; Singapore; Thailand; Timor-Leste; Viet Nam

Southern Asia
Afghanistan; Bangladesh; Bhutan; British Indian Ocean Territory*; India; Iran (Islamic Republic of); Maldives; Nepal; Pakistan; Sri Lanka

Western Asia
Armenia; Azerbaijan; Bahrain; Cyprus; Georgia; Iraq; Israel; Jordan; Kuwait; Lebanon; Occupied Palestinian Territory; Oman; Qatar; Saudi Arabia; Syrian Arab Republic; Turkey; United Arab Emirates; Yemen

EUROPE

Eastern Europe
Belarus; Bulgaria; Czech Republic; Hungary; Poland; Republic of Moldova; Romania; Russian Federation; Slovakia; Ukraine

Northern Europe
Denmark; Estonia; Faeroe Islands; Finland; Iceland; Ireland; Latvia; Lithuania; Norway; Svalbard and Jan Mayen Islands; Sweden; United Kingdom of Great Britain and Northern Ireland

Southern Europe
Albania; Andorra; Bosnia and Herzegovina; Croatia; Greece; Italy; Malta; Montenegro; Portugal; San Marino; Serbia; Slovenia; Spain; The former Yugoslav Republic of Macedonia

Western Europe
Austria; Belgium; France; Germany; Liechtenstein; Luxembourg; Netherlands; Switzerland

OCEANIA

Australia and New Zealand
Australia; New Zealand; Norfolk Island

Melanesia
Fiji; New Caledonia; Papua New Guinea; Solomon Islands; Vanuatu

Micronesia
Guam; Kiribati; Marshall Islands; Micronesia (Federated States of); Nauru; Northern Mariana Islands; Palau

Polynesia
American Samoa; Cook Islands; French Polynesia; Niue; Pitcairn; Samoa; Tokelau; Tonga; Tuvalu; Wallis and Futuna Islands

Appendix G Managing updates of MIRCA2000

This Appendix presents, first, a systematic overview on the thematic issues that have to be considered when MIRCA2000 is updated. In the second sub-section, the technical management for updating (or re-generating) MIRCA2000 with changed input data, and how steps, computer routines and necessary files interact, is described. The latter part shows which files should be manipulated and which computer routines or executables should be used.

Thematic issues for MIRCA2000 updates

The update of MIRCA2000 can consider three different thematic issues: First, an update of the input data (e.g. changes in area equipped for irrigation AEI, harvested area, or growing periods) within the same spatial units, second, an update of the spatial units in form of new spatial units or new borders, third, new algorithms or procedures (e.g. for downscaling or data handling of irrigated or rainfed crops). In the first two cases, the current file structure and software code can be used directly, with only formal adaptations described in the following sub-section on the technical management. The third case requires in-depth changes at several locations in the software code, which might involve restructuring the formats for data storage and data exchange, or different data preprocessing. The possible improvements mentioned in Chapter 5.4 and their interactions with the aforementioned three aspects are discussed in Table G-1.

Table G-1. Thematic issues involved in an update of MIRCA2000.

Theme concerned	Update element	Location of primary activity	Special aspects
Input data	Harvested area of irrigated crops	Excel sheets	Disaggregation of area of original crop classes into the crop classes of MIRCA2000 is often needed. Possibly increased grid cell level maximum monthly growing area needs re-scaling of AEI in units where AEI is exceeded.
Input data	Growing periods of crop calendars	Excel sheets	Extension or estimation of growing periods for new crops or for up to now not separately considered spatial units are needed. While some crops have better representation in a sub-national unit when specific information is available, the calendars of the others could be still the same as before. Results of dynamic global (or regional) vegetation model could be used to estimate relative shares of winter and spring varieties of temperate cereals. Possibly adaptation of calendars is needed, when unit-level irrigated maximum monthly growing area exceeds unit-level AEI.
Input data	Total crop-specific harvested area	Original grid files in NetCDF format External executables Python scripts for ArcGIS	Large data volume (175 classes). Currently only a Windows-based software tool is available that extracts layers of harvested area and yield and converts them to ASCII grids for ArcGIS. Correct layer in NetCDF files has to be selected. Re-aggregation of 175 crop classes to final 26 crop classes is needed, for which uncertainty with respect to fodder grasses exists. Probably FAO crop classes have changed! Possibly there is still inconsistency to cropland extent, and probably also to AEI.

Theme concerned	Update element	Location of primary activity	Special aspects
Input data	Area equipped for irrigation	GIS layer (original: polygon shapefile, used: grid)	Inconsistency to irrigated harvested area and growing periods due to different reference years or data sources can occur. AEI in some countries is derived from actually irrigated areas, which can lead to inconsistency, e.g. with cropland extent. Possibly during downscaling of crop calendars the changed maximum monthly growing area needs re-scaling of AEI where AEI is exceeded. Probably there is still the inconsistency that AEI exists in grid cells without total harvested area and/or cropland extent.
Input data	Cropland extent	ASCII grid file	Possibly there is still the inconsistency of CE to total harvested area, and probably also to AEI. Iterative preprocessing is needed in program AEIScaleIntersect.
Spatial units	Border of administrative units	GIS layer (original: polygon shapefile, used: grid)	New units need their own crop calendars with growing periods, and possibly a new disaggregation of irrigated harvested area from upper level units. When using sub-national units, the advantage of better spatial resolution in harvested area could be compromised by larger uncertainties in growing periods. Consistency of borders of new units with currently used borders is preferred when only a few units are introduced. Totally new borders could change geospatial location and result in different pattern during downscaling of the crop calendars.

Theme concerned	Update element	Location of primary activity	Special aspects
Input data / Software code / Algorithms	Input data update / new downscaling rules: Removal of artifacts of rainfed crops in arid countries by limitation of irrigated harvested area in CCC to total harvested area	Excel sheets / Software code (especially programs IrrigHarvArea, RainHarvArea, JoinCrops, SumCrops)	Irrigated crops and rainfed crops are downscaled in separate runs, unit by unit. Any limitation could be introduced through 2 different pathways: (1) A list of units (or a indicator grid) with exclusion of harvested area of (possibly unit-specific) rainfed crops during downscaling (concerned software code: RainHarvArea). This corrupts the consistency with the (up to now) unchanged grid cell crop-specific and overall total harvested area, unless they are adapted through new code (JoinCrops and SumCrops merged and adapted with code of IrrigHarvArea and RainHarvArea). (2) Increase of irrigated harvested area in crop calendars for irrigated crops to the total crop-specific harvested area. This might introduce uncertainty concerning the real harvested areas and the best data sources. As a consequence, the crop calendars for irrigated crops might contain new crops that were not included before, possibly introducing inconsistency to AEI if derived from another source. When a crop is grown under rainfed and irrigated conditions in only partially arid countries, then the re-definition of the irrigated area AHI, based on the total harvested area and AHI of the formerly used data source, has to be done manually and is prone to subjective decisions.
Input data / Software code / Algorithms	Input data update / new downscaling rules: Improved representation of	Excel sheets / Software code, especially programs IrrigHarvArea and RainHarvArea)	Up to now, the shares of winter and summer growing periods are defined independently in the crop calendars for irrigated crops and for rainfed crops. Especially the latter is prone to errors in downscaling when large units cover different climatic conditions (e.g. Russian Federation), for which preferentially either winter or spring cereals are grown in each 5 arc-minute grid cell, depending on the local climate.

Theme concerned	Update element	Location of primary activity	Special aspects
	winter and spring cereal varieties in large units, e.g. by improved limitation to specific locations or by prescription of improved estimates of relative shares.		Climate-induced potential location of temperate winter and spring cereals is modeled by dynamic global vegetation models such as LPJmL. Through a combination of this location information and crop-specific total harvested crop area, the relative shares of harvested area of winter and spring crops could be estimated at least for rainfed cereals and included in the respective crop calendar of the unit. However, it has to be made sure that the model parameterization covers the potential growing zone. For temperate zones, this is clear, but for tropical zones such as northern India where LPJmL did not always model wheat growth this has to be checked.
Software code / Algorithms	Increased number of crops, new special crops with growing periods >12 months	Software code (especially ms IrrigHarvArea and RainHarvArea	Currently the last 3 crops are fixed to be other perennial crops, fodder grasses, and other annual crops. Introduction of new crops needs re-classification of the crop code in the input data, which could introduce classification errors. Crops should be either annual or perennial. Special treatment of rainfed cassava (the 14 month growing period, averaged from 8 and 21 months, decouples grid cell level growing periods and harvested area) is difficult to understand and makes consistency checks very complicated.
Software code / Procedures	New downscaling rules: Unit-specific crop priorities	Software code, especially in programs IrrigHarvArea and RainHarvArea	Crop priorities per unit can already be individually defined in an external file and override the general priority rules specified uniformly for all units. Currently the last 3 crops are fixed in the code to be other perennial crops, fodder grasses, and other annual crops, and are treated in a special sequence with the other annual crops as the last ones.

Technical management of MIRCA2000 update

In the following tables, the technical management of the programs and files as performed for the current version 1.1 of MIRCA2000 is described. For an update of the data set, the sequence would be the same. The management includes three broad blocks:

(1) General service programs:
In that block, the usage of programs for the conversion of binary and ASCII grid files that are applied at several locations during the generation of the core MIRCA2000 data as mentioned in the next block are described (Table G-2).

(2) Generation of core MIRCA2000 data:
In that block, the usage of programs and necessary file manipulations to generate the core MIRCA2000 data in their original data format are explained (Table G-3). At this stage, the unit-level Condensed Crop Calendars (CCC) for irrigated and rainfed crops and the crop-specific Monthly Growing Area Grids (MGAG) are already in their final distribution-ready format, needing only compression to facilitate data transfer. Steps needed for validation, e.g. equal distribution of irrigated crop area within the units, are explained, and how monthly areas e.g. for display can be extracted from MGAG is shown. The core data with 5 arc-minute resolution may also be used by the Global Crop Water Model (GCWM) as input data for calculation of crop water use and crop yields of irrigated and rainfed crops.

(3) Generation of distribution-ready files:
In that block, the generation of additional files and of files that are fully consistent with GCWM is described. This concerns especially the Cropping Period List (CPL), which is only generated at this stage, as well as the Maximum Monthly Growing Area Grid (MMGAG), the Maximum Monthly Cropped Area Grids for the sum of all irrigated and rainfed crops (MMCAG), and the crop-specific (AH) and group-specific annual harvested area (AHI, AHR). Finally, it is explained how 5 arc-minute data are aggregated to 30 arc-minute data.

General service programs

Tools: Executables for PC platform with Windows XP operating system, code written by Felix Portmann.
Code: Available.
Input data format: ASCII or binary.
Output data format: ASCII or binary.

Location of files with source code, executable, parameter files (as of December 2010):
For BIN2ASC:
(local) D:\CROPMAP\CPP\BIN2ASC
(samba hydro server) /home/hydro/gm/projects/virtual_water_project/CROPMAP/CPP/BIN2ASC
For ASCII2BINARY:
(local) D:\CROPMAP\CPP\ASC2BIN\ASC2BIN\ASCII2BINARY
(samba hydro server) /home/hydro/gm/projects/virtual_water_project/CROPMAP/CPP/ASC2BIN/ASC2BIN/ASCII2BINARY.

In this block, Table G-2 describes the usage of programs for the conversion of binary and ASCII grid files that are applied at several locations during the generation of the core MIRCA2000 data as mentioned in the next block.

Table G-2. List of service programs to treat grid files.

No.	Program	Purpose	Parameter file
1	BIN2ASC	**Treats 5min grid data (data type: long int, float, double, short)** Writes 1 ArcView export grid file with 4230 columns by 2160 rows ASCII/ANSI text files (with **standardized header**) from 1 flat binary file (without header)	No, command line usage: Bin2asc.exe datatype infile outfile Data type: 0 = long integer, 1 = float, 2 = double, 3 = short integer
2	ASCII2BINARY	**Treats 5min grid data (data type: long int, float, double, short)** Write 1 flat binary file (without header) from 1 ArcView export grid file (with header) = grids with 4230 columns by 2160 rows ASCII/ANSI text files (with ArcView/ArcGIS header)	No, command line usage: ascii2binary.exe datatype infile outfile Data type: 0 = long integer, 1 = float, 2 = double, 3 = short integer

Generation of the MIRCA2000 data set for usage with the Global Crop Water Model (GCWM)

Tools: Executables for PC platform with Windows XP operating system, code written by Felix Portmann.
Code: Available.
Input data format: ASCII.
Output data format: ASCII and binary.

Location of files with source code, executable, parameter files (as of November 2011):
(local) D:\CROPMAP\CPP\program_name
(samba hydro server) /home/hydro/gm/projects/virtual_water_project/CROPMAP/CPP/program_name

Exceptional location of command file and executable of distribution-ready version of extraction and conversion program of monthly grids from binary Monthly Growing Area Grids (MGAG) (flt_to_asc.exe, without source code, as of November 2011):
(local) D:\MIRCA2000_FTP\computing\executables\conversion_flt_asc
(samba hydro server) /home/hydro/gm/projects/virtual_water_project/MIRCA2000_FTP/computing/executables/conversion_flt_asc)

In this block, Table G-3 describes the steps for the generation of the core MIRCA2000 data in 5 arc-minute resolution. These data are also used by the Global Crop Water Model (GCWM) for the calculation of crop water use and crop yields of irrigated and rainfed crops. The unit-level Condensed Crop Calendars (CCC) for irrigated and rainfed crops and the binary Monthly Growing Area Grids are then already in their form for public distribution.

The generation of distribution-ready files of the other MIRCA2000 products needs additional steps so that the data are fully consistent to GCWM output. Furthermore, the Cropping Period List (CPL) is only generated at that stage, as described in Table G-4 in the following block.

Table G-3. Sequence of programs and file manipulations to generate the MIRCA2000 data set (version 1.1) for usage with GCWM.

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
1-8			**GENERATION**			
1	1.25. (total duration 1.25)	JoinCrops (execution duration on PC ca. 70 min = ca. 1.25 h)	**Treats 5min grid data (main data type: float)** Reads ASCII files of harvested area fraction of grid cell area) for each crop as delivered by SAGE and writes binary files of fractions for program SumCrop. Calculates absolute area (ha) from fractions. Calculates areas that exceed the "allcrops" total, i.e. are missing in the allcrops (SAGE_ missingallcropsarea). Calculates sum of all crop classes besides "others annual" (SAGE_crops_1to25) Calculates "others annual control" as difference of "allcrops" and "SAGE_crops_1to25"	Yes (input / output [I/O] path)	Grid cell area (binary DOUBLE): grid_cellarea.dbl 28 ASCII files with fractions (incl. allcrops, others_annadj "citrus") "*cropname*__fr.asc" ATTENTION: file "others_annadj__fr.asc" contains the surplus of harvested area included in Chad Monfredas original file "allcrops" that obviously cites too much harvested area (larger than the directly calculated sum of all 175 individual crops) 26 Crop names (A-Z): (2 additional groups in italics: *allcrops__fr.asc* barley__fr.asc cassava__fr.asc citrus__fr.asc cocoa__fr.asc coffee__fr.asc cotton__fr.asc	Absolute area (ASCII), fractional area (ASCII, binary FLOAT) **"*cropname*__fr.flt" (first 26 files needed for SumCrops)** "*cropname*__ha.asc" "*cropname*__ha.flt" additional groups: (also __fr/ha.asc/flt) allcrops Check files: others_annctrl__fr/ha.asc/flt SAGE_missingallcropsarea__fr/ha.asc SAGE_crops_1to25__fr/ha.asc

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
					datepalm__fr.asc grapes__fr.asc groundnut__fr.asc maize__fr.asc managed_grassland__fr.asc millet__fr.asc oilpalm__fr.asc others_annual__fr.asc others_perennial__fr.asc potato__fr.asc pulses__fr.asc rapeseed__fr.asc rice__fr.asc rye__fr.asc sorghum__fr.asc soybean__fr.asc sugarbeet__fr.asc sugarcane__fr.asc sunflower__fr.asc wheat__fr.asc **(current status of original files: 2006-11-05)**	
2a			**Copy file with new filename**		cropland2000_5min.asc	grid_cropland2000_5min_fraction.asc
2b			**Copy file with new filename**		cropland2000_5min.asc	**Input data for AEIScaleIntersect (1st run):** grid_cropland_inputAEIScaleIntersect_fraction.asc

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
2c		ASCII2BINARY	**Treats 5min grid data (data type: long int, float, double, short)** Write 1 flat binary file (without header) from 1 ArcView export grid file (with header)	No (set parameter 1 for float)	grid_cropland2000_5min_fraction.asc **(current status of original file: 2006-10-20)**	**Input data for SumCrops:** grid_cropland2000_5min_fraction.flt
2c			**Copy file with new filename**		grid_gmia_v4_0_1_ha_limitcellarea.flt	grid_AEIscaled_ha.flt
2d			**Copy file with new filename**		codes_in_grid_AEIscaled__GMIAV401unscaled_withoutquotes_blanklinedeleted.txt	codes_in_grid_AEIscaled.txt
2e	0.25	SumCrops **(1st run)** (execution duration on PC ca. 15 min =)	**Treats 5min grid data (main data type: float):** Sums individual harvested area of 26 crops (wheat … cotton, others perennial, managed grassland, others annual) – as fraction (and also area) Cuts grid of cropland extent to the area with existing harvested area (valid grid cells) Calculates mask of presence of - harvested area - cropland AND harvested	Yes (I/O path)	**Files with LISTs:** codes_in_grid_AEIscaled.txt Files with GRIDs: Grid with entity codes (binary, LONG INTEGER): grid_mask_entity_code.lng Grid cell area (binary DOUBLE): grid_cellarea.dbl cropland fraction (binary FLOAT): grid_cropland2000_5min_fraction.flt Area equipped for irrigation	**Input data for AEIScaleIntersect (1st run) IrrigHarvArea (1st run)** AEIScaleIntersect (1st run) grid_cropland_synthesised_fraction.asc (to be renamed) 1 file (Band Interleaved Pixel – BIP) (binary: FLOAT) with all 26 crops, each ca. 900 MByte!): sage_allcrops_fractions.flt (input IrrigHarvArea) and sage_allcrops_area.flt (possible later usage) cropland_withpresenceharvesteda

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
			area (both masks have also nodata code for areas with values < zero)		(binary FLOAT): grid_AEIscaled_ha.flt (original: grid_gmia_v4_0_1_ha_limitcellarea.flt) Harvested area in 26 files "*cropname*__fr.flt" (list see JoinCrops)	rea (old input IrrigHarvArea, RainHarvArea, AEIScaleIntersect) Check files: entity_SAGE_congruent_croppingintensity.txt **Files with GRIDs:** BIP (26 crops): sage_allcrops_fraction.flt sage_allcrops_area.flt Cropland extent grid_cropland_SAGE_area.flt/asc grid_cropland_withpresenceHarvArea_SAGE_area.flt/asc & ..._fraction.flt/asc grid_cropland_synthesised_area.flt/asc & ..._fraction.flt/asc (new input to AEI (1) Original SAGE cropland (only area, as fraction is input) (2) Adapted cropland (where cropland AND harvested area is present) (3) Synthesised cropland (where cropland OR harvested area (possibly AEI) exist) Harvested area

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
						grid_total_HarvArea_SAGE_area .flt/asc & ..._fraction.flt/asc grid_total_HarvArea_SAGE_with cropland_area.flt/asc & ..._fraction.flt/asc grid_total_HarvArea_synthesised _area.flt/asc & ..._fraction.flt/asc (1) Original SAGE total harvested area (2) SAGE total harvested area where also SAGE cropland is present (3) Synthesised total harvested area where synthesised cropland exists Masks for harvested area and cropland extent (binary short integer / ascii): with NODATA values: grid_mask_crop_HarvArea_SAG E.sht/asc (number of crops) mask_cropland_SAGE.sht/asc mask_cropland_AND_HarvArea_ SAGE.sht/asc without NODATA values: mask_cropland_synthesised.sht/as c (1 = presence, 0 = absence)
2f			**Copy file with new filename**		entity_AEI_name__402entities_ noscaling_070614/080429.txt	entity_AEI_name.txt

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
2g			**Copy file with new filename**		IrrCal_MaxMonthlyCropArea_tab__irrcal080428.txt (current irrigation calendar: 2008-04-28)	IrrCal_MaxMonthlyCropArea_tab.txt
2h	0.25 (1.5)	AEIScaleIntersect **(1st run)** (execution duration on PC ca. 5 min)	**Treats 5min grid data (data type: float, double) and tabular data** Scales Area Equipped for Irrigation (AEI) of external 5 min grid to predefined sum (including zero) by entity for a given mask and list of entities (countries, subnational units). Calculates potential/maximum monthly irrigated area Calculates mask with intersection cropland – AEI (3 categories: 1 = AEI & cropland, 2 = AEI only, 3 cropland only)	Yes (I/O path) Switches/Parameters: switch_scaleAEI switch_writegrid_AEI	**Files with LISTs:** entity_AEI_name.txt (from entity_AEI_name__402entities_noscaling_070614/080429.txt) IrrCal_MaxMonthlyCropArea_tab.txt (from …_irrcal080428) **Files with GRIDs:** grid_mask_entity_code.asc grid_cellarea_ha.asc grid_gmia_v4_0_1_ha.asc **1st run:** grid_cropland_inputAEIScaleIntersect_fraction.asc (untreated original data, i.e. grid_cropland2000_5min_fraction.asc or cropland2000_5min.asc)	**1st run:** Input data for **SumCrops**: **Files with LISTs:** list of entity attributes (scaled AEI sums) into file: codes_in_grid_AEIscaled.txt list of entity codes only in grid into file: codes_in_grid_only.txt **Files with GRIDs:** grid_AEIscaled_ha.asc/dbl/flt (flt input for **SumCrops**) grid_cropland_areaduringAEIscaling.asc/dbl/flt (to copy to file grid_cropland_area.flt as input for ValidateResultsIrrigHarvArea and for RainHarvArea) grid_mask_intersectionAEIcropland.asc/sht grid_intersectionAEIcropland_ha.asc/dbl/flt
2i	(1.5)		**Copy file with new filename**		grid_mask_intersectionAEIcropland.sht	grid_mask_intersection_code.sht

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
2j	(1.5)		**Delete last (void) line in file:** codes_in_grid_AEIscaled.txt		codes_in_grid_AEIscaled.txt	codes_in_grid_AEIscaled.txt
2k	(1.5)	BINArea2Fraction	**Treats 5min grid data and transforms absolute area in fractions of grid cell area (datatype 1 = float or 2 = double)**	No: program.exe datatype infile_cellarea(binary,double) infile(binary) outfile(binary) (parameter	grid_cellarea.dbl grid_AEIscaled_ha.flt	grid_AEIscaled_fraction.flt
2L	5.5 (7)	IrrigHarvArea **(1st run: for definition of AEI entities that have to be scaled)** (execution duration on PC ca. 5.5-6.5 h) Output size ca. 13.5 GB	**Treats 5min grid data (data type: float, cell area: double) and tabular data (double)** Distributes irrigated areas of tabulated crop calendars for irrigated crops to grid, with framework of AEI grid (as potential/maximum monthly irrigated area, or: possibly AEI) (from AEIScaleIntersect) and harvest area (from SumCrops)	Yes (I/O path) switch_simple_distribution (0 = comples, 1 = simple)	**Files with LISTs:** codes_in_grid_AEIscaled.txt IrrCal_allcrops_seasons.txt codes_cropprioritysequence_toppriority.txt (potentially without content) **Files with GRIDs:** grid_mask_entity_code.lng grid_mask_intersection_code.sht grid_cellarea.dbl BIP (26 crops): sage_allcrops_fraction.flt **(Simple distribution:** grid_gmia_v4_0_1_ha_limitcellarea.flt) *****Complex distribution:** grid_AEIscaled_fraction.flt	**1st run for definition of AEI entities that have to be scaled** ASCII: cropping_calendar_irrigated.txt **Simple distribution:** Entities_distributedareas_simpledistribution.txt **Complex distribution:** Entities_IrrCalSAGEIrrArea_distributedareas (Binary: float = .flt, double = .dbl, short integer = .sht, BIP = Band Interleaved Pixel): BIP (26 crops): basic area: cropsall_irrigated_basicarea_fraction.flt BIP (12 months): **growing area** (per crop) crop_*CC*_irrigated_12_fraction.flt For usage with

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
						GlobalCropWaterModel (GCWM) the first 26 files must be converted to binary: crop_*CC*_irrigated_12.flt via **Crop12Area.exe** **Harvested area**: crop_*CC*_irrigated_harvestedarea.flt cropsall_irrigated_harvestedarea.flt **Optional check grids**: *EC*_crop_*CC*_season_*SS*_cropoverlaymask.sht *EC*_crop_*CC*_season_*SS*_freearea_*FA*_fraction.flt *EC*_crop_*CC*_season_*SS*_croparea_fraction.flt *EC*_crop_*CC*_season_*SS*_croparea_ha.flt *EC*_crop_*CC*_season_*SS*_currentsumharvestedarea_ha.flt *EC*_crop_*CC*_harvestedarea_ha.flt (*EC* = entity code (4-6 digits), *CC* = 2 digits crop code/class (1-26) *SS* = 2 digits sub-crop/season number (1-5), *FA* = 2 digits free area array index (0 or 1))

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
2m	0.25 (7.25)	AEIScaleInters ect **(2nd run)** (execution duration on PC ca. 5 min)	**Treats 5min grid data (data type: float, double) and tabular data** Scales Area Equipped for Irrigation (AEI) of external 5 min grid to predefined sum (including zero) by entity for a given mask and list of entities (countries, subnational units). Calculates potential/maximum monthly irrigated area Calculates mask with intersection cropland – AEI (3 categories: 1 = AEI & cropland, 2 = AEI only, 3 cropland only)	Yes (I/O path) Switches/Parameters: switch_scaleAEI switch_writegrid_AEI	**Files with LISTs:** entity_AEI_name.txt (from entity_AEI_name__402entities_IrrCalMAX080428_080429.txt) IrrCal_MaxMonthlyCropArea_tab.txt (from …_irrcal080428) **Files with GRIDs:** grid_mask_entity_code.asc grid_cellarea_ha.asc grid_gmia_v4_0_1_ha.asc **2nd run:** grid_cropland_inputAEIScaleIntersect_fraction.asc (untreated original data, i.e. grid_cropland2000_5min_fraction.asc or cropland2000_5min.asc)	**2nd run:** Input data for **SumCrops**: **Files with LISTs:** list of entity attributes (scaled AEI sums) into file: codes_in_grid_AEIscaled.txt list of entity codes only in grid into file: codes_in_grid_only.txt Files with GRIDs: grid_AEIscaled_ha.asc/dbl/flt (flt input for **SumCrops**) grid_cropland_areaduringAEIscaling.asc/dbl/flt (to copy to file grid_cropland_area.flt as input for ValidateResultsIrrigHarvArea and for RainHarvArea) grid_mask_intersectionAEIcropland.asc/sht grid_intersectionAEIcropland_ha.asc/dbl/flt

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
3a	0.25 (7.5)	SumCrops **(2nd run)** (execution duration on PC ca. 15 min =)	**Treats 5min grid data (main data type: float):** Sums individual harvested area of 26 crops (wheat … cotton, others perennial, managed grassland, others annual) – as fraction (and also area) Cuts grid of cropland extent to the area with existing harvested area (valid grid cells) Calculates mask of presence of - harvested area - cropland AND harvested area (both masks have also nodata code for areas with values < zero)	Yes (I/O path)	**Files with LISTs:** codes_in_grid_AEIscaled.txt Files with GRIDs: Grid with entity codes (binary, LONG INTEGER): grid_mask_entity_code.lng Grid cell area (binary DOUBLE): grid_cellarea.dbl cropland fraction (binary FLOAT): grid_cropland2000_5min_fraction.flt Area equipped for irrigation (binary FLOAT): **grid_AEIscaled_ha.flt (from 2nd run AEIScaleIntersect)** Harvested area in 26 files ”*cropname*__fr.flt” (list see JoinCrops)	**Input data for AEIScaleIntersect (3rd run) IrrigHarvArea (2nd run)** AEIScaleIntersect (1st run) grid_cropland_synthesised_fraction.asc (to be renamed) 1 file (Band Interleaved Pixel – BIP) (binary: FLOAT) with all 26 crops, each ca. 900 MByte!): sage_allcrops_fractions.flt (input IrrigHarvArea) and sage_allcrops_area.flt (possible later usage) cropland_withpresenceharvestedarea (old input IrrigHarvArea, RainHarvArea, AEIScaleIntersect) Check files: entity_SAGE_congruent_croppingintensity.txt **Files with GRIDs:** BIP (26 crops): sage_allcrops_fraction.flt sage_allcrops_area.flt

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
						Cropland extent grid_cropland_SAGE_area.flt/asc grid_cropland_withpresenceHarvArea_SAGE_area.flt/asc & ..._fraction.flt/asc grid_cropland_synthesised_area.flt/asc & ..._fraction.flt/asc (new input to AEI (1) Original SAGE cropland (only area, as fraction is input) (2) Adapted cropland (where cropland AND harvested area is present) (3) Synthesised cropland (where cropland OR harvested area (possibly AEI) exist) Harvested area grid_total_HarvArea_SAGE_area.flt/asc & ..._fraction.flt/asc grid_total_HarvArea_SAGE_withcropland_area.flt/asc & ..._fraction.flt/asc grid_total_HarvArea_synthesised_area.flt/asc & ..._fraction.flt/asc (1) Original SAGE total harvested area (2) SAGE total harvested area where also SAGE cropland is present

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
						(3) Synthesised total harvested area where synthesised cropland exists Masks for harvested area and cropland extent (binary short integer / ascii): with NODATA values: grid_mask_crop_HarvArea_SAGE.sht/asc (number of crops) mask_cropland_SAGE.sht/asc mask_cropland_AND_HarvArea_SAGE.sht/asc without NODATA values: mask_cropland_synthesised.sht/asc (1 = presence, 0 = absence) REMARK 2008-10-13: for calculation of cropping intensity (CI) per entity, the CI for permanent crops in cells with cropland is now limited to 1, this changed the synthetic cropland extent by max. 3.259 ha per grid, but reduced at 9 grid cells the (wrongly attributed) extra harvested area in cells with cropland extent from > 13,000 ha to less than 6900 ha e.g. in South Africa (see MIRCA2000 documentation)

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
3b			**Copy file with new filename**		grid_cropland_synthesised_fraction.asc	**Input data for AEIScaleIntersect (3rd run):** grid_cropland_inputAEIScaleIntersect_fraction.asc (implicitly via grid_cropland_areaduringAEIscaling.asc/dbl/flt (to copy to file grid_cropland_area.flt) as input for ValidateResultsIrrigHarvArea and for RainHarvArea)
3c	0.25 (7.75)	AEIScaleIntersect **(3rd run: for definition of final scaled AEI and final synthesised cropland extent)** (execution duration on PC ca. 5 min)	**Treats 5min grid data (data type: float, double) and tabular data** Scales Area Equipped for Irrigation (AEI) of external 5 min grid to predefined sum (including zero) by entity for a given mask and list of entities (countries, subnational units). Calculates potential/maximum monthly irrigated area Calculates mask with intersection cropland – AEI (3 categories: 1 = AEI & cropland, 2 = AEI only, 3 cropland only)	Yes (I/O path) Switches/Parameters: switch_scaleAEI switch_writegrid_AEI	**Files with LISTs:** entity_AEI_name.txt (from entity_AEI_name__402entities_IrrCalMAX080428_080429.txt) IrrCal_MaxMonthlyCropArea_tab.txt (from …_irrcal080428) **Files with GRIDs:** grid_mask_entity_code.asc grid_cellarea_ha.asc grid_gmia_v4_0_1_ha.asc **3rd run:** grid_cropland_inputAEIScaleIntersect_fraction.asc (from 2nd run of SumCrops)	**3rd run:** Input data for IRRigHArvARea / RainHarvArea: **Files with LISTs:** list of entity attributes (scaled AEI sums) into file: codes_in_grid_AEIscaled.txt list of entity codes only in grid into file: codes_in_grid_only.txt Files with GRIDs: grid_AEIscaled_ha.asc/dbl/flt (flt input for **SumCrops**) grid_cropland_areaduringAEIscaling.asc/dbl/flt (to copy to file grid_cropland_area.flt as input for ValidateResultsIrrigHarvArea and for RainHarvArea)

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
						grid_mask_intersectionAEIcropland.asc/sht grid_intersectionAEIcropland_ha.asc/dbl/flt
4a	()		**Copy file with new filename**		grid_mask_intersectionAEIcropland.sht	grid_mask_intersection_code.sht
4b	()		**Delete last (void) line in file:** codes_in_grid_AEIscaled.txt		codes_in_grid_AEIscaled.txt	codes_in_grid_AEIscaled.txt
4c	()	BINArea2Fraction	**Treats 5min grid data and transforms absolute area in fractions of grid cell area (datatype 1 = float or 2 = double)**	No: program.exe datatype infile_cellarea(binary,double) infile(binary) outfile(binary) (parameter	grid_cellarea.dbl grid_AEIscaled_ha.flt (from 3rd run of AEIScaledIntersect)	grid_AEIscaled_fraction.flt
4d	5.5 (13.25)	IrrigHarvArea **(2nd run: complex, with scaled AEI)** (execution duration on PC ca. 5.5-6.5 h) Output size ca. 13.5 GB	**Treats 5min grid data (data type: float, cell area: double) and tabular data (double)** Distributes irrigated areas of tabulated crop calendars for irrigated crops to grid, with framework of AEI grid (as potential/maximum monthly irrigated area, or: possibly AEI) (from AEIScaleIntersect) and harvest area (from SumCrops)	Yes (I/O path) switch_simple_distribution [0 = complex, 1 = simple]	**Files with LISTs:** codes_in_grid_AEIscaled.txt IrrCal_allcrops_seasons.txt codes_croppriorityseqence_toppriority.txt (potentially without content) **Files with GRIDs:** grid_mask_entity_code.lng grid_mask_intersection_code.sht grid_cellarea.dbl BIP (26 crops): sage_allcrops_fraction.flt **(Simple distribution:**	ASCII: cropping_calendar_irrigated.txt **Simple distribution:** Entities_distributedareas_simpledistribution.txt **Complex distribution:** Entities_IrrCalSAGEIrrArea_distributedareas (Binary: float = .flt, double = .dbl, short integer = .sht, BIP = Band Interleaved Pixel): BIP (26 crops): basic area: cropsall_irrigated_basicarea_fract

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
					grid_gmia_v4_0_1_ha_limitcellarea.flt) *****Complex distribution:** grid_AEIscaled_fraction.flt	ion.flt BIP (12 months): **growing area** (per crop) crop_*CC*_irrigated_12_fraction.flt For usage with GlobalCropWaterModel (GCWM) the first 26 files must be converted to binary: crop_*CC*_irrigated_12.flt via **Crop12Area.exe** **Harvested area**: crop_*CC*_irrigated_harvestedarea.flt cropsall_irrigated_harvestedarea.flt **Optional check grids**: *EC*_crop_*CC*_season_*SS*_cropoverlaymask.sht *EC*_crop_*CC*_season_*SS*_freearea_*FA*_fraction.flt *EC*_crop_*CC*_season_*SS*_croparea_fraction.flt *EC*_crop_*CC*_season_*SS*_croparea_ha.flt *EC*_crop_*CC*_season_*SS*_currentsumharvestedarea_ha.flt *EC*_crop_*CC*_harvestedarea_ha.flt (*EC* = entity code (4-6 digits), *CC* = 2 digits crop code/class (1-26)

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
						SS = 2 digits sub-crop/season number (1-5), *FA* = 2 digits free area array index (0 or 1))
	0.5 (13.75)	CHECK that harvested area could be fully distributed (potentially re-run AEIScaleIntersect, SumCrops and IrrigHarvArea)			entity_AEI_name.txt with AEI specified for entities that have undistributed area in Entities_IrrCalSAGEIrrArea_distributedareas (else AEI = -1.00000)	
5	0.25 (14)	Crop12Area (execution duration on PC ca. 0.25-2 h) Output size ca. 11.5 GB (monthly area)	**Converts monthly irrigated area in fractions to absolute areas** **(1) for subsequent programs Crop12allcropsIrrArea & RainHarvArea** **(2) for usage with GlobalCropWaterModel (GCWM)**	Yes (I/O path)	**Files with GRIDs:** grid_cellarea.dbl BIP (12 months): crop_CC_irrigated_12_fraction.flt	BIP (12 months): crop_CC_irrigated_12.flt
6	ca. 9 (21)	Crop12allcrops12IrrArea (execution duration on PC ca. 9.0 h) Output size ca. 0.5 GB	**Calculates total sum of monthly irrigated area (area) of all crops in BIP format (12 months)**	Yes (I/O path)	BIP (12 months): crop_CC_irrigated_12.flt **(as provided by Crop12Area.cpp from complex run of IrrigHarvArea)**	BIP (12 months): crop_all_irrigated_12.flt

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
7	32 (53)	RainHarvArea (execution duration on PC ca. 32-24h) Output size ca. 13 GB including 225 MB log file	**Treats 5min grid data (data type: float, cell area: double) and tabular data (double)** Distributes rainfed areas as difference between (on entity level) harvested area from SAGE and irrigated harvested area as distributed by IrrigHarvArea Considers cell-level free rainfed area harvested of "others perennial", "managed grassland" and "others annual"	Yes (I/O path)	**Files with LISTs:** codes_in_grid_AEIscaled.txt cropping_calendar_irrigated.txt FAOSTAT_harvestedarea_countries.txt entity_hemisphere_name.txt RainCal_allcrops_seasons.txt **Files with GRIDs:** grid_mask_entity_code.lng grid_mask_intersection_code.sht (from run3 of AEIScaleIntersect) grid_mask_winter_cereals_m10_p6.sht grid_cellarea.dbl grid_cropland_synthesised_area.flt (from run2 of SumCrops) **Allways complex distribution!:** grid_AEIscaled_ha.flt (from run3 of AEIScaleIntersect) crop_*CC*_irrigated_harvestedarea.flt (from run2 of IrrigHarvArea) sage_allcrops_fraction.flt (from run2 of SumCrops) crop_all_irrigated_12.flt	ASCII: cropping_calendar_rainfed_areastodistribute.txt entity_rainfed_unsatisfiedareas.txt cropping_calendar_rainfed.txt (Binary: float = .flt, double = .dbl, short integer = .sht, BIP = Band Interleaved Pixel) BIP (12 months): **growing area** (per crop) **ONLY CROPS that are USED** (<= 26) in treated entities crop_*CC*_rainfed_12.flt (all irrigated crops:) crop_all_irrigated_12.flt **Harvested area**: crop_*CC*_rainfed_harvestedarea.flt cropsall_rainfed_harvestedarea.flt

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
8	**4**		**VALIDATION**			
8a	1.5 (1.5)	IrrigHarvArea (simple distribution, for calculation of uncertainties) (execution duration on PC ca. 1.5 h) Output size ca. 12.5 GB	**Treats 5min grid data (data type: float, cell area: double) and tabular data (double)**	Yes (I/O path, **switch_simple_distribution** [0 = complex, **1 = simpl**e]	**Files with LISTs:** codes_in_grid_AEIscaled.txt IrrCal_allcrops_seasons.txt codes_croppriority sequence_toppriority.txt (potentially without content) **Files with GRIDs:** grid_mask_entity_code.lng grid_mask_intersection_code.sht grid_cellarea.dbl BIP (26 crops): sage_allcrops_fraction.flt **Simple distribution:** grid_gmia_v4_0_1_ha_limitcellarea.flt	ASCII: cropping_calendar_irrigated.txt **Simple distribution:** Entities_distributedareas_simpledistribution.txt (Binary: float = .flt, double = .dbl, short integer = .sht, BIP = Band Interleaved Pixel): BIP (12 months): **growing area** (per crop) crop_*CC*_irrigated_12.flt **Harvested area**: crop_*CC*_irrigated_harvestedarea.flt cropsall_irrigated_harvestedarea.flt *Check:* *EC_crop_CC_harvestedarea_ha.flt*

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
8b	2 x 1 (3.5)	Crop12Sum26 IrrArea (execution duration on PC ca. 2 x 1 h for irrigated complex / irrigated simple distribution) Prepares input for ValidateResults Output size ca. 1.5 GB	**Reads monthly irrigated growing area (as fractions of grid cell area or absolute area in BIP format for 12 months)** **If necessary calculates absolute areas (when fractions are treated)** **Calculates maximum monthly area (per grid cell)** **Compares cell area to reference maximum (unscaled AEI) and writes error masks (grids) for each month and for monthly maximum** **Lists errors per entity**	Yes (I/O path **switch_readfractions** [0 = area, 1 = fractions]	**Files with LISTs:** entity_AEI_name.txt Files with GRIDs: grid_mask_entity_code.lng **(switch_readfractions = 1):** grid_cellarea.dbl grid_gmia_v4_0_1_fraction_limitcellarea.flt BIP (12 months): crop_*CC*_irrigated_12_fraction.flt **else (switch_readfractions = 0):** grid_gmia_v4_0_1_ha_limitcellarea.flt BIP (12 months): crop_*CC*_irrigated_12.flt	**(switch_readfractions = 1):** **Files with LISTs:** entity_cellerrors__fractions.txt **Files with GRIDs:** crop_all_irrigated_month_*MM*_areafromfraction.asc mask_errors_month_*MM*_areafromfraction.asc crop_all_irrigated_maximumallmonths_areafromfraction.asc mask_errors_maximumallmonths_areafromfraction.asc **else (switch_readfractions = 0):** **Files with LISTs:** entity_cellerrors__area.txt **Files with GRIDs:** crop_all_irrigated_month_*MM*_area.asc mask_errors_month_*MM*_area.asc crop_all_irrigated_maximumallmonths_area.asc mask_errors_maximumallmonths_area.asc (**to convert via ASCII2BINARY)** (MM = 2 decimals for month 01-12)

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
8c	2 x 0.25 (4)	ValidateResultsIrrigHarvArea (execution duration on PC ca. 2 x 10 min for irrigated complex / irrigated simple distribution) Output size ca. 2 x 300 KB	**Reads monthly irrigated growing area (as fractions of grid cell area or absolute area in BIP format for 12 months)** **If necessary calculates absolute areas (when fractions are treated)** **Calculates maximum monthly area (per grid cell)** **Compares cell area to reference maximum (unscaled AEI) and writes error masks (grids) for each month and for monthly maximum** **Lists errors per entity**	Yes (I/O path**)**	**Files with LISTs:** entity_AEI_name.txt (AEI of ALL entities!) Files with GRIDs: grid_mask_entity_code.lng grid_mask_intersection_code.sht grid_gmia_v4_0_1_ha_limitcellarea.flt grid_cropland_area.flt (from AEIScaleIntersect, **converted via ASCII2BINARY**) crop_all_irrigated_maximumallmonths_area.flt (from Crop12Sum26IrrArea, **converted via ASCII2BINARY**) crop_*CC*_irrigated_harvestedarea.flt BIP (26 crops): sage_allcrops_fraction.flt	**Files with LISTs:** excessareas_MMIAvsAEIcropland__byentity.txt excessareas_IrrHarvArea_vs_SAGE__bycrop_byentity.txt

No.	Time [h]	Program	Purpose	Parameter file	Input data files	Output data
9	**> 5 min**		**DISPLAY**			
9a	Ca. 5 min per crop	Crop12SeparateMonths	**Separates monthly irrigated growing area for each month, for selected crops in (BIP format)**	Yes (I/O path **start/end crop code** **switch_rainfed** [1 = rainfed, 0 = irrigated] **switch_readfractions** [0 = area, 1 = fractions])	**Files with GRIDs:** BIP (12 months): **(switch_readfractions = 1)** crop_*CC*_irrigated_12_fraction.flt else **(switch_readfractions = 0)** crop_*CC*_irrigated_12.flt crop_*CC*_rainfed_12.flt	**(compilation parameter: convert_to_percent == 1)** **Files with GRIDs:** **(switch_readfractions = 1):** crop_*CC*_irrigated_month_*MM*_pcnt.asc **else (switch_readfractions = 0):** crop_*CC*_irrigated_month_*MM*_area.asc crop_*CC*_rainfed_month_*MM*_area.asc (MM = 2 decimals for month 01-12)
9b	<5 min per crop	flt_to_asc.exe (code written by Stefan Siebert, code not available, distribution-ready batch_conversion_mirca2000_flt_to_asc.zip)	**Separates monthly irrigated growing area for each month, for selected crops in (BIP format), from distribution-ready files with absolute area (as used by GCWM).** Possible treatment of BIP formats of other dimensions, simple output file naming.	Yes (command file "batch_conversion_mirca2000_flt_to_asc.cmd" for batch conversion, adapt file names - **crop code** and **irrigated or rainfed**)	**Files with GRIDs:** BIP (12 months): crop_*CC*_irrigated_12.flt crop_*CC*_rainfed_12.flt	crop_*CC*_irrigated_0*MM*.asc crop_*CC*_rainfed_0*MM*.asc (MM = 2 decimals for month 01-12)

Generation of distribution-ready files consistent to Global Crop Water Model (GCWM) output

Generation of distribution-ready files with 5 arc-minute resolution consistent to Global Crop Water Model (GCWM) output: cell-specific Cropping Period List (CPL), crop-specific harvested area, and maximum monthly cropped area

Tool:	Executable (subset of GCWM) for 64bit platform with Linux (SUSE v.10) operating system, code written by Stefan Siebert.
Code:	Available.
Input data format:	ASCII and binary.
Output data format:	ASCII.

Location of files with source code, executable, parameter files (as of November 2011):
(local, only backup) D:\CROPMAP\CPP64\CPL64
(samba hydro server) /home/hydro/gm/projects/virtual_water_project/CROPMAP/CPP64/CPL64

Table G-4. Sequence of programs and file manipulations to generate distribution-ready files of CPL, harvested area and maximum monthly cropped area consistent to GCWM output in 5 arc-minute resolution from MIRCA2000 internal data.

No.	Time [h]	Program	Purpose	Parameter file	Input data files from MIRCA2000	Output data
1	0.25 (total duration 0.25)	-	**Copy data with new filenames. If necessary transform from binary to ASCII format (service program BIN2ASC)**	No	**Files with GRIDs:** grid_mask_entity_code.asc grid_cellarea_ha.asc grid_AEIscaled_ha.flt (from run3 of AEIScaleIntersect) grid_cropland_synthesised_area.flt (from run2 of SumCrops)	 entity_code.asc cell_area.asc aei.asc cropland.asc

No.	Time [h]	Program	Purpose	Parameter file	Input data files from MIRCA2000	Output data
2	0.1 (0.35)	Create_crop_calender_64	**Executable made from 64bit-platform adapted code to** **(1) check calendars** **(2) generate cell-specific Cropping Period List (on 5 arc-minute)** **(3) (consistent) crop-specific annual harvested area (5 arc-minute grids)** **(4) (consistent) maximum monthly cropped area (irrigated vs. rainfed) (5 arc-minute grids)**	Yes (OPTIONS.DAT)	cropping_calendar_irrigated.txt (from run2 of IrrigHarvArea) cropping_calendar_rainfed.txt (from RainHarvArea) crop_*CC*_irrigated_12.flt (from run2 of IrrigHarvArea) crop_*CC*_rainfed_12.flt (from RainHarvArea) (*CC* = crop 01..26) plus 4 output files from step 1	IRC = irrigated RFC = rainfed *c* = crop 1..10,11..26 **GRIDs:** Harvested area per crop ANNUAL_AREA_HARVESTED_IRC_CROP*c*_HA.ASC ANNUAL_AREA_HARVESTED_RFC_CROP*c*_HA.ASC Maximum monthly cropped area (MMCA) MAX_CROPPED_AREA_IRC_HA.ASC MAX_CROPPED_AREA_RFC_HA.ASC Harvested area per unit ENTITY_HARVESTED_AREA_IRC.TXT ENTITY_HARVESTED_AREA_RFC.TXT **Cropping Period List (CPL)** CELL_SPECIFIC_CROPPING_CALENDARS.TXT

<u>Generation of aggregated 30 arc-minute Cropping Period List from 5 arc-minute version</u>

Tool:	Executable for PC platform with Windows XP operating system, code written by Stefan Siebert.
Code:	Available (including command file).
Input data format:	ASCII.
Output data format:	ASCII.

Command file:	**aggregate_calendars.cmd (adaptation of path needed, possibly of file names)**
Input file:	CELL_SPECIFIC_CROPPING_CALENDARS.TXT
Output file:	CROPPING_CALENDAR_30MN.TXT
Executable:	**aggregate_calendars.exe**

Location of command file and executable file (as of November 2011):
(local) D:\MIRCA2000_FTP\computing\executables\aggregate
(samba hydro server) /home/hydro/gm/projects/virtual_water_project/MIRCA2000_FTP/computing/executables/aggregate)

Location of files with source code, executable, command file (as of November 2011):
(local) D:\CROPMAP\CPP\aggregate_calendars
(samba hydro server) /home/hydro/gm/projects/virtual_water_project/CROPMAP/CPP/aggregate_calendars

Generation of aggregated 30 arc-minute ASCII grid files from 5 arc-min grid files

Tool: ArcGIS 9.3, using Python-Scripts written by Felix Portmann.
Code: Available (Python scripts).
Input data format: ASCII.
Output data format: ASCII.

Logical sequence for each grid file:

1. Import procedure
   (ASCIIToRaster_conversion (rasterin_abspath, rasterout_abspath, "FLOAT"))
2. Aggregate cells with a factor of 6
   (gp.Aggregate_sa(rasterout_aggrid, aggrout_aggrid, "6", "SUM", "EXPAND", "DATA"))
3. Export procedure
   (gp.RasterToASCII_conversion(aggrout_aggrid, aggrout_GCWM_ascii))

Python-scripts:
py_ag93__mirca2000__aggregate_5to30min_annual_harvested_area_26crops__090831.py
py_ag93__mirca2000__ascii2raster__harvested_area_30min__090827.py
py_ag93__mirca2000__ascii2raster__max_monthly_cropped_area.py

Location of script files (as of November 2011):
(local) D:\CROPMAP\ArcGIS\Python_Scripts\AG93\MIRCA_ascii2raster_aggregate5to30min
(samba hydro server)
/home/hydro/gm/projects/virtual_water_project/CROPMAP/ArcGIS/Python_Scripts/AG93/MIRCA_ascii2raster_aggregate5to30min

Appendix H Curriculum Vitae / Lebenslauf

Persönliche Daten

Name:	PORTMANN, Felix Theodor
Geburtsdatum:	13.04.1963
Geburtsort:	Pforzheim, Deutschland
Familienstatus:	verheiratet, 1 Kind
Nationalität:	deutsch, schweizerisch

Berufserfahrung

03.2011 – heute

Wissenschaftlicher Mitarbeiter am Biodiversität und Klima Forschungszentrum (BiK-F, Kooperation der Senckenberg Gesellschaft für Naturforschung, Frankfurt am Main, und der Johann Wolfgang Goethe - Universität Frankfurt am Main),
Projektbereich E (Daten und Modellierzentrum),
Nachwuchswissenschaftlergruppe von Dr. Arne Micheels.

- Klimasimulationen zu Auswirkungen der Variabilität des Golfstroms in der Erdneuzeit auf das kontinentale Klima und die Biodiversität beiderseits des Atlantischen Ozeans.
- Arbeiten mit dem Erdsystemmodell Planet Simulator,
GrADS (Grid Analysis and Display System), ArcGIS und FORTRAN.

07.2009 – 05.2011

Wissenschaftlicher Mitarbeiter an der Johann Wolfgang Goethe-Universität Frankfurt am Main, im Institut für Physische Geographie (IPG), Arbeitsgruppe Hydrologie unter Leitung von Prof. Dr. Petra Döll.

- Erstellung eines globalen Datensatzes sektorspezifischer Grundwasserentnahmen.
- Erweiterung des globalen hydrologischen Modells WaterGAP.
- Arbeiten mit ArcGIS und C^{++}.

09.2005 – 10.2008

Wissenschaftlicher Mitarbeiter im IPG, Arbeitsgruppe Hydrologie.

- Erstellung des globalen Datensatzes monatlicher Anbauflächen bewässerter und Regenfeldbau-Feldfrüchte MIRCA2000.
- Arbeiten mit ArcGIS und C^{++}.

02.1993 – 08.2004

Wissenschaftlicher Angestellter in der Bundesanstalt für Gewässerkunde, Koblenz, Deutschland, im Referat M2 Wasserhaushalt, Vorhersagen und Prognosen unter Leitung von Dr. Klaus Wilke.

- Hydrologische Modellierung unter Nutzung von Geographischen Informationssystemen (GIS) und Fernerkundung.
- Bearbeitete Projekte:
EUMETSAT Satellite Application Facility for Land Surface Analysis (Entwicklungsphase)
European River Flood and Total Risk Assessment System (EUROTAS)
Datenauswertung für das Weltdatenzentrum Abfluss (Global Runoff Data Centre, GRDC)
Hydrologisches Untersuchungsprogramm Gorleben
Global Water Information Network (GLOBWINET)
- Mitwirkung bei der „Koordinationsstelle Fernerkundung“

Aktives Studium

10.2005 – 06.2011 Promotionsstudium der Geowissenschaften / Physische Geographie, Johann Wolfgang Goethe-Universität Frankfurt am Main, am Institut für Physische Geographie, Prof. Dr. Petra Döll (Hydrologie).

Titel der Dissertation:

Global estimation of monthly irrigated and rainfed crop areas on a 5 arc-minute grid
(Gutachter: Prof. Dr. Petra Döll, Prof. Dr. Wolfgang Cramer, Gesamtnote: sehr gut, Dissertation: sehr gut, Disputation: sehr gut).

10.1983 – 06.1992 Studium der Physischen Geographie, Schwerpunkte und Vertiefungen: Hydrologie, Fernerkundung, (Geo)Statistik, Geobotanik, Bodenkunde, Mineralogie, Limnologie, Umweltanalytik.

- Albert-Ludwigs-Universität Freiburg im Breisgau (Geographie, Fachrichtung Hydrologie) (WS 1983/84 – SS 1985): Mathematisch-naturwissenschaftliches Grundstudium, Vordiplom mit Nebenfächern Botanik und Chemie (Note: sehr gut).
- Ludwig-Maximilians-Universität München (Geographie) (SS 1986).
- Universität Trier (Angewandte Physische Geographie) (WS 1986/87 – SS 1992): Erwerb der Nebenfachqualifikationen für Hydrologie, Fernerkundung, Geobotanik und Bodenkunde.

Diplomhauptprüfung mit Nebenfächern Hydrologie und Fernerkundung (Gesamtnote: gut).

Titel der Diplomarbeit:

Niederschläge in Trockengebieten: raum-zeitliche Strukturanalyse und geostatistische Auswertung für den Piedmont und die Präkordillere von Mendoza (Argentinien)
(Gutachter: Prof. Dr. Wolfhard Symader, Prof. Dr. Ralph Jätzold, Note: gut).

10.1985 – 03.1986 Studium der Humanmedizin, Vorklinik.

- Universität Ulm (Donau) (WS1985/86)

Schulabschluss

05.1982 Abitur, Okengymnasium in Offenburg
Note: sehr gut

Frankfurt am Main, November 2011