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Water Requirements for Irrigation in the European Union

A model based assessment of irrigation water requirements and regional water demands in Europe

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Summary

Agriculture is an essential driving force in the management of water use. Especially in Southern European countries, irrigation is an essential element of agricultural production and agricultural water use has a substantial share in total water use (exceeding 50%). The presented work contributes to the assessment of impacts of irrigated agriculture on water resources at European scale. We developed a modeling approach to estimate irrigation water requirements and regional irrigation water demands in the EU at high spatial resolution. The modeling approach was applied for a first assessment of irrigation water requirements.

A prerequisite of the analysis was the compilation of a European Irrigation Map (EIM), providing information on the distribution of irrigated areas in EU25 for modeling studies. The EIM complements the underlying European land use map (Grizzetti et al. 2007), combining FSS statistics on irrigated area and crop area and information from the Global Map of Irrigated Areas (Siebert et al. 2005). The map was used to derive irrigated areas (as total and per crop) for spatial modeling units.

To estimate irrigation water requirements we applied the soil water and crop growth model EPIC that was implemented in a European agricultural modeling system EAGLE and calculates water and nutrient flows at a spatial resolution of 10x10 km raster cells. Different irrigation strategies were defined to analyze the effect of application rates and irrigation intervals on water requirement. The final results were given per raster cell and per crop, based on the most efficient irrigation strategy (maintaining optimum yield with lowest irrigation).

We show that allowing higher soil water deficit does not automatically lead to non-tolerable reduction of crop yields and soil moisture. Irrigation requirements (irrigation per unit irrigated area) in Europe range up to 2368 mm/yr in average per cell. Water demands (volume for defined spatial units) are calculated subsequently based on the irrigated area within each cell.

Resulting water abstractions were calculated using rules-of-thumb values of irrigation efficiency and conveyance efficiency. A comparison with reported national statistics on water abstraction data showed considerable discrepancies for many countries, indicating not only model uncertainties, but also illustrating shortcomings of national statistics. Such a comparison is a useful tool to check the consistency of both, model assumptions and underlying statistical information.

The results provide a spatial overview on irrigation water demands in Europe and allow analysis of agricultural pressures on water resources in Europe at a considerable high spatial

resolution. Being based on a single methodology applied to official data sources, the estimation supports inter-comparison of national statistics, which are based on different methodological approaches. This pilot assessment was based on irrigation and land use statistics from the years 2000 and 2003. The methodology was designed for application in an operational context, allowing future updates of the assessment corresponding to statistical data. The approach can therefore principally be applied and extended to track ongoing development or run future scenarios of land use and climate. Future improvements will rely on the development of the underlying statistical information and on the incorporation and improvement of crop specific information.

1 Introduction

Agriculture is an essential driving force in the management of water use. Water serves different uses, such as agricultural use, domestic and industrial use and environmental uses to maintain aquatic and terrestrial ecosystems. In the EU, agricultural water demands vary considerably depending on climatic conditions and the relevance of irrigation in agriculture. For most Mediterranean countries it is the major user of water resources (for irrigated farming and the livestock sector) (OECD, 2006), having significant impacts on water quantity and water quality. The total area equipped for irrigation (total irrigable area) in EU-27 in the year 2003 accounts for 16 million ha on a total of 182 million ha of agricultural land (Statistical Office of the European Communities, Eurostat), Farm structure survey data 2000, 2003). The majority of irrigated areas are concentrated in the Mediterranean region. France, Greece, Italy, Portugal and Spain account for 12 million ha corresponding to 75 % of the total area equipped for irrigation in EU-27.

In Central and Northern European countries agricultural water abstractions account for less than 1 % of total abstractions (e.g. Belgium 0.1%, Germany 0.5%, Netherlands 0.8%). In these regions, temporary irrigation is generally used to improve production in dry summers, especially when the dry period occurs at a sensitive crop growth stage. In southern Europe, however, irrigation is an essential element of agricultural production and agricultural abstractions account for more than 60% of total abstractions (e.g. Spain 64%, Greece 88%, Portugal 80%) (OECD/Eurostat Joint Questionnaire on Inland waters). Country data on irrigated area and agricultural water use are provided in Table 1.

Pressures on water resources culminate during summer (dry season) when the irrigation demand from agriculture is highest. In the Mediterranean region high water demand of agriculture and population (MGWWG 2005) are exacerbated by the limited natural availability of water resources and high climatic variability. Climate change is expected to intensify problems of water scarcity and irrigation requirements in the Mediterranean region (IPCC 2007, Goubanova and Li 2006, Rodriguez Diaz et al. 2007).

The main policy objectives in relation to water use and water stress at EU level set out in the 6th Environment Action Programme (EAP) (1600/2002/EC) and the Water Framework Directive (WFD, 2000/60/EC) aim at ensuring a sustainable use of water resources. Accurately estimating irrigation demands (and other water uses as well) is therefore a key requirement for more precise water management (Maton et al. 2005) and a large scale overview on European water use can contribute to developing suitable policies and management strategies. There is however a significant lack of information since "The information needed by policy decision makers on aquifer recharge and pumping by farmers, irrigation pollution emissions from either surface or subsurface water, soils, transport and fate processes […] is not available in countries with significant irrigated agriculture such as Spain, Italy, Portugal and Greece (Albiac et al. 2005)”.

In support to the EU-wide policy developments that requisite large scale overviews with sufficiently high resolution, we developed a model based approach to estimate irrigation requirements in Europe. In this report we present the modeling approaches and the results of the initial assessment. The work presented in this report is based on two main components. First, we development a European irrigation map (see also Wriedt et al., in press) disaggregating available statistical information and combining the information with a land use map for distributed agricultural modeling. Second, the irrigation map was included in the EPIC-EAGLE modeling tool, which was applied to calculated crop water requirements in Europe. The results were compared with reported statistics on national water abstractions (see also Wriedt et al., unpublished b). We discuss the results with respect to specific problems, potentials and limitations of the approach.

Table 1: Irrigable and irrigated areas by country (FSS 2000, FSS2003 national sources) and irrigated areas finally used for compilation of the EIM, Agricultural water abstractions (AWA) in % of total water abstractions reported in OECD/Eurostat Joint Questionnaire (data of 2000).

Country	Country	Irrigable Area (ha) 2000	Irrigated Area (ha) 2000	Irrigable Area (ha) 2003	Irrigated Area (ha) 2003	Irrigated Area (ha) EIM	AWA (%)
AT	Austria	95240		90420	34230	35900	2.7
BE	Belgium	31970		21110	1610	1610	0.1
BG	Bulgaria			124480	79370	79370	19.6
CH	Switzerland					43820*	74.5
CY	Cyprus			44930	35410	35410	0.8
CZ	Czech Republik			39380	16450	16850	26.4
DE	Germany					234587*	2.9
DK	Denmark	446930		448810	201460	201460	2.2
EE	Estonia					0	14.9
ES	Spain	3475560	3233020	3135930	2849830	3233020	0.5
FI	Finland	88140		100480	0	0	87.8
FR	France	2633350	1575520	2233110	1656780	1575520	3.9
GR	Greece	1321340	1161000	1487210	1278950	1161000	13.7
HU	Hungary	308110	67080	242160	148680	67080	-
IE	Ireland	0	0	0	0	0	18.3
IT	Italy	3855960	2453440	2902000	1746990	2453440	1.9
LT	Lithuania			250		0	0.3
LU	Luxemburg	0	0	0	0	0	-
LV	Latvia	450	0	450	0	0	0.8
MT	Malta			2000	1850	1850	9.7
NL	Netherlands	498280		350560	62150	62150	80.1
PL	Poland			98450	46920	46920	11.8
PT	Portugal	792000		674820	229910	229912	7.8
RO	Romania			1510830	400420	400420	2.1
SE	Sweden	136730		188440	53450	53450	64.9
SI	Slovenia	2230		1880	1880	1880	5.6
SK	Slovakia	225310	110670	209060	104540	110670	
UK	United Kingdom	950[1)]		96120[1)]	96120[1)]	148019*	-
	EU27 and CH					**10158440**	

1) Statistics were incomplete

* National sources

2 Material and Methods

2.1 General definitions and concepts

Crop water requirement, irrigation requirement, irrigation water use and irrigation abstractions are often used synonymously or without clear division. To avoid confusion we define these concepts briefly taking into account our modeling task:

Crop water requirement (CWR) is the total amount of water required for transpiration by a well-managed crop grown under optimum growth conditions without water- and nutrient stress. For practical purposes, the CWR is calculated as the potential crop evapotranspiration (FAO 1996), avoiding the problem of clearly defining optimum growth conditions and optimum crop yield.

Irrigation water requirement (IWR) is the amount of water that has to be applied in addition to rainfall to serve crop water requirements. For irrigation planning it is determined as the difference between CWR (i.e. potential crop evapotranspiration) and the actual crop evapotranspiration under rain fed conditions with periods of water stress (FAO 1996).

Strictly speaking, these definitions constitute an operational approach to calculate CWR and IWR only. Neither CWR nor IWR are absolute values that could be attributed to a certain crop under a certain climate as standard or optimum growth and growth conditions depend on other external factors: Crop growth and crop yields can be influenced by inputs of fertilizer, pesticide and water, which will also feed back to crop evapotranspiration; the crop water requirement has an economic dimension that is determined by the marginal costs of irrigation with respect to crop yield and thus farmers income (Britz, W., 2007, oral communication). Also the IWR is not static, as different levels of water stress may be tolerable without significant impacts on crop yield depending on crop type and growth stage; also the timing of irrigation operations and application rates influence irrigation water requirement considerably. We include irrigation scheduling explicitly in our concept of irrigation requirement, although strictly speaking we are already transgressing the boundary to actual irrigation water use. We express the IWR always as volume per year and per unit irrigated area ($l/m^2/yr = mm/yr$).

Part of irrigation water may be lost by percolation rather than by crop evapotranspiration. Therefore it can potentially be re-used for irrigation or recharge other water bodies. Especially in rice cultivation on flooded fields the amount of water lost by percolation exceeds potential evapotranspiration by far (see Section 2.5.5). Having a general focus on the resulting regional water application on the field rather than on net water use, we include percolation losses in our concept of irrigation requirement (gross-requirement) and do not calculate a net requirement based on crop evapotranspiration only.

We further define **irrigation water demand** as the volume of water required in a certain region to satisfy irrigation requirements. It can be calculated by multiplying IWR (mm/yr) by irrigated area. The distinction between irrigation demand and irrigation requirement was introduced to better separate field scale and regional water requirements on a semantic level.

The actual **irrigation water use** is not only determined by IWR, but depends also on legal regulations of water use, irrigation infrastructure and systems, irrigation management and economic considerations and can therefore deviate significantly from irrigation requirements (in both directions).

The actual **water abstractions** or water diversions from the water bodies are generally higher than the irrigation water requirement (field level) or irrigation demands (at regional level). Losses during transport, the application efficiencies of different irrigation systems and losses caused by ineffective management will be included in the actual water abstraction.

Global irrigation maps such as the GMIA (Siebert et al. 2005) and the GIAM (Thenkabail et al. 2006) have become available, providing irrigated areas at a relatively high spatial resolution (GMIA: 5-minute raster, GIAM: 10km raster). Such global maps are currently the only sources providing a spatially distributed overview on irrigated areas over large geographical regions. The GMIA also forms an integral part of the global water balance model WaterGap (Döll et al. 1999, Alcamo et al. 2003) to analyse irrigation requirements (Döll & Siebert 2002). The GIAM is complemented by additional datasets on rainfed agriculture and global land use.

More detailed regional maps of irrigated areas may be available in certain regions, the global data sets, however, are currently the only available source covering large geographical areas at a resolution below sub-regional (NUTS3) level.

Although the spatial resolution of such global datasets is far below the spatial resolution of available statistical data, their integration in modelling applications is not straightforward, if the modelling studies are not specifically designed for this dataset. Modelling approaches may apply a different spatial concept using spatial units with a similar or lower order of magnitude. The information (total (ha) or relative (%) irrigated area) needs to be disaggregated meaningful and accurately from the source units to all intersected target units. Disaggregating according to intersected area is not appropriate, as the generalised information of the source data may be inconsistent with the underlying land use distribution of the target application. Furthermore the spatial distribution of potentially irrigable area needs to be respected. The target application may also incorporate a specific land use classification, which requires further assignment of irrigated areas to different crops or land use categories. Also, discrepancies in the irrigated area derived from the global maps and regional statistics may exist and have to be accounted for.

Data on irrigable and irrigated areas are available in European national and regional statistics and are regularly assessed in the Farm Structure Survey (FSS) and reported at regional and sub-regional level (corresponding to the European statistical regions NUTS2 and NUTS3).

Spatially distributed modelling requires integration of the available information in a format consistent with the model structure, the spatial modelling units and other information sources included in the assessment. Typically, regional statistics based on administrative regions, are not consistent with spatial modelling units derived as natural (for example catchments) or artificial (for example raster cells) entities and suitable procedures to transfer the data are required. The problems of disaggregating the information to modelling units or adapting to a specific land use classification are similar to those described for the global maps.

To calculate crop irrigation requirements various modeling tools have been developed. A widespread approach are the FAO guidelines to estimate crop water requirement (Allen et al. 1998), calculating irrigation requirements as the difference between potential crop evapotranspiration under standard-conditions (no water stress) and under non-standard conditions, using a simple soil water balance accounting model to determine soil moisture and actual crop evapotranspiration. This approach was also implemented in field scale models (e.g. CROPWAT, Smith, 1992 and ISAREG, Pereira et al., 2003) and spatially distributed models (e.g. GISAREG, Fortes et al., 2005). A GIS-based monthly water balance approach was developed by Portoghese et al. (2005) for regional assessment of net irrigation requirements in Southern Italy. More detailed soil water balance models implement irrigation triggered by certain thresholds of soil moisture, as done in the spatially disitributed, integrated hydrological models such as WASIM (Schulla 1997, Schulla and Jasper 2007) and SWAT (Neitsch et al. 2005). At global scale, the WaterGAP model (Doell and Siebert 2002, 2003) also comprises a module to estimate irrigation requirements based on the water balance approach. We previously developed the EPIC-EAGLE modeling tool (Bouraoui & Aloe, 2007, van der Velde et al, 2008) which is a spatial implementation of the soil, water, and crop growth model EPIC (Sharpley and Williams 1990, Williams 1995) for Europe. Primarily developed to analyze agricultural losses of nutrients and pesticide at European scale, it’s capability to calculate crop irrigation requirements and the associated database for Europe-wide applications make it a promising tool to analyze agricultural pressures on water resources. The simulation model runs on a per crop basis, the crop categories were adapted to the European Farm Structure Survey. A specific land use map was developed by Grizzetti et al. (2007) as a basic input data set for the model. Therefore it was not only necessary to integrate spatial information on the distribution of irrigated areas, but also to distribute irrigated areas to individual crops according to the underlying land use information. However, European statistics provide crop specific irrigated areas only for 10 selected crops (at regional level), compared to over 40 crop categories (arable and permanent crops) included in the FSS. Therefore a suitable distribution approach was required to combine statistics on crop irrigation with soft information on irrigation practices in the EU.

2.2 Data sources

CORINE Land cover 2000 (ETC, 2005) provides a high resolution data set of land use over Europe at a resolution of 1 ha. The minimum mapping unit is 25 ha and the map scale is 1:100000. CORINE Land Cover maps the spatial distribution of various land use categories, including irrigated and non-irrigated arable land, rice and various permanent crop classes. Permanently irrigated land and rice fields were distinguished based on detection of irrigation infrastructure (water supply and drainage canals).

A land use map (LUM, Grizzetti et al. 2007) was derived from land use distribution of CORINE Land Cover 2000 and European and national statistics on crop areas for the year 2000. Forty-three (43) agricultural crop categories are distinguished in consistency with FSS crop categories and distributed to arable land, grassland and permanent cropland of the CORINE data set. FSS crop areas were directly assigned to corresponding land use classes where possible. Field crops were distributed to irrigated and non-irrigated agricultural land. Where FSS crop areas do not match CORINE land cover data, a set of enlargement and shrinking rules was applied to ensure consistency with FSS data. Additional land use classes only contained in CORINE were maintained. Altogether, the LUM contains 98 land use classes in 1 ha resolution for EU-25. The spatial crop distribution is consistent with statistical data at sub-regional (NUTS 3) level and can be used as basic information for large scale modelling purposes.

Member States report regularly Farm Structure Survey (FSS) results to Eurostat. The data is aggregated to sub-regional and regional level (European statistical regions NUTS3 and NUTS2, Figure 1). FSS data include information on agricultural area and crop areas for 46 crop types. Irrigation data are reported as area equipped for irrigation (area covered with irrigation infrastructure or irrigable area) and area irrigated at least once a year (actual irrigated area) (Table 1). In addition to regional totals, the irrigable and irrigated area are also reported for 10 main crops (Durum wheat, Vines, Maize, Potatoes, Sugar beet, Soya, Sunflower, Fodder plants, Fruit and berry orchards and Citrus fruits, Table 2). Full census data were reported in 1990 and 2000 while data for 1993, 1995, 1997 and 2003 were based on a sample of farm holdings. The FSS 2000 survey contains data from 17 Member States. France, Greece, Hungary, Italy, Slovakia and Spain were the only countries to report actually irrigated areas, while the other Member States except for Germany have reported data as irrigable area. The FSS 2003 reports irrigable area as well as area irrigated at least once a year for 24 EU countries. Especially in regions with typically rain-fed agriculture and temporary or supplementary irrigation, the discrepancy between irrigable and irrigated area can be considerable. Therefore data from the FSS 2003 were used substitute missing data on irrigated area and to add countries not included in FSS 2000. Although the irrigated area may vary from year to year, also due to climatic conditions, we consider irrigated areas of 2003 to be an acceptable estimator of irrigated areas.

Although more recent data are available (FSS 2005), we gave preference to 2000 data (extended by 2003 data) to maintain consistency with the underlying LUM.

Additional national statistics or reports were used to fill some gaps in the Eurostat data. This included regional and national statistics or reports giving further information on irrigated areas and irrigated crops at sub-national scale (Germany: Statistisches Bundesamt 2004, Netherlands: Hoogeveen et al. 2003, United Kingdom: Downing et al. 2003, Switzerland: Weber & Schildt 2007).

The Global Map of Irrigated Areas (GMIA, Siebert et al. 2007) is a global data set providing percentage of irrigated area and absolute irrigated area at a global resolution of 5' (a grid resolution of 5' equals a grid size of 9.2 x 7.1 km at 40° latitude). The latest release included major improvements in Europe. The data set has been compiled from various sources, including land use maps, remote sensing and statistics. For methodological reasons, discrepancies between statistical data and the information of the GMIA can exist. Within the scope of this study, the GMIA provides additional information on the heterogeneous distribution of irrigated areas within each sub-region.

A qualitative survey on regional irrigation practices was collected during the EU project FOOTPRINT (www.eu-footprint.org) and provided by I. Dubus (personal communiation, 2007). The survey indicates at regional (NUTS2) level for selected crops (cotton, durum wheat, maize, olives, orchards, pulses, rape, sugar beet, soft wheat, tobacco, vegetables and vinyards) if irrigation is used for crop cultivation or not.

Water abstraction data are collected regularly by Eurostat via the OECD/Eurostat Joint Questionnaire on Inland Waters. These data include annual water abstraction data per sector at *national* level. Abstractions for agriculture, fisheries and forestry are combined as agricultural abstractions while a separate indicator on agricultural water abstractions for irrigation is also included. However, information on water abstraction for agricultural purposes is very incomplete if not inexistent. Not all EU member states report this information regularly and consistently. Most of the irrigation systems have no metering device and figures are based on estimates rather than measurements (P. Nadin, Eurostat, personal communication).

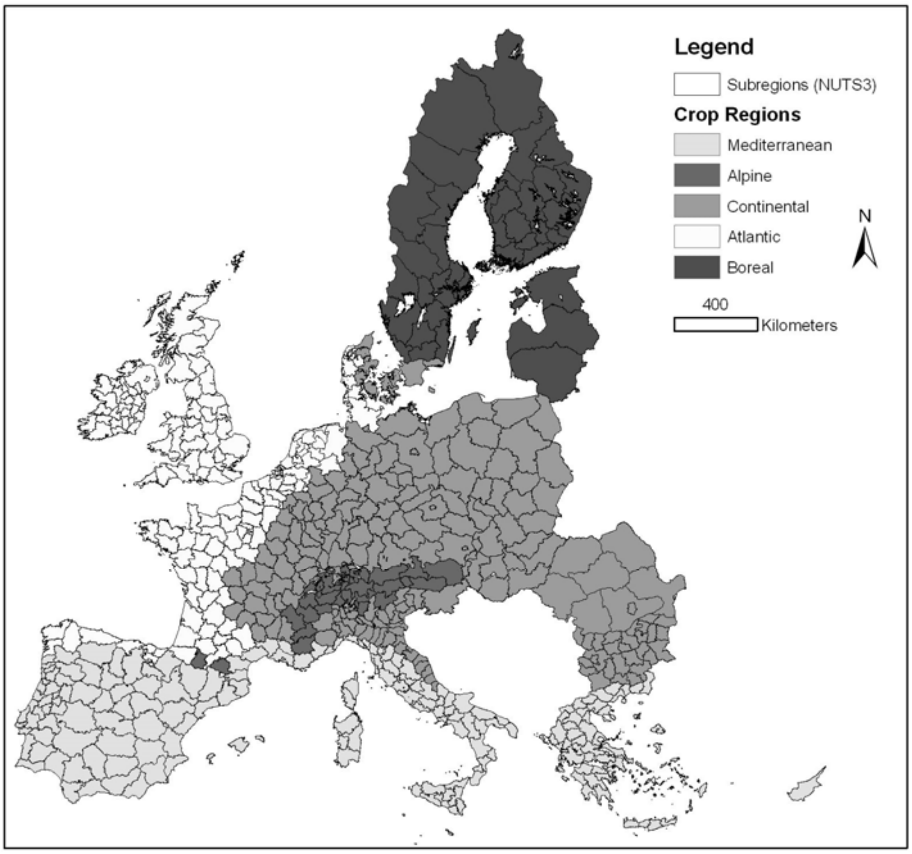


Figure 1: Subregions (European statistical regions NUTS3) and major crop regions.

2.3 *The European Irrigation Map*

The generation of the irrigation map followed a two step procedure (Figure 2). First, irrigated area was distributed to crop categories at sub-regional level (NUTS3) based on statistical information and distribution rules. Second, the regional information was disaggregated to a high resolution dataset based on the crop distribution and the GMIA.

2.3.1 Estimating crop specific irrigated area for sub-regions

Regional irrigation statistics indicate that generally only a fraction of crop area within a region is irrigated (partial irrigation). The distribution of irrigated areas may be influenced by the internal physiogeographic or anthropogenic organization of the area. For example, irrigated areas may cluster in irrigation districts, reflecting existence of (and dependence on) water distribution infrastructure or availability of ground- or surface water resources; soil properties and topographic features may favour or prevent irrigation measures; and different climatic conditions may result in areas of dominantly rain-fed and dominantly irrigated agriculture. The ratio of irrigated crop area to total crop area is the crop irrigation share, which was calculated from the statistical information.

The total irrigated areas given for each sub-region (NUTS3) were distributed to potentially irrigated crops, combining FSS data on irrigated area, crop-specific irrigated area (whenever available) and total crop areas (Figure 2).

Crop categories only partly refer to specific crops. Where categories were used to group different crops (for example ‘Root and other fodder’, ‘Forage crops’), the categories were used as given. Where categories split one crop into different categories (for example olives and table olives or wine, table wine, raisins, table grapes), these were not further distinguished but treated as one category (resulting in a total of 34 crop categories, Table 2). Crop categories were classified into three irrigation categories: compulsory irrigation (cotton, rice), partially irrigated crops and non-irrigated crops.

For crops with reported irrigation shares the irrigated areas could directly be assigned. Given that crop specific irrigated area was reported for ten crops only, the remaining irrigated area needed to be distributed to the 24 remaining crop categories. This distribution step was based on assigning crop specific priorities for irrigation.

Distribution rules

The distribution algorithm generated a table of irrigated area per crop and per region applying the following distribution rules:

- Irrigated area was first assigned to crops with compulsory irrigation, including the entire crop area of these crops.
- Where the crop specific irrigated area was reported in statistics, the irrigated area was then directly assigned to the corresponding crops.
- For crops where irrigated area was unknown, the irrigated area remaining from the previous steps was distributed according to a priority weighting function. Priorities were defined including expert knowledge and statistical analysis (see below).
- Crop specific irrigated area could not exceed crop area.
- If the calculated area of a region overshot the reported irrigated area of that region, irrigated area was shrunk for all partially irrigated crops (this affects only crops where the area was reported in statistics, as there would be no left-over to be distributed to other crops). In this case priority was given to match the regional statistics.
- Irrigated area of crops with compulsory irrigation was not shrunk or expanded.
- Crops which were defined as non-irrigated could not be assigned irrigated area.

In some cases, the distribution approach encountered the following inconsistencies: i) irrigated area of crops with compulsory irrigation exceeded reported irrigated area (no shrinking possible) and ii) the total area of potentially irrigable crops is smaller than total irrigated area from statistics (no further expansion possible). These problems result from inconsistencies in the underlying statistical information on crop area and irrigated area. In these rare cases deviations from the reported irrigated area were accepted, as the total crop areas were fixed in the LUM and could not further be expanded. Cases were the calculated irrigated area of a region undershot the reported irrigated area did not occur, as the left-over of irrigated area (after subtracting the area of always irrigated crops and crop specific irrigated areas) could always be distributed to crops for which no statistical information was available.

Table 2: List of crop categories distinguished in the irrigation map and corresponding categories of the land use map

Nr	Crop categories distinguished in the irrigation map	Crop identifier(s) (corresponding to crop categories of the land use map)	European regional statistics available
1	Barley	BARL	
2	Citrus	CITR	+
3	Durum wheat	DWHE	+
4	Flowers	FLOO, FLOI (Flowers and flowers indoor)	
5	Fodder maize	MAIF	
6	Fruit and Berry Orchards	APPL	+
7	Grassland	GRAE, GRAI (rough grazings, pasture & meadows)	
8	Hops	HOPS	
9	Leguminous forage crops	LEFO	
10	Maize	MAIZ	+
11	Medicine crops	MEDI	
12	Oats	OATS	
13	Olives	OLIV, TABO (Olives, Table olives)	
14	Other cereals	OCER	
15	Other crops	OTHR	
16	Other forage crops	OFAR	
17	Other forage crops other	OFAO	
18	Other industrial crops	INPO	
19	Other oil crops	OOIL	
20	Other permanent crops	NURS, OCRO, OCRG (Nurseries and other permanent crop)	
21	Potatoes	POTA	+
22	Pulses	PULS	
23	Rape	RAPE	
24	Rice	RICE	
25	Roots and other fodder	ROOF	+
26	Rye	RYEM	
27	Soft wheat	SWHE	
28	Soya	SOYA	+
29	Sugar beet	SUGB	+
30	Sunflower	SUNF	+
31	Textile crops	COTS	
32	Tobacco	TOBA	
33	Vegetables	TOMA, OVEG (Vegetables and vegetables under glass)	
34	Wines	TWIN, TWIO, TARA, TAGR (Wine, raisins, grapes)	+

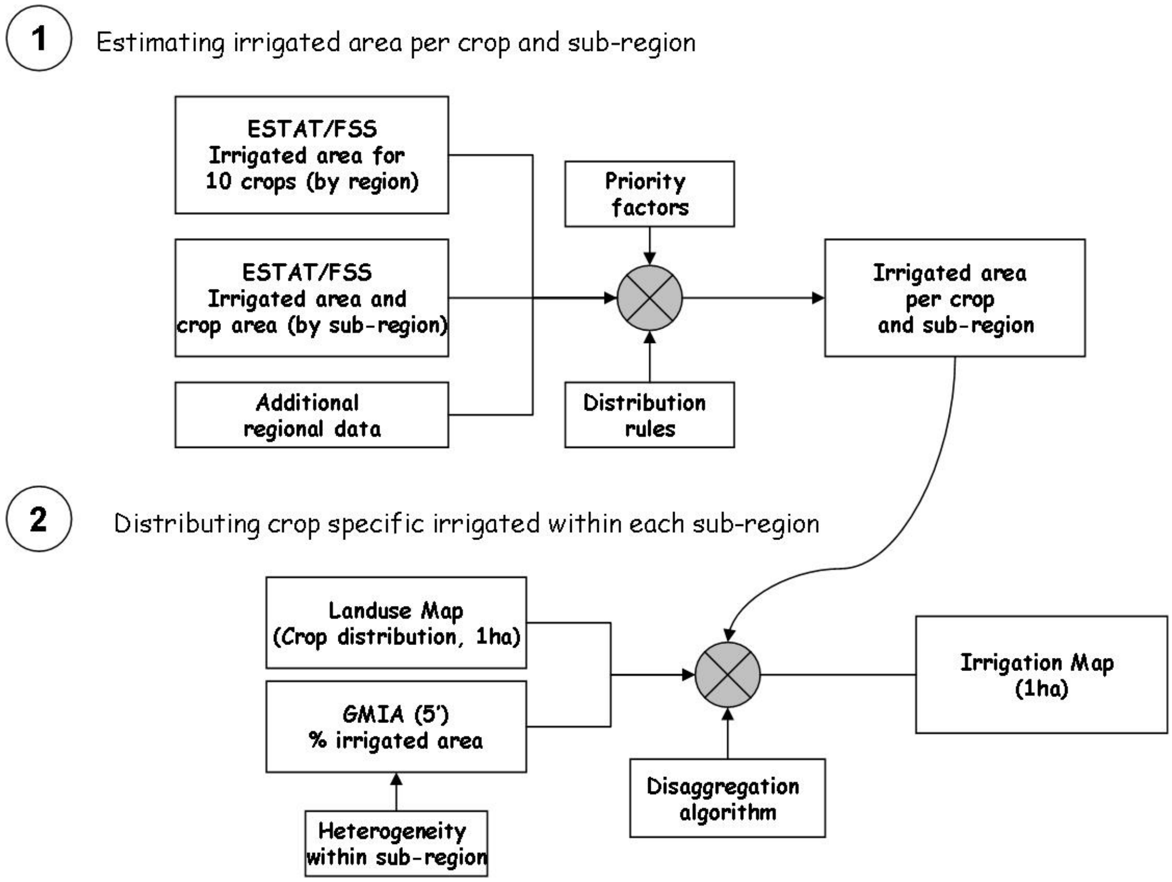


Figure 2: Generation of the European Irrigation Map (EIM) – basic processing steps

Calculating crop irrigation shares using priority factors

Where no statistics on crop specific irrigated area were available, the irrigated area was calculated using priority factors. These priority factors do not directly determine the irrigated fraction of each crop in advance, but define the priorities for distributing the irrigated area of each spatial unit to the crops (see below for an explanation of priority factors).

The priority factors were crop specific. It was generally assumed that the ranking of priority factors is similar all over Europe (for example: vegetables = maize > barley > rape; citrus > olives > durum wheat). The priority factors were regionalized in a second step, as described in section 2.2.3.

Within each region, the final irrigation shares do not only depend on the priority factors, but also on the actual crop composition and the absolute crop areas and on the crops for which data actually were available.

Putting it in a more descriptive way, crops will compete for the available irrigated area based on their abundance (crop area) and their individual competitiveness (priority factor), using the following calculation scheme:

The crop specific (*i*) irrigated area (*CIA*) was expressed as fraction of crop area *CA*. The irrigation share φ was expressed as product of a constant scaling factor *c* and a crop specific priority factor ω:

$$CIA_i = CA_i \cdot \varphi_i = CA_i \cdot c \cdot \omega_i \qquad [1]$$

The distributable remaining irrigated area (*RAI*) has to be distributed to those irrigable crops where irrigation shares were not reported in statistics.

$$RIA = \sum_i CIA_i = \sum_i CA_i \cdot c \cdot \omega_i \qquad [2]$$

As *RIA*, *CA* and ω are known, we can calculate *c* using the formula:

$$RIA = c \cdot \sum_i CA_i \cdot \omega_i \qquad [3]$$

$$c = \frac{RIA}{\sum_i CA_i \cdot \omega_i}$$

Finally, an estimate for crop specific irrigated areas can be obtained inserting into Equation [1]. The *RIA* was limited to the total area of the irrigable crops under consideration. A potential leftover was distributed by proportionally rescaling the irrigation shares *df* for all crops (except for non-irrigated crops and crops which are already entirely irrigated).

Determining priority factors

Crop specific information on irrigated areas was missing in some regions and for various agricultural crops. The priority factors controlling the distribution of irrigated areas to these crops were based on a combination of regression analysis, survey of irrigation practices and personal judgement.

An initial approach to derive meaningful priority factors was based on the relation of crops to irrigated areas by developing a linear regression model by stepwise forward regression.

The regression model takes the form

$$IrrA = \sum_i b_i \cdot CA_i + e \qquad [4]$$

where *IrrA* = relative irrigated area (% of agricultural area), *b* = regression coefficient, *CA* = Crop area in % of agricultural area, *i* = crop index, *e* = error term.

Stepwise regression is a technique for choosing the variables, i.e., terms, to include in a multiple regression model. Forward stepwise regression starts with no model terms. At each step it adds the most statistically significant term (the one with the highest F statistic or lowest p-value) until no terms are left. An important assumption behind the method is that some input variables in a multiple regression do not have an important explanatory effect on the response. If this assumption is true, then it is a convenient simplification to keep only the statistically significant terms in the model. One common problem in multiple regression analysis is multicollinearity of the input variables. The input variables may be as correlated with each other as they are with the response. If this is the case, the presence of one input variable in the model may mask the effect of another input.

The basic idea was to use the regression coefficients as an indicator of the relative importance of each crop to share in irrigated area. Priority factors could reflect equal weight for each potentially irrigable crop setting the same value (for example 1) for each crop. Then all crops would be assigned the same ratio of irrigated area to crop area. Alternatively priority factors could be used to distinguish crops or groups of crops. Then the individual fraction of irrigated crop area would be modified according to the specified priority. As an example, categories of non-irrigated crops, crops with a low share of irrigated areas and crops with a high share of irrigated areas could be defined and increasing priority factors can be used to enforce a preferred distribution to crops with higher irrigation shares. Choosing linearly (0, 1, 2, 3, 4) or exponentially (0, 1, 2, 4, 8) increasing factors may give more or less preference to highly irrigated crops compared with less irrigated crops.

The results of the regression analysis are displayed in Table 3. Some of the regression coefficients take values greater than 1, indicating that they do not only account for their own crop area, but also for the area of other crops as well.

As problems of multicollinearity do exist and data themselves are subject to various uncertainties, regression coefficients were not directly used to determine priority factors. Instead we distinguished crops into four classes, based on the significance of the regression term and the direction of the regression term (see Table 3): ‘non-irrigated’ (significant negative relation), ‘insignificant irrigation’ (non-significant positive correlation), ‘low level irrigation’ (significant positive correlation), ‘high level irrigation’(significant positive correlation, coefficient > 0.5). All crops falling into one class were assigned the same priority factor. The regression approach may result in spurious correlations resulting in inappropriate assignment of priority factors. Also rain-fed crops may have significant correlations to irrigated areas, if they have similar distribution patterns. Vice versa, no correlation does not necessarily indicate no irrigation. Therefore many crops having negative correlations to irrigated areas where finally grouped into the low-level irrigation class (Table 3), still allowing a small fraction to be irrigated.

There are potentially numerous ways to assign priority factors or individual weights to the crop categories without prior information. We tested three different settings of priority factors: one setting defining equal priority for all crops (all factors set to 1), one setting with linearly increasing factors (0,1,2,3) and one setting with increasing factors emphasizing the crops significantly related to irrigated area in the analysis (“progressive”, factors set to 0,1,5,10). Comparing the three different approaches we found only minor changes in irrigated areas. Figure 4 displays the aggregated effect on the irrigated fraction of all irrigated crops for the Mediterranean and the Atlantic crop region (see also Figure 1). In the Mediterranean crop regions, the highest effect was found for rape, which falls into the category of insignificant irrigation. A difference of 5% in irrigated fraction of crop area was found. Here the relative magnitude of the priority factor with respect to the factors of other crops has a considerable impact on the irrigated area that can be attributed to rape. The irrigated area of other crops in the same category was constrained by statistical information and therefore lower variations were found (for example soya, sunflower, sugar beet). Though some adjustments of irrigated areas took place, the total difference in irrigation share between the three approaches was generally less than 5% in irrigated fraction of crop area. For many other crops, irrigation shares were at least partly constrained by the statistical information included. Minor adaptations took take place to redistribute remaining irrigated area or because certain subregions lack statistical information. Similar results were found for the Atlantic crop region (and other crop regions not displayed here). Here relatively high differences were found for flowers and vegetables, where irrigation shares changed in the order of 15-20%.

In general, the progressive setting of factors (0,1,5,10) increased the irrigated area of crops in the 'high level irrigation' category (for example vegetables, flowers), while decreasing the irrigated area for crops in the 'insignificant irrigation category' (for example sugar beet, rape) with respect to the equal factors setting (0,1,1,1). The linear setting (0,1,2,3) stayed in between. For the final map generation the progressive setting of priority factors (0,1,5,10) was chosen, favouring a distribution to crops which had a significant relation to irrigated areas in the regression analysis. We think the errors made due to alternative settings of the factors are negligible, given that without statistical data on irrigated crop areas the true irrigation share is unknown. Assuming no irrigation of grassland, we observed that the statistical irrigated area could not be entirely distributed to crops and a re-distribution to crops where irrigated areas were given in statistics was necessary to buffer the overhead. This raised the irrigation shares of these crops significantly creating inconsistency with the statistical information. This indicates that grassland irrigation must not be neglected and therefore grassland was finally grouped into the 'high-level irrigation' category.

Table 3: Final regression model (variables included, regression coefficient b, standard error se, probability p) and final classification and priority factors included in map generation

Crop type	Model**	b	se	p-value	Irrigation class	Priority factor
SWHE	1	-0.3373	0.06859	1.23e-006	-	0
DWHE	0	0.02025	0.05557	0.7157		1
RYEM	1	1.215	0.3357	0.0003288	++	10
BARL	1	0.2309	0.07932	0.003785	+	5
OATS	1	-0.4909	0.1358	0.0003333	-	0
MAIZ	1	1.02	0.0563	0	++	10
RICE	1	1.114	0.1063	0	++	always irrigated
OCER	0	-0.7322	0.5437	0.1787		1
PULS	1	2.275	0.4372	2.958e-007	++	10
POTA	1	1.629	0.231	6.676e-012	++	10
SUGB	1	-0.5414	0.2131	0.01138	-	1
ROOF	0	-0.5762	2.489	0.817		1
TOBA	1	1.649	0.4415	0.0002121	++	10
HOPS	1	-37.14	14.45	0.0105	-	0
TEXT/COTS	1	1.261	0.1022	0	++	1
RAPE	0	0.06365	0.2412	0.792		1
SUNF	0	0.01881	0.1771	0.9155		1
SOYA	0	-0.2926	0.2922	0.3172		1
VEGT	1	1.162	0.2523	5.383e-006	++	10
FORAGE	1	0.1564	0.03975	9.582e-005	+	5
FRUIT	1	0.4852	0.1098	1.247e-005	+	5
CITR	1	0.9341	0.185	6.484e-007	++	10
OLIV	1	0.1715	0.04204	5.348e-005	+	5
VINE	1	0.2655	0.0707	0.0001953	+	5

* always irrigated by definition

** 1 – included in final model, 0 – not included

Irrigation class: - unirrigated, 0 insignificant, + low level irrigation, ++ high level irrigation

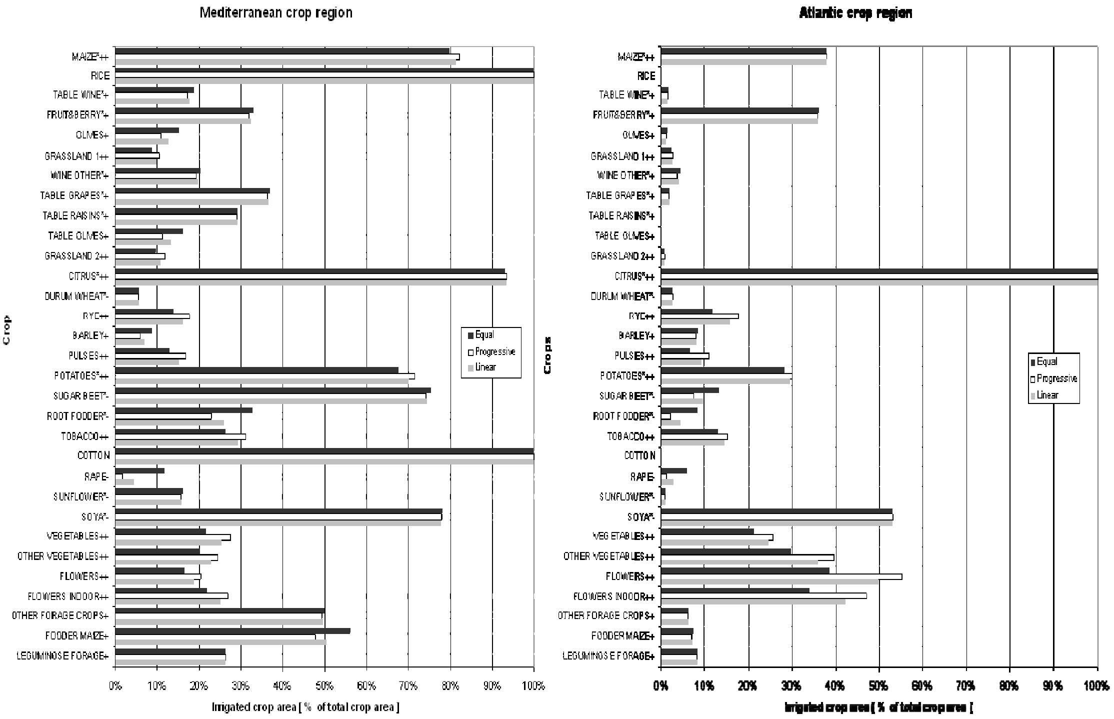


Figure 4: Effects of different priority factor settings on the final distribution of irrigated area for the Mediterranean crop region (left) and the Atlantic crop region (right) (Symbols indicate: *: Statistical data available, ++: high level irrigation, +: low level irrigation, - insignificant irrigation).

Regional differentiation and specific modifications

Irrigation practices may differ between regions and countries according to environmental and economical conditions or differing agricultural practices. While the approach described in the previous section 2.2.3 helped to derive some global relations and to define the initial values assigned as priority factors, further regional differentiation was necessary.

The qualitative survey of irrigation practices taken from the FOOTPRINT-project (I. Dubus, personal communication, 2007) allowed further regional differentiation of the priority factor approach, applying priority factors as determined in 2.2.3 only in those regions where irrigation is carried out. For other regions, the priority factors were set to zero (no irrigation) or to a lower priority value (1). For other crops, we generally assumed a constant priority factor all over Europe but some additional crop-specific modifications were included. For textile crops statistical information does not distinguish between cotton and other crops used for textile production. We assumed compulsory irrigation for cotton in Southern European countries, where textile crops are likely to be cotton. For other regions textile crops were assigned a low priority for irrigation (no further data available). For rye, the regression approach suggests a high priority factor due to strong positive correlation with irrigated areas, although it is a typically rain-fed crop and irrigation benefits may even be negative, as for example in Germany where the benefit is -65 € (Fricke, 2006). Following the distribution of irrigated rye given in the MIRCA global data set of irrigated crop areas (Portmann et al. 2008), we excluded irrigation of rye in most countries. Another issue was the consideration of grassland irrigation. There are currently no statistical data available at European level, but there are regions where considerable grassland irrigation has to be taken into account (for example Val d'Aosta in Italy, the Netherlands, and the United Kingdom). Grassland irrigation generally has the purpose to provide quality fodder for stock breeding and dairy farming. In the Netherlands, grassland is irrigated with regional shares of 6% up to 43% (Hoogeveen et al. 2003) and the regional data were directly included in the map generation. Similar assumptions can be made for the entire Benelux region as well as for UK, Ireland, Denmark, Poland and Sweden, while grassland irrigation is less common in Germany (Anonymous Reviewer, 2008).

In addition to serving crop water requirements, irrigation may also be applied for frost protection. This can be found for example in traditional mountain pasture irrigation and also in fruit orchards. Such areas can, however, not be identified from the available data and are therefore not specifically distinguished.

2.3.2 Redistributing irrigated areas within each sub-region

The second processing step performed the disaggregation of crop-specific irrigated area within each sub-region (NUTS3) to a 1ha grid equivalent to the LUM (Figure 2).

Constraints to the internal distribution were set by the spatial distribution of corresponding crop areas in the land use map and by the internal irrigation density inferred from the GMIA. Due to the relatively high resolution of 5', the GMIA provides information on the heterogeneous distribution of irrigated areas within each sub-region. The percentage of irrigated area within each GMIA cell was used as an indicator of irrigation density. For each GMIA grid cell we calculated the deviation from the average irrigation density (per sub-region, NUTS 3). According to this deviation we modified the local probability of each land use raster cell to be irrigated.

Starting point of the calculation procedure is the calculation of the average irrigation probability *p* for each sub-region *i* and for each crop based on the crop specific irrigated areas for each sub-region:

$$p^{i}_{Crop} = \frac{IA^{i}_{Crop}}{CA^{i}_{Crop}} \qquad [5]$$

where IA^{i}_{crop} = irrigated area of sub-region i per Crop, CA^{i}_{crop} = Crop Area of Crop in sub-region i, p^{i}_{crop} = average crop specific irrigation probability for sub-region i.

The average crop specific irrigation probability within each sub-region was modified by a local (cell based) correction, increasing or decreasing irrigation probability based on the density of irrigated areas, as derived from the GMIA (Siebert et al. 2007). The percentage of irrigated area given by a 5’ geographic raster was transferred to a raster of the final resolution of 1 ha, giving a local irrigation density pct_{xy} for each cell of the final raster. In addition to the local density, the average irrigation density pct^{i} of the GMIA within each sub-region was calculated. Now for each 1ha cell, the local deviation d_{xy} was calculated as the relative difference of the local irrigation density pct_{xy} (derived from GMIA 5’ cell) to the sub-regional average irrigation density pct_{i}:

$$d_{xy} = \frac{pct_{xy} - pct_{i}}{pct_{i}} \qquad [6]$$

The relative deviation d_{xy} was rescaled to absolute deviation D_{xy} by multiplication with the average crop specific irrigation probability p^{i}_{crop} of the sub-region.

$$D_{xy} = p^{i}_{Crop} \cdot d_{xy} \qquad [7]$$

Adding the deviation D_{xy} to the crop specific irrigation probability within the sub-region provided the local crop specific irrigation probability p^{xy}_{crop} for each 1ha cell.

$$p^{xy}_{Crop} = p^{i}_{Crop} + D_{xy} \qquad [8]$$

where p^{xy}_{crop} = Local crop specific irrigation probability at 1ha, p^{i}_{crop} = average crop specific irrigation probability within sub-region i, D_{xy} = local deviation from average irrigation probability.

We obtain a crop specific irrigation probability for each 1ha cell, respecting the distribution of crops within each sub-region, the percentage of crop area irrigated within each sub-region and the spatial patterns of irrigation densities as derived from the GMIA.

For each crop, the corresponding raster cells were extracted. From this set, cells were randomly selected. The cell was defined as ‘irrigated’ and assigned a value of 1, if a random number (from uniform distribution) was less than or equal to the local irrigation probability. Otherwise it was declared as ‘not-irrigated’ and assigned a value of 0. The procedure was repeated iteratively until the available irrigated area was distributed. Figure 3 is a graphical overview of the disaggregation procedure.

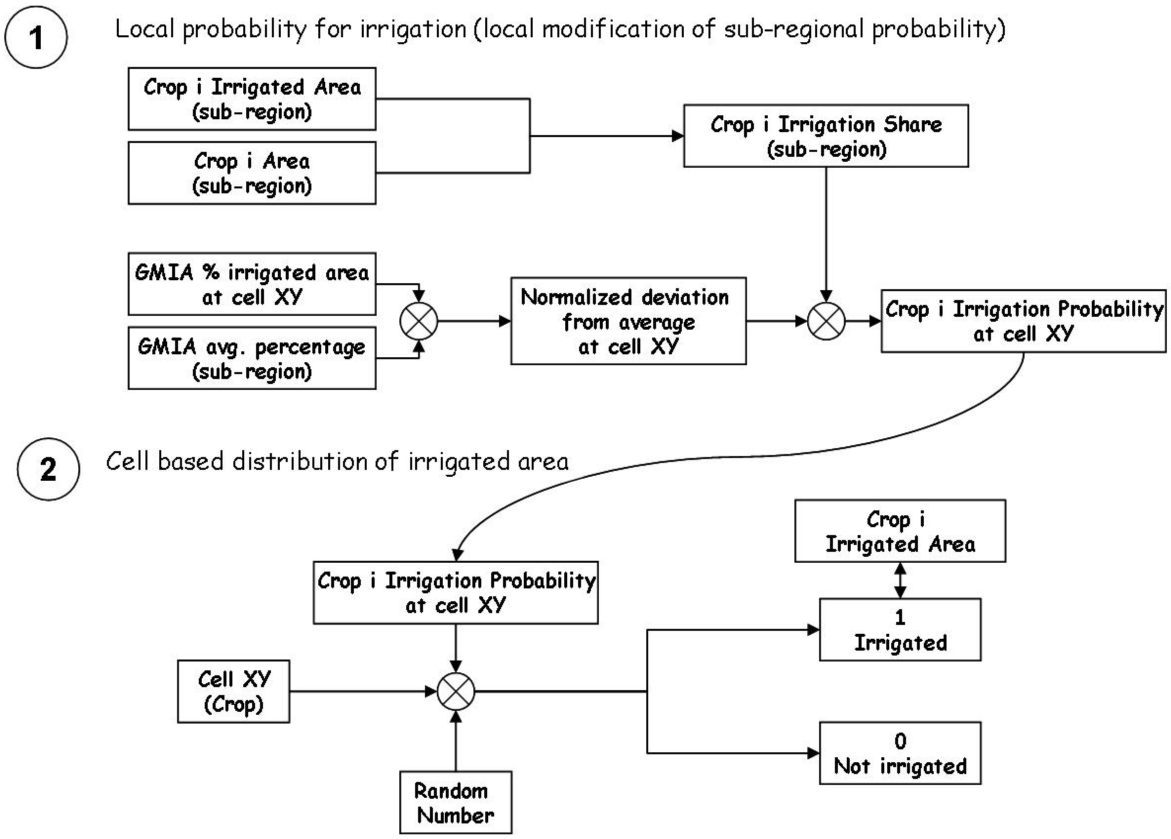


Figure 3: Generation of the European Irrigation Map (EIM)– Disaggregation scheme based on local deviation from average crop specific irrigation density

2.4 Calculating irrigation requirements

Based on crop growth and soil water and nutrient model EPIC, we estimate irrigation water requirements using the auto-irrigation option of the EPIC model. The simulations are carried out in a spatial framework (EAGLE tool) based on a 10x10 km raster covering the European territory.

2.4.1 The European Agrochemical Geospatial Loss Estimator (EAGLE)

The EPIC-EAGLE tool (Bouraoui & Aloe 2007) was developed to assess the fate of agrochemicals at EU level using readily available data. The components of the EAGLE tool are i) the EPIC model (Sharpley & Williams 1990, Williams 1995) simulating soil hydrology, nutrient cycling, and crop growth, ii) the EAGLE database holding all relevant input data to perform EPIC simulations at European scale (Mulligan et al. 2006), iii) a GIS interface providing all functionalities to apply the EPIC model at European scale and to access simulation results.

The elementary spatial units (‘Sites’) of the EAGLE modeling framework are defined by a 10x10 km raster covering EU and Switzerland. Each cell or site is assigned uniform climate and soil data. Each site is composed of crop specific subunits respecting the different crop categories and crop area within each site. The EPIC model is applied to these individual subunits. The runs for each site can be limited to the five predominant crops to save computation time.

Input data include (Bouraoui & Aloe 2007) meteorological data taken from the MARS database (Micale and Genovese 2004), soil data based on the European Soil Bureau Database (ESBD 2.0), the above mentioned European land use map, crop growth and management information from the European Crop Growth Monitoring System (Lazar and Genovese 2004) and crop growth parameters from Blackland Research and Extension Center provided with the EPIC model.

The crop categories defined in the LUM partly refer to individual crop species (for example maize, soft wheat) partly refer to crop categories grouping different species according to certain characteristics (for example, vegetables, fruit and berry orchards, and other). Generally, all crop categories have been associated with a 'characteristic' crop for modeling (Table 4).

Table 4: List of crop categories distinguished in the irrigation map and corresponding categories of the land use map

Nr	Crop categories distinguished in the irrigation map	Crop identifier(s) (corresponding to crop categories of the land use map)	Characteristic EPIC crop
1	Barley	BARL	
2	Citrus orchards	CITR	Citrus
3	Durum wheat	DWHE	Durum wheat
4	Flowers	FLOO, FLOI (Flowers and flowers indoor)	
5	Fodder maize	MAIF	Fodder Maize
6	Fruit and Berry Orchards	APPL	Apple
7	Grassland	GRAE, GRAI (rough grazings, pasture & meadows)	Summer pasture
8	Hops	HOPS	
9	Leguminous forage crops	LEFO	
10	Maize	MAIZ	
11	Medicine crops	MEDI	
12	Oats	OATS	
13	Olives	OLIV, TABO (Olives, Table olives)	
14	Other cereals	OCER	
15	Other crops	OTHR	
16	Other forage crops	OFAR	
17	Other forage crops other	OFAO	
18	Other industrial crops	INPO	
19	Other oil crops	OOIL	
20	Other permanent crops	NURS, OCRO, OCRG (Nurseries and other permanent crop)	
21	Potatoes	POTA	
22	Pulses	PULS	
23	Rape	RAPE	
24	Rice	RICE	
25	Roots and other fodder	ROOF	
26	Rye	RYEM	
27	Soft wheat	SWHE	
28	Soya	SOYA	
29	Sugar beet	SUGB	
30	Sunflower	SUNF	
31	Textile crops	COTS	
32	Tobacco	TOBA	
33	Vegetables	TOMA, OVEG (Vegetables and vegetables under glass)	Tomatoe
34	Wines	TWIN, TWIO, TARA, TAGR (Wine, raisins, grapes)	Grape

2.4.2 Soil hydrology and irrigation in the EPIC model

The EPIC model is composed of various sub-models including climate, soil hydrology, crop growth and nutrient cycling. Here we highlight only some key features relevant to the estimation of crop water requirements. For a detailed model description including model equations see Williams 1995.

A curve number approach is used to calculate surface runoff from precipitation. A storage routing technique simulates water flow through soil layers. All water exceeding field capacity percolates downward until field capacity is restored. Simultaneously, lateral flow from each layer is considered. The EPIC-EAGLE implementation uses the Penman-Monteith method (Monteith 1965) to calculate potential evapotranspiration, allowing plant specific transpiration to be taken into account. The potential plant transpiration is distributed to soil layers based on the depth of the root zone. If the soil water content in a layer is less than 25% of plant-available soil water, the actual transpiration is reduced accordingly. The phenomenological development of crops is based on a daily heat unit accumulation, affecting harvest date and senescence, leaf area growth, root depth and crop height, partition of biomass among roots, shoots and yield. Biomass is calculated from conversion of intercepted photosynthetic active radiation. Crop yield is determined using a harvest index concept. The harvest index determines yield as fraction of above-ground biomass. Water stress, nutrient stress and temperature stress can limit phenomenological development and crop growth.

The automatic irrigation option performs an irrigation operation when triggered by predefined thresholds. The trigger can be specified either as plant water stress level (0-1), plow layer soil water tension (kPa), or root zone soil water deficit (mm). The application rates equal the water deficit of the root zone respecting specified minimum and maximum application rates. The simulated irrigation can be interpreted as irrigation requirement. It is, however, necessary to take into account the effects of different irrigation strategies.

2.4.3 Model setup to estimate irrigation requirements

The automatic irrigation option was activated for all crops to implement demand-based irrigation scheduling and application rates. The irrigation controls of the EPIC models allow various irrigation strategies to be implemented and also in practice there are numerous options for a farmer to decide how and when to perform irrigation operations.

To evaluate the impact of irrigation strategy on yields and irrigation water use, we defined different irrigation strategies (the associated model settings are listed in Table 5):

- Irrigation strategy S0 assures optimum water supply, the soil water content is always kept at field capacity. This reference-scenario provides a theoretical maximum irrigation requirement.

- Irrigation strategies S1, S2 and S3 trigger irrigation based on a soil water deficit of 50, 100 and 150 mm respectively.
- Irrigation strategy SX implements a non-irrigation strategy.

For each modeling site (i.e. 10x10km grid cell) the irrigated area per crop category was determined based on the European Irrigation Map (EIM). To save computation time, the EPIC-EAGLE model was run for the 5 dominant irrigated crops at each site only. We assumed that irrigation requirements of the remaining crops will not considerably affect average requirements per site. The results were then rescaled according to the total irrigated area of each site. The simulations comprised a period of 8 years using climatic data from 1995-2002 taken from the MARS climatic database. The irrigation requirement (in mm) at each site is the area-weighted average net irrigation requirement of these five crops. The irrigation demand (m3) per site was derived from the irrigation requirement (converted from mm to 1000 m^3/ha) by multiplying the requirement with irrigated area (ha).

Model results extracted include annual values and average annual values of yield (t/ha), biomass production (t/ha), precipitation (mm), potential evapotranspiration (mm), actual evapotranspiration (mm), surface runoff (mm), subsurface runoff (mm), percolation, irrigation (mm) and water stress (days).

Table 5: Relevant EPIC parameter settings implementing different irrigation strategies defined for the EPIC-EAGLE simulations

EPIC Parameter	Scenario	S0	S1	S2	S3	SX
	Description	No water deficit	Low water deficit	Moderate water deficit	High water deficit	No Irrigation
BIR BIR < 0 0 < BIT < 1	Irrigation trigger : soil water deficit [mm] : water stress factor [-]	1.0	-50	-100	-150	-
EFI	Runoff Fraction [-]	0	0	0	0	-
ARMN	Minimum application rate [mm]	1	40	90	140	0
ARMX	Maximum application rate [mm]	150	60	110	160	0

2.4.4 Generating the final result set

We generated a final result set, selecting the optimum irrigation strategy per crop and per site from the different irrigation strategies based on the average annual irrigation requirements and crop yields. The optimum strategy should provide high yields while having the lowest possible water requirement. For each site and crop category, we selected all strategies with a crop yield at least 80% of the maximum crop yield and from this set chose the strategy with the lowest irrigation requirement as final strategy.

This procedure assured that unproductive strategies generating yields far below the maximum yield were excluded from the analysis. At the same time, some flexibility was given to retain strategies with yields close to the maximum but with probably different irrigation requirements. Finally, new result tables were created based on the final strategies selected per site and crop. In addition to the average results, we extracted simulation results for the years with minimum and maximum irrigation requirements (and calculated irrigation water demand and abstractions accordingly) to analyze the range of irrigation requirements during the simulation period.

2.4.5 Treatment of specific cropping systems - Rice production

The EPIC modeling approach can not represent irrigation of rice. In Europe, rice is dominantly grown in flooded fields. In addition to evapotranspiration, a considerable amount of water is lost by percolation from the flooded field and the true application rates are highly dependent on local soil conditions (hydraulic conductivity) and management practice. Rice cultivation requires water applications in the range of 1500 to 5000 mm (Table 6), depending on local conditions. Given these irrigation rates, rice cultivation has a considerable impact on the regional water demand. While the lower range of reported irrigation values corresponds to crop evapotranspiration, the higher range of values refers to soils with considerable percolation losses. The infiltration and percolation from a flooded field can not be represented by the EPIC model. Therefore we provisionally assigned a constant irrigation requirement of 3500 mm to rice crops, which is in the upper range of the reported values.

Table 6: Water use in rice cultivation

Irrigation depth (mm)	Region	Comment	Source
4492	Andalusia, Spain	Traditional flooding management	Aguilar & Borjas, 2005
2921	Andalusia, Spain	Optimised flooding strategy	Aguilar & Borjas, 2005
2300	Camargue, France		Chauvelon, 1996
2100-5000	Camargue, France	Cooperative systems	Chauvelon et al., 2003
1500 – 3000	Camargue, France	Private systems	Chauvelon et al., 2003
1590	Aragon, Spain	Model estimation	Nogues & Herrero, 2003

2.5 From water demand to potential water abstractions

Irrigation requirements (or irrigation water demand) constitute only part of the total water abstracted for irrigation purposes. The actual amount of water drawn from the water bodies is generally higher than the water required by plants for transpiration. Additional water abstraction results from the need to compensate for losses during transport (infiltration and percolation or evaporation), the need to apply water in excess to prevent salinization (‘leaching fraction’) and the water use efficiency of the irrigation method. Statistical information on irrigation refers to water abstractions for irrigation or agriculture rather than irrigation water use at field level. Therefore water losses and efficiencies of irrigation systems must be taken into account, comparing model results with statistics.

The **irrigation efficiency (water use efficiency)** expresses the ratio of irrigation water used efficiently by plants (for evapotranspiration) to the amount of water supplied or abstracted. The **scheme irrigation efficiency (es)** is that part of the water pumped or diverted through the irrigation scheme inlet which is used effectively by the plants (Brouwer et al. 1989), being composed of **conveyance efficiency (ec)** and **field application efficiency (ea).** The field application efficiency mainly depends on the irrigation method and the level of farmer discipline. Some indicative values of the average field application efficiency are given in Table 7. The conveyance efficiency mainly depends on the length of the canals, the soil type or permeability of the canal banks and the condition of the canals. Some indicative values of the conveyance efficiency are given in Table 8. Once the conveyance and field application efficiency have been determined, the **scheme irrigation efficiency (es)** can be calculated, using the following formula:

$$es = ec \cdot ea \qquad [9]$$

The irrigation efficiency can be used to estimate potential water abstractions for irrigation if the irrigation demand is known:

$$WA = \frac{1}{es} \cdot IWD \qquad [10]$$

where WA = potential water abstraction (m^3), es = scheme irrigation efficiency (-), IWD = irrigation water requirement (m^3).

Starting in 2003, a survey of irrigation methods was included in the Farm Structure Survey, reporting the area covered by specific irrigation methods (surface irrigation, sprinkler irrigation, drip irrigation and mixed methods). The results for 2003 were provided by Eurostat at regional level (NUTS 2). We assumed that the ratio of irrigation methods is comparable to the FSS 2000, which forms the basis for estimating crop areas in this assessment. It should be mentioned, however, that there is a general trend of replacing surface irrigation by sprinkler or drip irrigation.

The regional application efficiency was calculated as average efficiency of the indicative application efficiencies in Table 7 weighted by the percentage of irrigated area covered by the individual methods.

There are no simple rules of thumb to estimate conveyance efficiency at regional scale due to the possible diversity of irrigation schemes, differing in size, irrigation infrastructure, maintenance, management etc. Supporting data at European scale are lacking. As indicative values, we used the minimum efficiency of 0.6 and the maximum efficiency of 0.95 of all values given in Table 8.

We calculated the resulting scheme irrigation efficiency and determined minimum and maximum irrigation water abstractions per site and per region. The regional values were applied uniformly to each site within each region, as currently no further assumptions on the spatial distribution of irrigation methods below regional level could be made. The resulting scheme efficiencies at regional average range from 0.36 to 0.85, meaning that irrigation requirement or demand is multiplied with a factor (1/es) in the range of 2.78 to 1.17 to estimate potential water abstractions.

Table 7: Indicative values for field application efficiency (ea) by irrigation method (Brouwer et al. 1989)

Irrigation methods	Field application efficiency
Surface irrigation (border, furrow, basin)	0.60
Sprinkler irrigation	0.75
Drip irrigation	0.90

Table 8: Indicative values of conveyance efficiency (ec) for adequately maintained canals (Brouwer et al. 1989)

	Earthen canals			Lined canals
Soil type	**Sand**	**Loam**	**Clay**	
Canal length				
Long (> 2000m)	0.60	0.70	0.80	0.95
Medium (200-2000m)	0.70	0.75	0.85	0.95
Short (< 200m)	0.80	0.85	0.90	0.95

2.6 Comparison with observed data

National statistics on water abstractions for irrigation and agriculture (OECD/Eurostat Joint Questionnaire on Inland Waters) were compared with irrigation requirements and with potential water abstractions assuming high and low irrigation scheme efficiency. Another comparison was made with regional water abstraction data from France (Agences de l'Eau – Ifen (Institut Français de l'Environnement), 2007). Due to its geographical extent, the French data set includes Mediterranean agricultural systems as well as the rain-fed agricultural systems of Western and Central Europe. National and regional water abstraction data were expressed as ‘Statistical irrigation’ in mm/yr. The statistical irrigation was calculated dividing reported water abstractions by reported irrigated area. Accordingly, the simulated irrigation was calculated dividing the regional (national) irrigation demand by regional (national) irrigated area.

3 The European Irrigation Map

3.1 *Spatial distribution of irrigated areas and comparison to the Global Map of Irrigated Areas*

The resulting European Irrigation Map (EIM) is a binary data set (1 = irrigated, 0 = not irrigated) of 1ha resolution, complementing the LUM. The overlay of both maps provides a map of irrigated crop areas (and non-irrigated crop areas). Figure 5 provides an overview on irrigation intensity in the EU, summarizing irrigated areas for raster cells of 10x10km. The Map displays very well the focal areas of irrigation in Southern Europe (for example, the Po plain, the Guadalquivir, the Ebro basin, smaller plains in Southern Italy and Greece). In Central and Northern Europe a belt of irrigated areas extends from France to the Benelux-Countries and Denmark.

The general distribution patterns are consistent with the GMIA and provide a considerable improvement to the statistical data on irrigated area available at sub-regional (NUTS 3) level (Figure 6). Deviations to the GMIA occur in detail. In many regions, the irrigated areas in the GMIA are more clustered while the distribution is more disperse in the EIM. This is an effect of the disaggregation procedure of the EIM that theoretically allows assigning irrigated area anywhere within each NUTS3 region (though conditioned on crop distribution and irrigation intensity), while in the GMIA many areas are explicitly un-irrigated.

Given the constraints of the land use map and the GMIA distributing irrigated areas within each sub-region, we think that a reasonable distribution is achieved for modelling units larger than 100km^2 (10x10km), while at smaller units the location of irrigated areas (and land use as well) is randomly determined and therefore uncertain. As the EIM is not a mapping of true irrigated areas, the map should not be used to extract information for small scale assessments. Total irrigated areas match statistical information at sub-regional level (NUTS3).

We present details of the irrigation map for the provinces Seville (Spain, Figure 7), Argolida (Greece, Figure 8) and Noord-Brabant (Netherlands, Figure 9). The details show the distribution of irrigated areas, the distribution of selected crops and the extraction of the corresponding crop specific irrigated area overlaying the EIM and the LUM. In some areas, the spatial resolution (5’ cells) of the GMIA is partly imprinted in the distribution patterns of the EIM (Figure 7). This is the case where the crop distribution patterns do not change significantly over large areas and distinct changes in irrigation density are given in the GMIA. In other regions, crop distribution patterns override and dissolve the patterns of the GMIA. As said before, global maps provide consistent information at the highest available resolution for assessment of large geographical areas (a grid resolution of 5’ equals a grid size of 9.2 x 7.1 km at 40º latitude). Despite some artefacts in the distribution patterns, consideration of the GMIA information allowed to increase the accuracy of the spatial distribution within each sub-region.

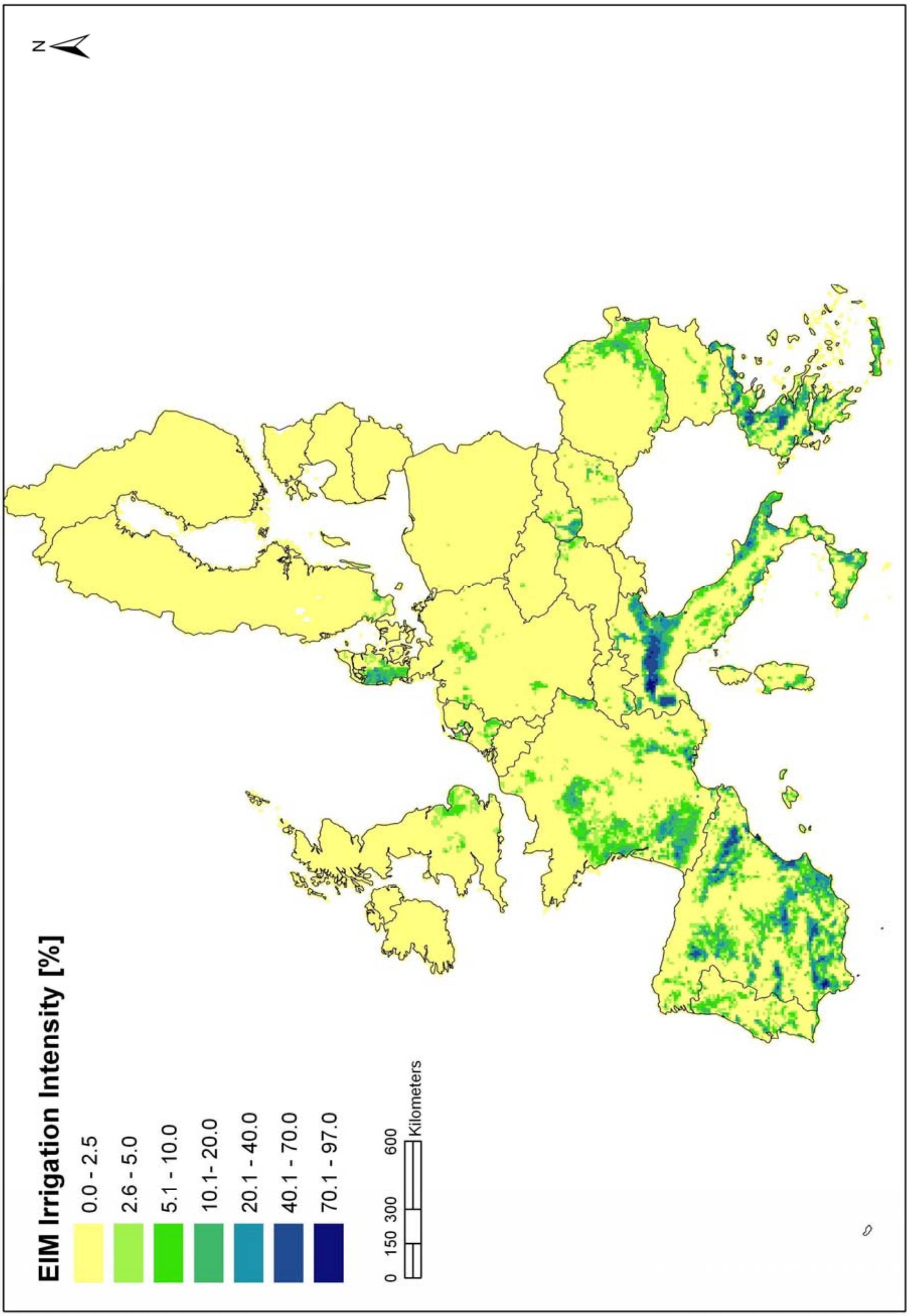


Figure 5: European Irrigation Map (EIM) - Irrigation intensity in the EU as irrigated area in % of total area calculated over a 10x10km raster. NB: the regions shown are at the NUTS 2 level.

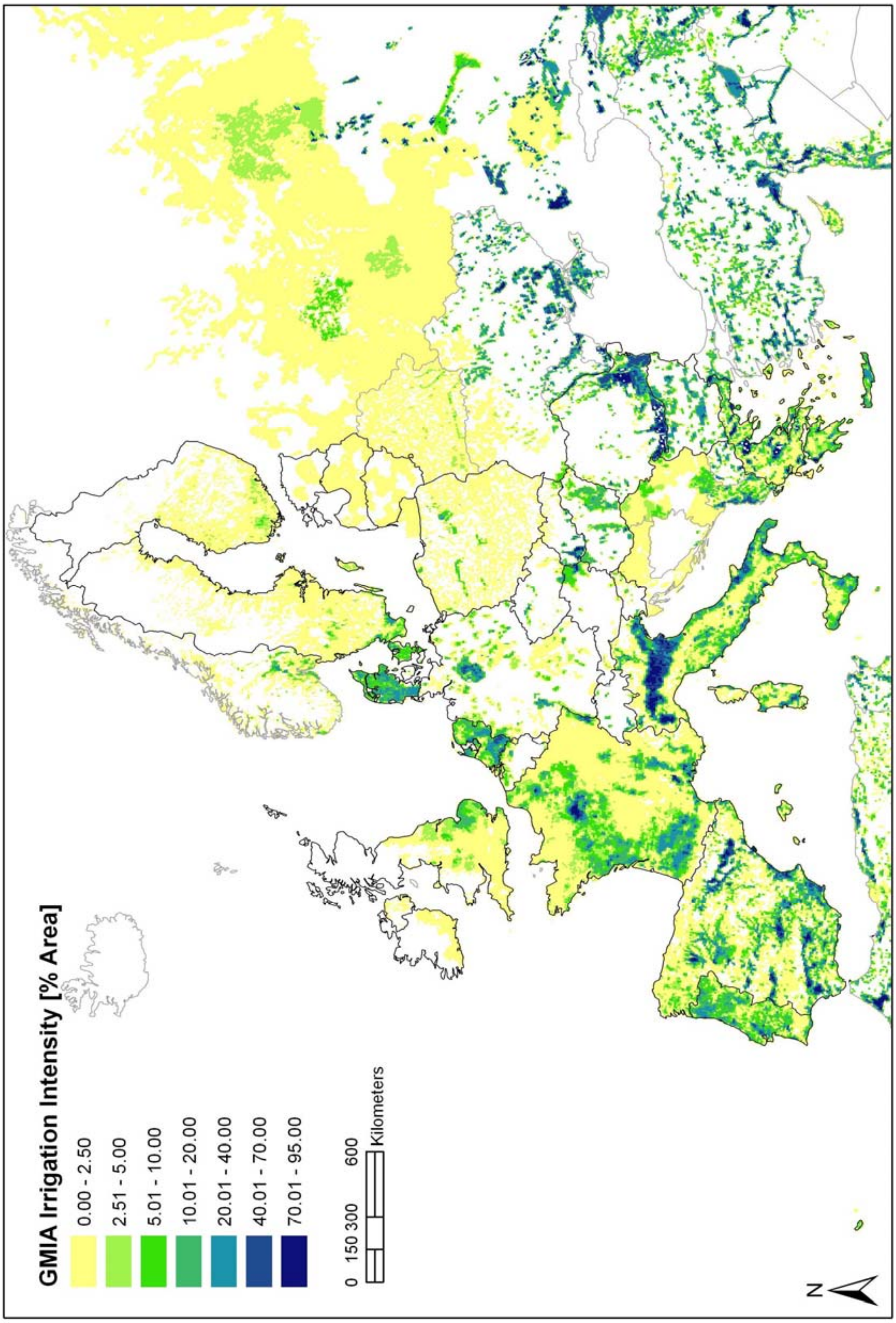


Figure 6: Global Map of Irrigated Areas (Siebert et al. 2007) - Irrigation intensity in the EU as area equipped for irrigation in % of total area by 5' cell.

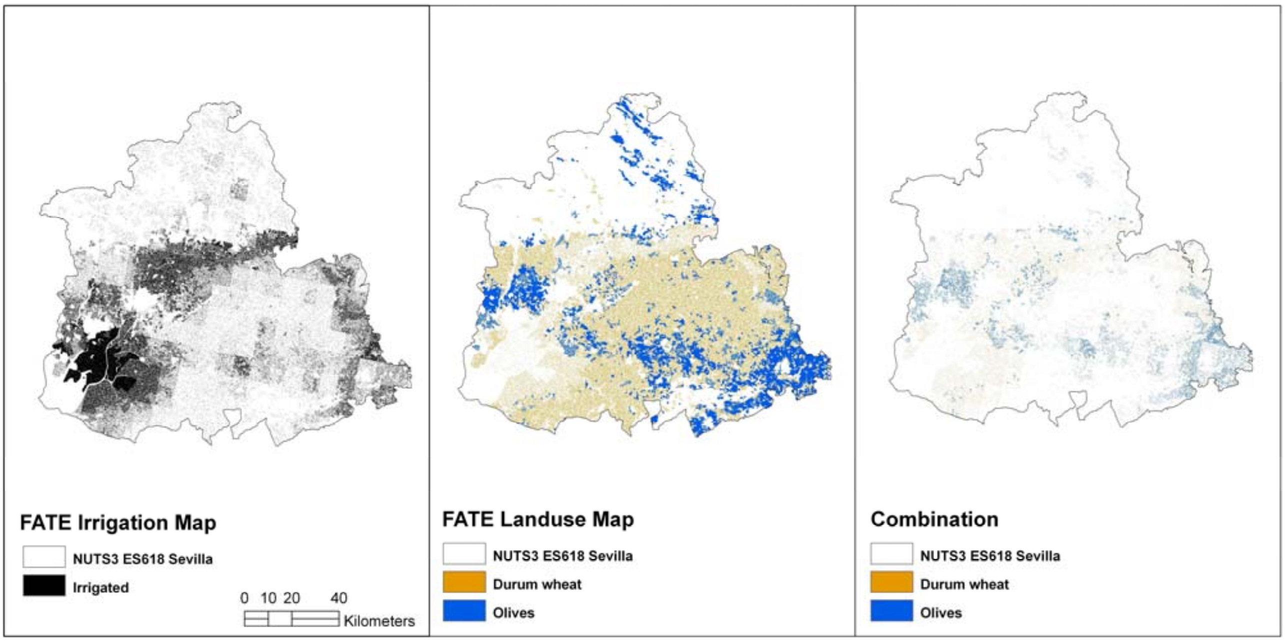


Figure 7: Distribution of total irrigated area (left), crop area of cotton, durum wheat and olives (middle) and irrigated area of cotton, durum wheat and olives (right) in the province of Seville, Spain.

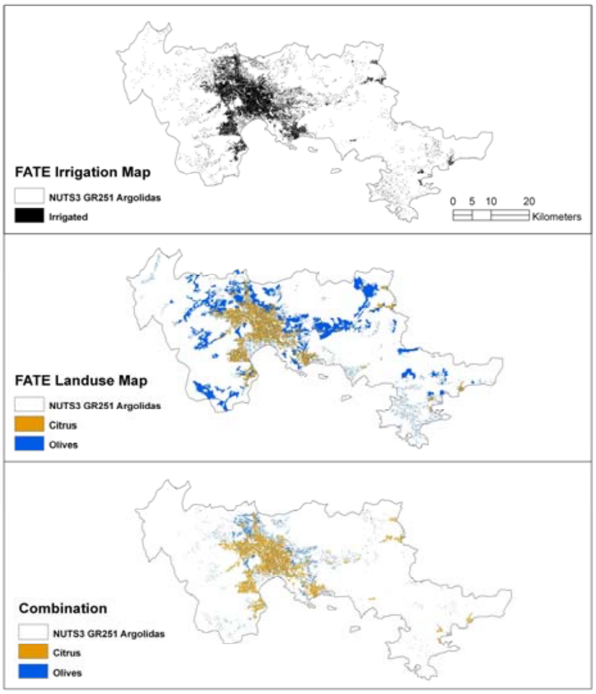


Figure 8: Distribution of total irrigated area (top), crop area of citrus and olives (middle) and irrigated area of citrus and olives (bottom) in the province of Argolida, Greece.

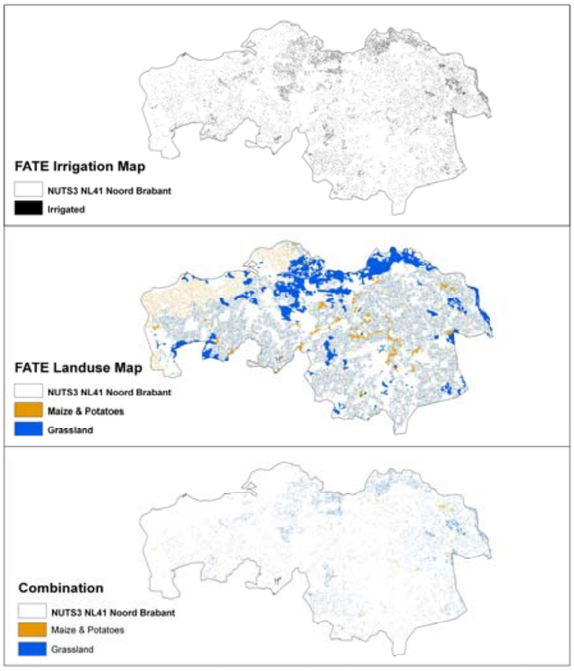


Figure 9: Distribution of total irrigable area (top), crop area of maize/potatoes and grassland (middle) and irrigable area of maize/potatoes and grassland (bottom) in the province of Noord-Brabant, Netherlands.

3.2 Discussion of the European Irrigation Map

The European Irrigation Map (EIM) displays irrigated areas in EU27 and Switzerland. It was developed as an input dataset for large-scale modelling purposes consistent with the underlying land use information. The map matches regional statistics on irrigated areas and was further conditioned on the distribution of irrigated areas given in the GMIA. The specific function of the dataset in our research is to extract crop specific irrigated areas for agricultural modelling at large scale. Due to the high map resolution of 1 ha, irrigated areas can be aggregated for any type of modelling units. Modelling units may refer to administrative regions, catchments or other natural boundaries or raster cells, depending on the modelling approach.

Although different data sources were used to generate the map, a choice was made to match the statistical information rather than trying to lump all information together, achieving a ‘best fit’ to all sources. Statistical data are the only source assessed regularly and that can easily be used in an operational context regularly updating the irrigation map. The current release of the EIM applies a mix of irrigation data from 2000 and 2003. The underlying land use distribution was based on 2000 data. Actually irrigated areas may change from year to year (extending in dry years and contracting in wet years) and general agricultural trends may result in changes of irrigated areas. The possibility to generate new versions based on easily accessible sources is therefore a promising option not only to visualise irrigation trends in space but also for related model applications. The approach presented here is a prototype for the generation of subsequent maps, based more consistently on data from specific years and surveys.

The distribution of irrigated areas to crop categories is straightforward. Priority was given to statistical data if available. In a second step, the priority factor approach proved a simple and flexible method allowing including qualitative information based on surveys, expert judgement and statistical relations to substitute missing data. Starting from priority factors derived from global regression analysis, subsequent regionalization allowed considering qualitative information on regional and crop specific irrigation practices. The present survey of regional irrigation practices includes only few additional (though important) crops. For most crop categories little or no information on irrigated areas and irrigation practices was available and the setting of priority factors includes various assumptions. For those crop categories were quantitative information was not available, discrepancies between true and assigned irrigated area are likely. Further assessments on crop specific regional irrigation practices are needed to complete and extend the underlying information, which will be part of future research.

Portmann et al. (2008) released a global map of irrigated crop areas (MIRCA 2000), that includes 26 crops and was compiled from various statistical data sources and spatial datasets, including GMIA, SAGE cropland extent and harvested areas (Monfreda et al., 2008). In Europe, statistical information on irrigated areas was included at national level. For crops not included in statistics, crop irrigation shares in MIRCA were defined at national level based on expert judgement and literature survey. Of the 26 crop classes contained in the MIRCA data set, 15 crop classes can directly be related to EIM crop categories (wheat, maize, rice, barley, rye, soya, sunflower, potatoes, sugar beet, rapeseed, pulses, citrus, vine, cotton, grassland). Of those, 9 crop classes are covered by European statistics on irrigated areas and 4 categories (rice, cotton, rapeseed, pulses) are covered by the regional survey of irrigation practices. For three crops (rye, barley, grassland), the distribution in EIM was based entirely on the priority factor approach.

We made a qualitative comparison of large scale crop distribution patterns for selected crops to evaluate the general consistency of both data sets. We found similarities as well as differences. For example, potato, sugar beet and maize have consistent distribution patterns in both maps. Local deviations in distribution patterns exist caused by different underlying data, the different disaggregation procedures and different soft information and expert knowledge included to fill data gaps. In some cases (as for sugar beet, citrus and grapes), we found that irrigated areas are more concentrated in the EIM (following general irrigation intensity), while they are often more dispersedly distributed in the MIRCA dataset. Portmann et al. 2008 indicate the need to increase the density of spatial entities to improve consistency with regional statistics.

The example of barley combines some of the issues raised in a very illustrative way. In Spain, the focal areas are displayed in both data sets. Both data sets reflect the concentration of barley in the main agricultural (and irrigated) areas of Spain. In France, MIRCA has a rather disperse distribution of barley irrigation, while it is more focused around the Ile-de-France in EIM. In Germany, there is no barley irrigation in MIRCA, while we accepted low priority irrigation in the EIM. A focal area at the border triangle of Czech Republic, Slovakia and Hungary is present in EIM but not in MIRCA, were again a more disperse distribution in Slovakia and Hungary is given. This may be due to differences in the underlying land use distribution but also a result of the assignment of irrigated area to barley in these regions (priority factors) or the different disaggregation procedures.

The distribution of irrigated areas for potatoes, sugar beet and barley are shown in Figure 10. The distribution patterns of maize, citrus and grapes were already compared with Eurostat regional statistics by Portmann et al. (2008) and are not shown here, as the EIM was based on Eurostat regional and sub-regional data and results are therefore similar.

A qualitative comparison of irrigated crop areas was made for potatoes, sugar beet and barley (Figure 11). For potatoes and sugar beet, irrigated crop areas correspond quite well, due to the availability of national and regional statistics. Minor deviations are most likely caused by using data from different years in MIRCA and EIM and possible minor adjustments in the EIM distribution algorithm. Larger deviations were found for potatoes in Germany, Portugal and the United Kingdom, where the irrigated area of MIRCA is much higher than in the EIM. The priority factor approach was applied in Germany and UK assigning already a high priority factor of 10, while for Portugal regional statistics were available. For sugar beet large deviations were found in Germany, where the irrigated area is much smaller than in MIRCA. This may indicate that the irrigation priority of 1 assigned in Germany is too low and should be set to a higher value. For barley, inconsistencies were much more pronounced, which is not surprising given that the distribution is based on soft knowledge rather than statistical data.

It can be concluded that the EIM achieves a higher degree of spatial differentiation, as it was based on regional and sub-regional statistics. The MIRCA data set starts the disaggregation procedure at national level (in Europe) and a different cropland distribution (SAGE) is applied as well. This can cause major deviations; the highest agreement is achieved, if crop distributions are similar and crop areas are closely related to irrigated areas (for example maize, potatoes). Quantitative agreement depends on the availability of statistical information included in the data sets.

The data set bridges a gap between global information sources and detailed regional data. The generalized information of global data sets such as the GMIA and the GIAM is extended by crop specific information, adapted to official European statistics and providing a higher resolution not restricting the analysis to a spatial concept determined by the input data sources. Good detailed regional data may exist in some areas but are lacking in others. They are also difficult to collect into a data set of large geographic extent.

Applications of the dataset may focus on large scale assessment of crop yields, irrigation requirements and environmental impacts of irrigated agriculture: Regional crop yield data are weighted averages of irrigated and non-irrigated crop areas and therefore relations between yield and irrigation shares exist as demonstrated for regional data in Greece (Figure 12). Such effects may be less visible where irrigation is less important or other factors override the irrigation effect (see for example region GR23 in Figure 12). Nevertheless, a prior estimate of irrigated and non-irrigated fractions of crop area can considerably improve yield estimations. Also for estimating irrigation water use and resulting water abstractions, the irrigated area is required to calculate total volumes of water applied or abstracted for irrigation.

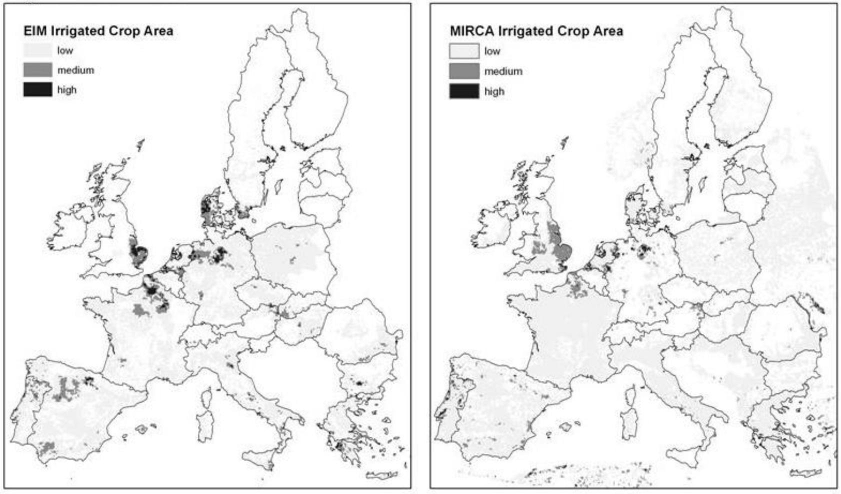
In addition to general uncertainties inherent to the survey methodologies and reporting of the data, additional sources of uncertainty need to be taken into account.

The map does not allow conclusions on the intensity of irrigation and the irrigation water use, as those depend on crop specific water requirements, irrigation practices, climatic conditions and economic aspects. Irrigation practices differ considerably in Europe. In large parts, agriculture is generally rain-fed and irrigation is only temporarily used to overcome water shortages during summer optimizing crop yields. Especially in areas of highly industrialized agriculture fields are frequently equipped with irrigation facilities, even if not permanently used. In Southern Europe irrigation is a substantial part of agriculture to maintain crop production, supplementing insufficient rainfall during the growth season. There is, however, also a trend to extend the irrigated area, also by shifting traditionally rain-fed agricultural systems to irrigation. Main improvements of the irrigation map depend on the development of the statistical information. Apart from improving the general accuracy of the data and consistency in reporting, a general availability at sub-regional (NUTS3) level or higher would be desirable. The consideration of additional crop types or crop categories (for example reporting irrigated areas for arable crops, permanent crops and grassland) would help to improve the crop specific distribution of irrigated areas. Since 2003, the FSS includes also information on irrigation methods (surface, sprinkler and drip irrigation and mixed types) and sources of irrigation water (groundwater, surface water, public supply, mixed sources) expressed as irrigated area covered by each class. This information may be used to further develop the irrigation map adding additional data layers.

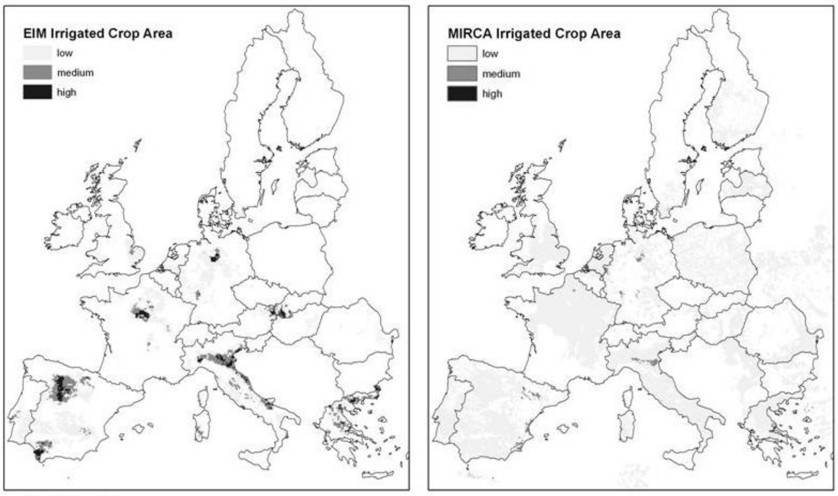
Further development of the European Irrigation Map is focusing on extending the underlying data base and collection of further country and crop specific information. Another focus will be the development of an operational framework for regular updates of the irrigation map (and the underlying land use map) in line with the Farm Structure Surveys to track temporal changes in land use and irrigated area.

The presented European Irrigation Map (in combination with the underlying land use map) is an example how different spatial data sources can be merged and integrated to serve specific needs and data requirements for modelling purposes. The methodology can be easily adapted to other land use classifications and maps, allowing adaptation for applications in different regions of the world.

a) Potatoes



b) Sugar beet



c) Barley

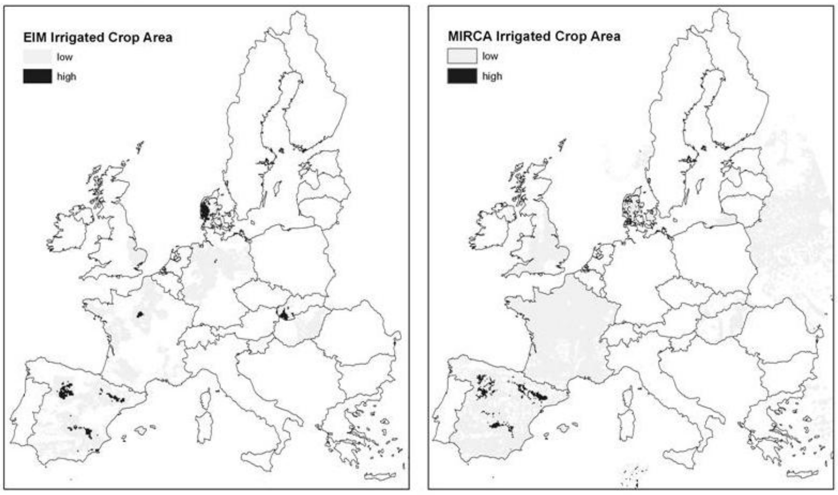
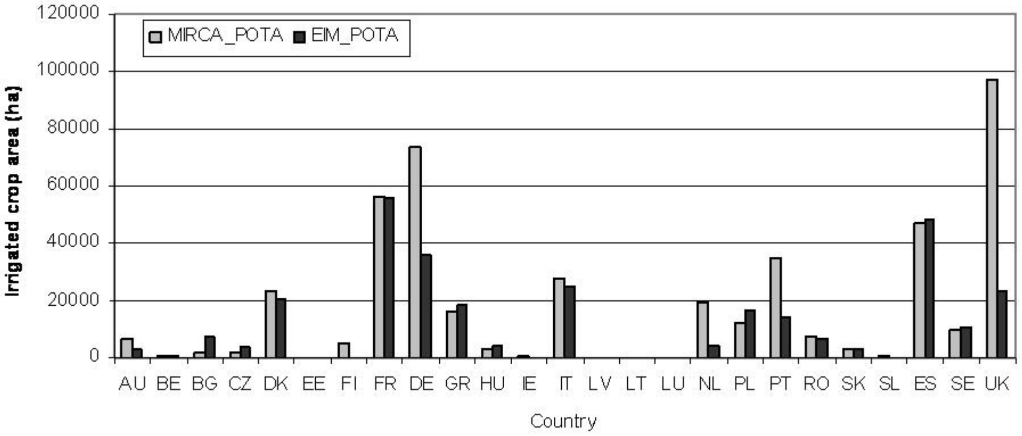
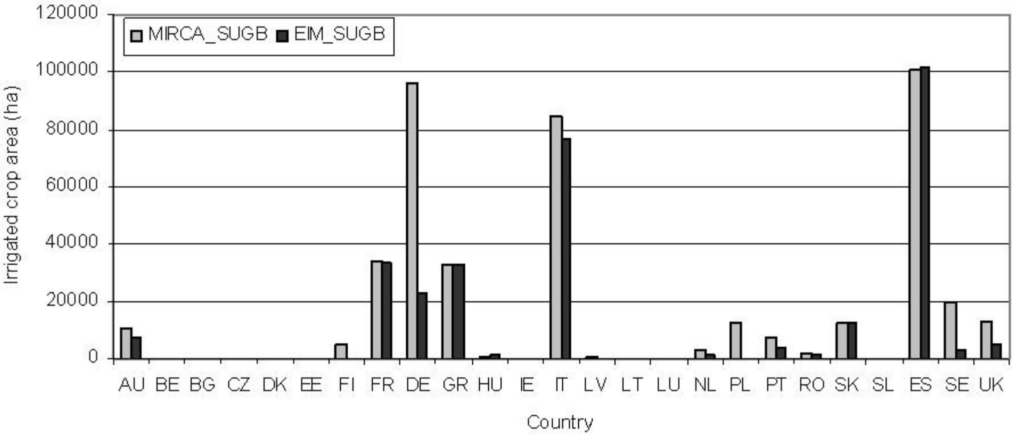


Figure 10: Comparison of the distribution of irrigated crop areas between EIM and MIRCA for potatoes (top), sugar beet (middle) and barley (bottom). Distribution patterns are displayed as classes of low to high concentration of irrigated crop areas distinguished by ‘natural break’ classification of irrigated crop area per spatial unit (EIM: 10x10km cell grid, MIRCA: 5’ raster grid).

a) Potatoes



b) Sugar beet



c) Barley

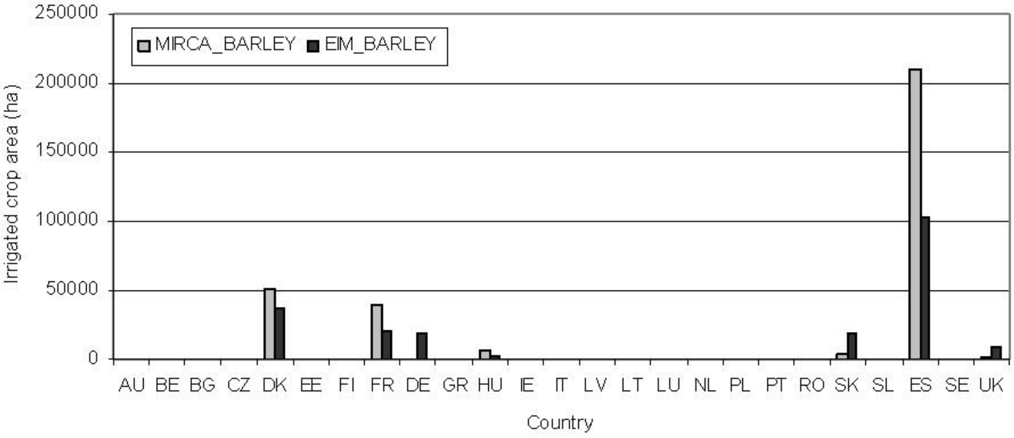


Figure 11: Comparison of irrigated crop areas at national level between EIM and MIRCA for potatoes (top), sugar beet (middle) and barley (bottom).

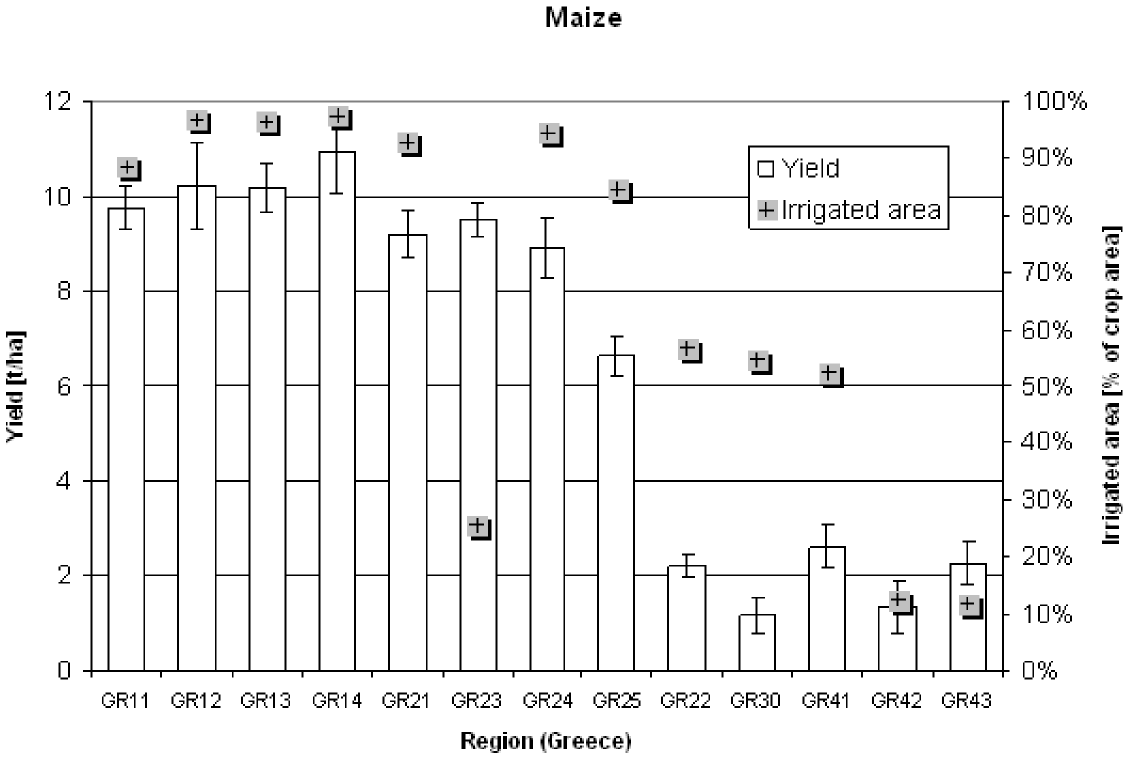


Figure 12: Average Maize yields (1991-2003) and irrigated area of maize (as percent of total maize area) for regions in Greece (Source: Eurostat).

4 Irrigation requirements in Europe

4.1 Effect of irrigation strategies

Irrigation strategies have different effects on crop yield, biomass and net irrigation requirement (Table 9). For simplification we present average results of irrigation (Figure 11) and yield reduction (Figure 12) for different crop regions (Figure 1).

Irrigation requirement (Figure 11) decreases from strategy S0 in the order S1, S2, S3, SX, according to the higher water deficit required to trigger irrigation. For example, in the Mediterranean crop region, irrigation requirements range from 1220 mm/yr (S0) to 171 mm/yr (S3). The first step from S0 (soil water content maintained at field capacity) to S1 (allowing water deficit of 50 mm) cuts irrigation requirements by roughly speaking 50%. In the Mediterranean the reduction is from 1220 mm/yr to 886 mm/yr). The absolute irrigation requirements are highest in the Mediterranean and lowest in the boreal crop region, reflecting the general climatic characteristics of these regions.

Crop yields (Figure 12) are given as relative change with respect to crop yield in irrigation strategy S0, averaged over all crops and the entire crop region. The decrease of yields from strategy S0 to SX is highest in the Mediterranean (81%), while the decrease is less than 20% in the Atlantic, Alpine and Boreal crop regions. This reflects the substantial requirement for irrigation in the Mediterranean agriculture, while the other parts of Europe receive sufficient rainfall for crop cultivation. Except for the Mediterranean, strategy S1 provides higher yields (in average) than strategy S0 reflecting negative effects of soil aeration and nutrient stress. The yield reduction of S1 and S2 compared with S0 is generally below 10%, except for the Mediterranean region (16%). The results demonstrate that exceeding a certain amount of irrigation does not substantially increase crop yields while considerable water savings could be achieved (with respect to S0) with no or little yield reduction. This finding supports the idea of applying deficit irrigation practices (FAO 2002) to enhance water savings in agriculture. It is also a strong argument for a consequent irrigation planning based on soil moisture monitoring and adaptation of water application rates to soil moisture and weather forecasts.

The findings suggest that especially irrigation strategies S0 and S1 apply irrigation water in excess. This can be explained when reviewing some concepts of soil water modeling: Crop evapotranspiration falls below the potential rate only after falling below a limiting soil water content, which lies below field capacity (Shuttleworth 1992). To maintain crop production it is therefore not necessary to fill soil water storage up to field capacity and some elasticity of water requirement has to be taken into account. Strategies S2 and S3 seem to be the most appropriate strategy in a general sense, although other strategies were favored locally.

Providing a selection of defined irrigation strategies can not cover all possible combinations of scheduling and application rates. It is also likely that actual irrigation strategies are not related to the strategies suggested by the model, as management practices also depend on irrigation technology, education and habits, and economic aspects. With respect to our focus on a large scale overview on irrigation requirements, we consider this limitation to be acceptable.

Table 9: Comparison of irrigation strategies: relative yield change with respect to irrigation strategy S0 and irrigation requirement (mm/yr) by crop region.

Yield change compared with S0	**S0**	**S1**	**S2**	**S3**	**SX**
Mediterranean	0	-0.04	-0.16	-0.66	-0.81
Alpine	0	0.01	-0.02	-0.09	-0.15
Continental	0	0.01	-0.01	-0.13	-0.26
Atlantic	0	0.05	0.01	-0.10	-0.16
Boreal	0	0.05	0.05	0.00	-0.02
Irrigation (mm/yr)	**S0**	**S1**	**S2**	**S3**	**SX**
Mediterranean	1220	886	724	171	0
Alpine	456	189	127	59	0
Continental	569	273	205	105	0
Atlantic	521	215	147	54	0
Boreal	355	148	96	42	0

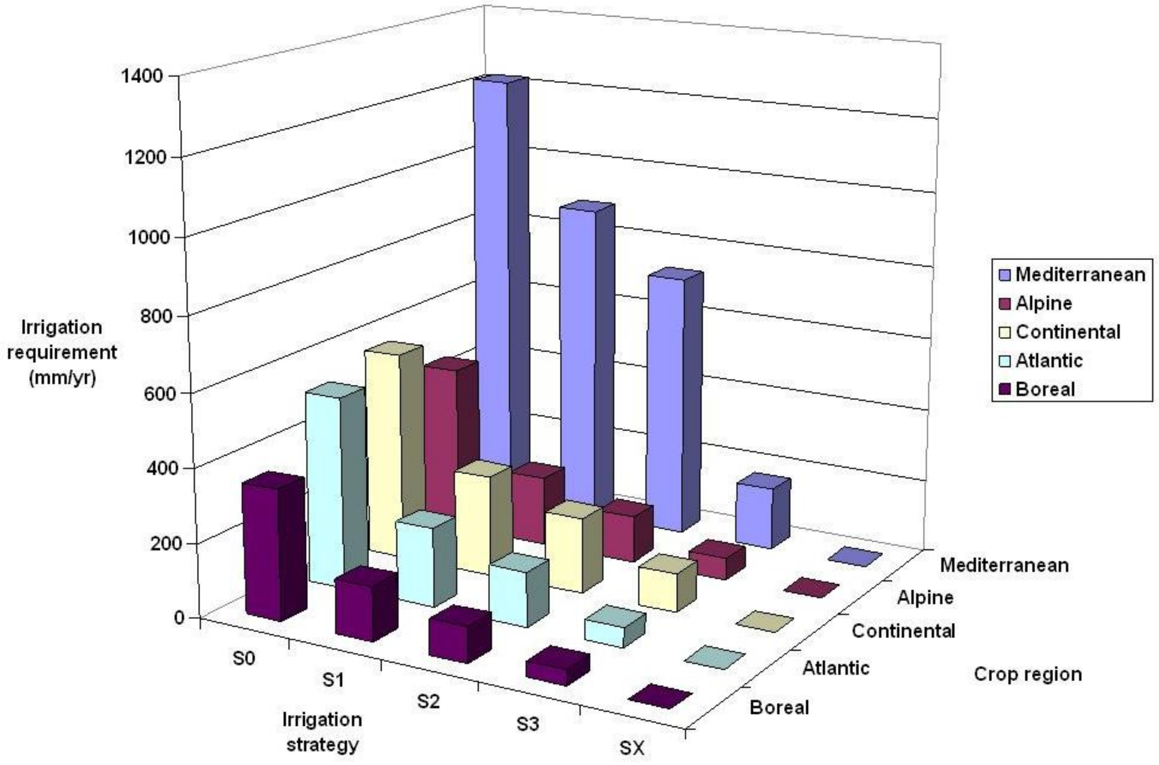


Figure 11: Average irrigation requirement for different irrigation strategies and crop regions.

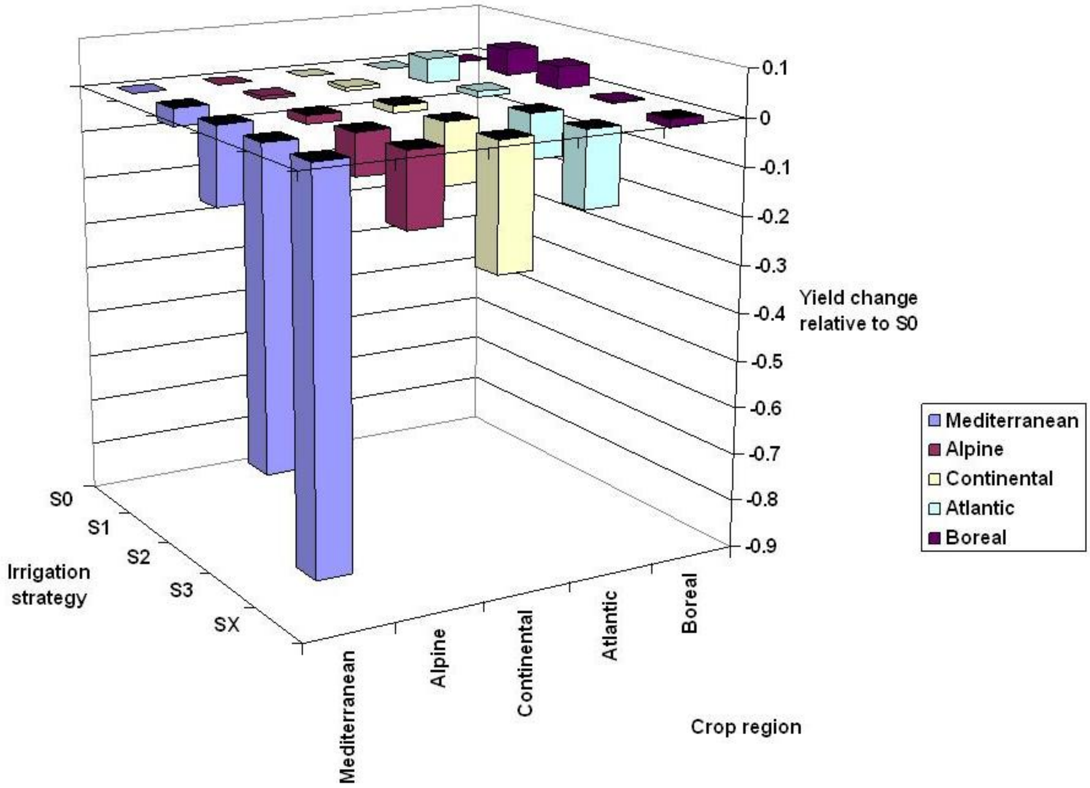


Figure 12: Average yield for different irrigation strategies and crop regions (given as relative yield to irrigation strategy S0).

4.2 Irrigation requirements

We determined an optimum strategy per site and crop for generating the final result set. The spatial distribution of the selected irrigation strategies is displayed in Figure 13. The frequency is given by the number of crops irrigated with a specific strategy divided by the total number of crops simulated per site. Strategies S0 and S1 are only marginally relevant with very limited distribution. Strategy S2 and S3 were the most frequently chosen strategies and are distributed all over Europe. The average irrigation requirements in the final result set are displayed in Figure 14. They are not only determined by climatic conditions, but result from the interplay of climate, soil properties and crop composition at each site. The general patterns reflect well the different irrigation requirements in Northern and Southern countries, though at smaller scale complex patterns exist reflecting specific local conditions. Cross-cutting geographical locations, crop types and local soil and climate, the average site irrigation requirements range from 0 mm/yr up to 2368 mm/yr (including correction for rice cultivation).

Multiplying irrigation requirements by irrigated area yields the irrigation demand (Figure 15), which we defined as the volume of irrigation water required within a defined spatial unit (here: 10x10 km site). The spatial patterns therefore do not only reflect the irrigation requirements, but also the distribution of irrigated areas.

During the 8-year simulation period, irrigation requirements varied considerably (Figure 16) reflecting inter-annual variability of climatic conditions. The highest ranges (exceeding 600 mm) were observed in Southern Portugal, Southwest Spain, Southern Italy and Greece. In Central and Northern Europe (United Kingdom, Belgium, Netherlands, Luxemburg, Germany, Denmark and Sweden) the range was below 250 mm.

Figure 17 illustrates the effect of irrigation (Strategy S2) on crop yields in comparison with the no-irrigation strategy SX. The relative increase in yield shows distinct regional differences. In Central, Northern and Eastern countries, relative yield increase due to irrigation is less than 2 (=100% increase relative to SX), reflecting the supplementary and temporary character of irrigation in these countries. On the contrary, in Southern countries, the relative yield increase is considerably higher by orders if magnitude (>5). These extremely high relative yield increases reflect the severe limitation of agricultural production by climatic water scarcity (driving yields towards zero without irrigation) and show that in these regions irrigation is of substantial importance to maintain agricultural production.

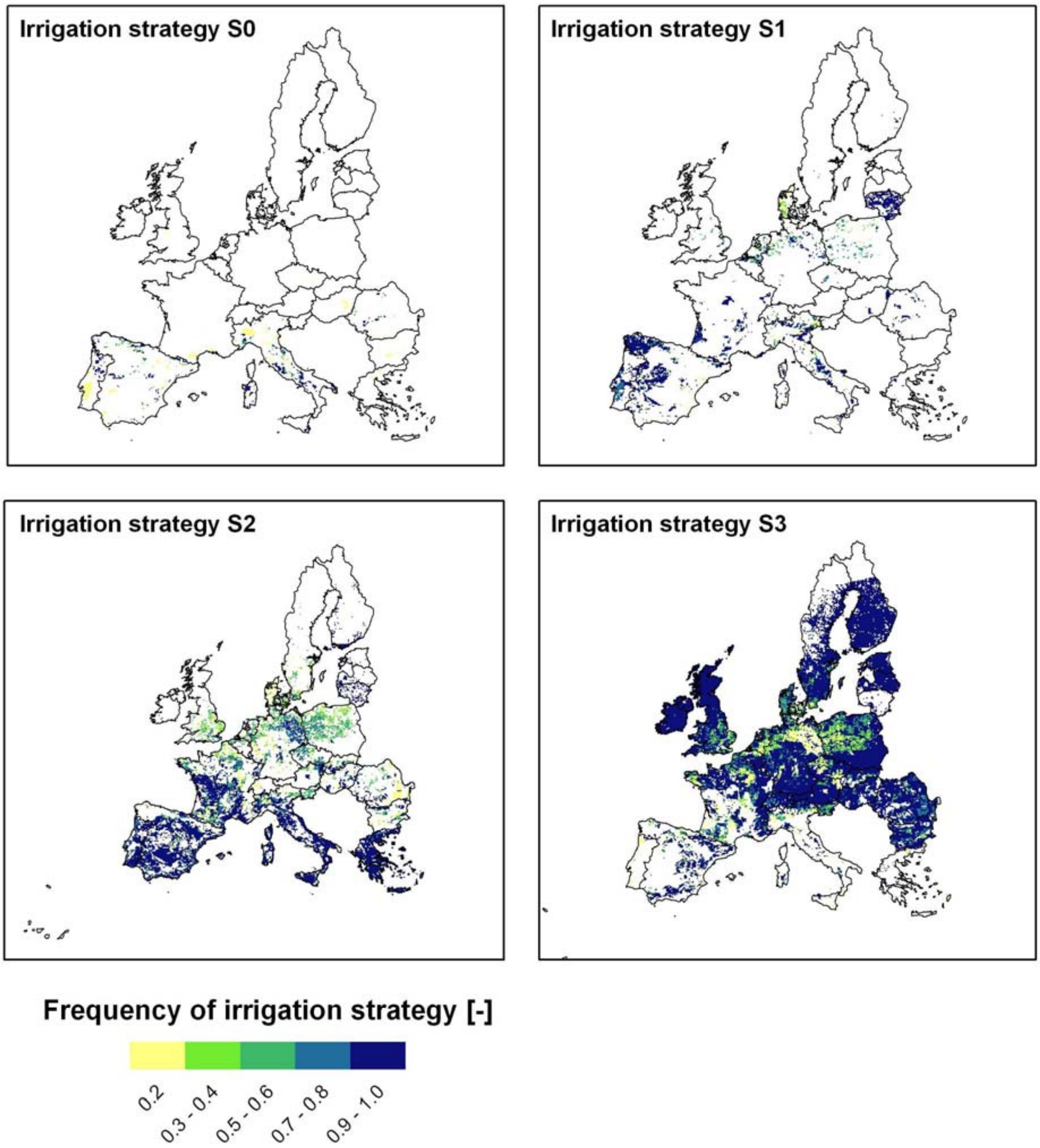


Figure 13: Spatial distribution of irrigation strategies selected for final results based on . The frequency is the number of crops irrigated with a certain strategy divided by total number of crops simulated in a particular site.

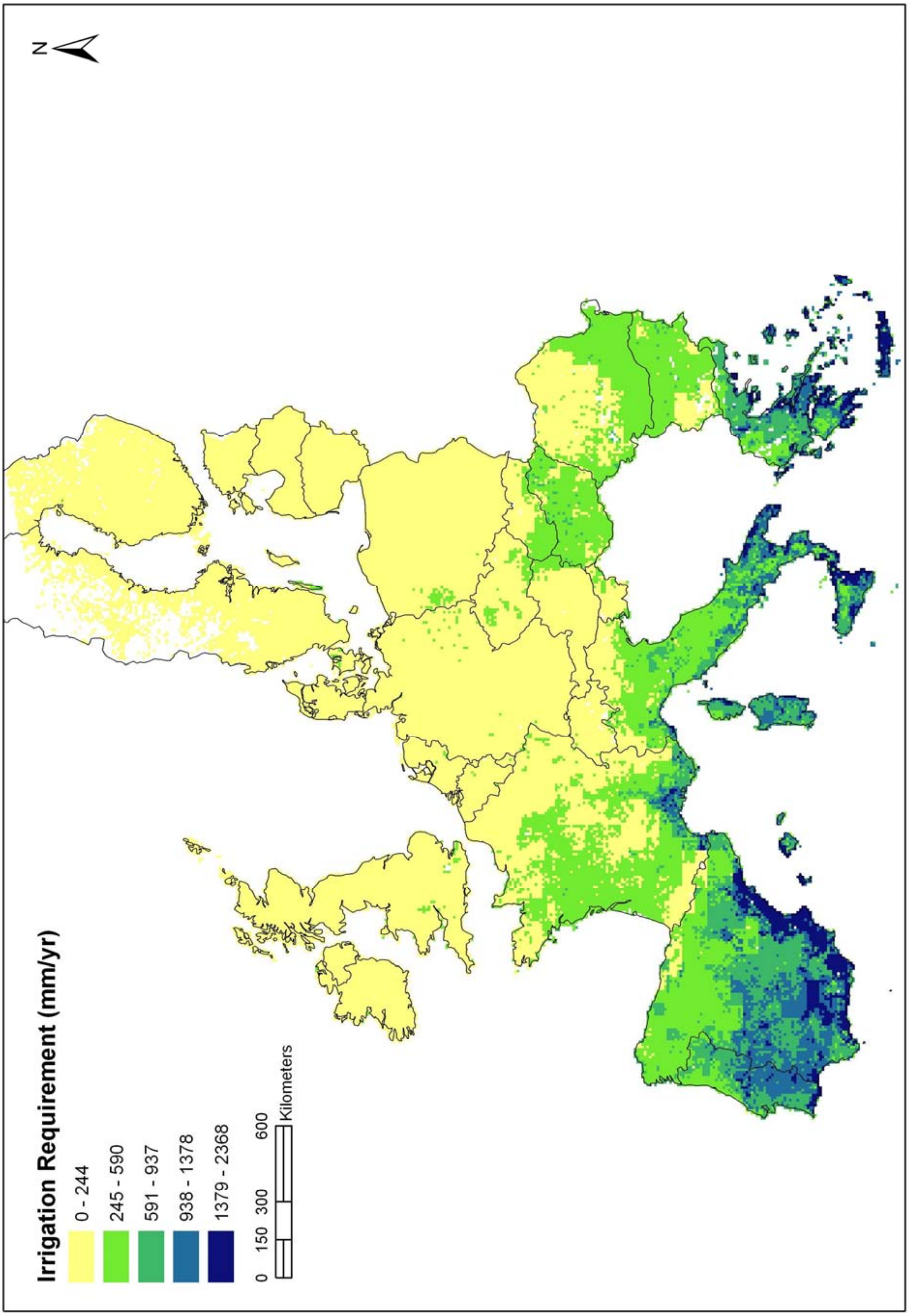


Figure 14: Average irrigation requirement (mm/yr) in EU and Switzerland (simulation period 1995-2002)

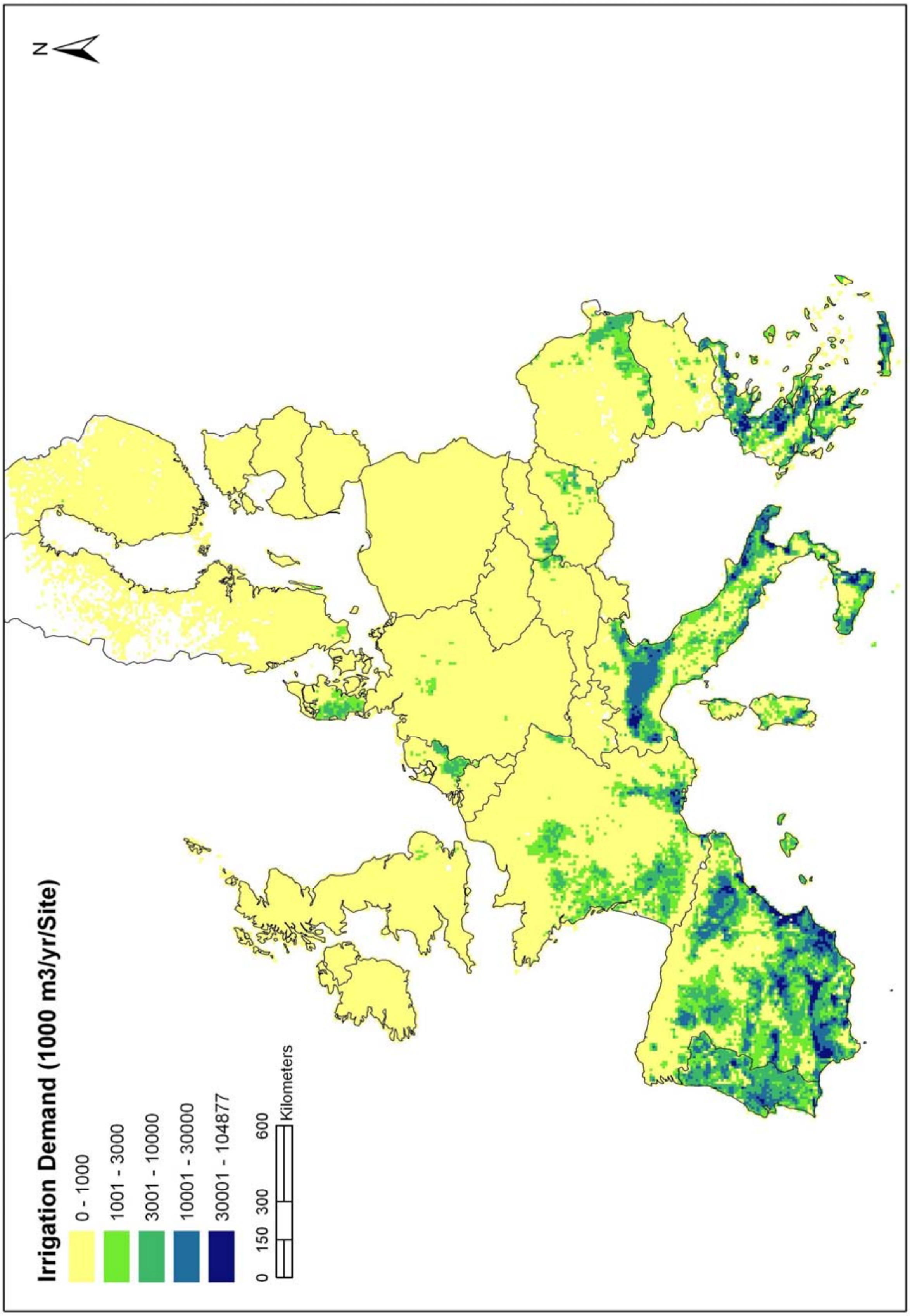


Figure 15: Average irrigation demand per site (10x10km cell) in EU and Switzerland (1000 m3/yr/site, simulation period 1995-2002)

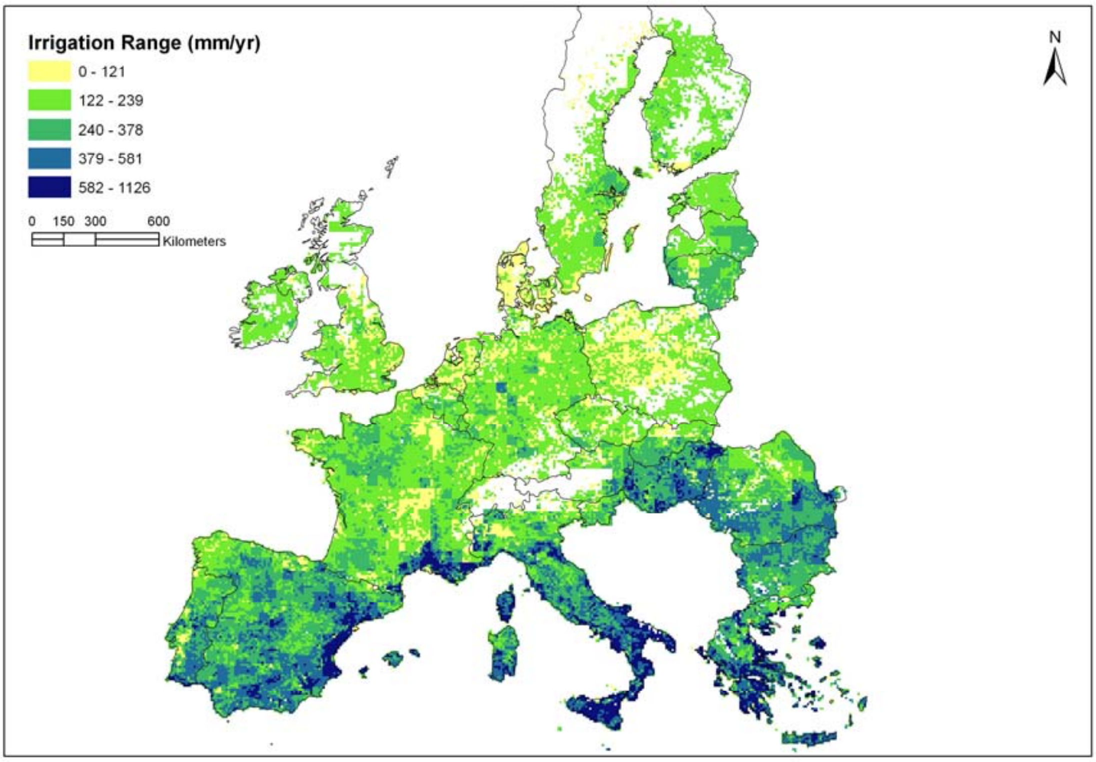


Figure 16: Range of irrigation requirements (Max – Min) in EU and Switzerland (simulation period 1995-2002).

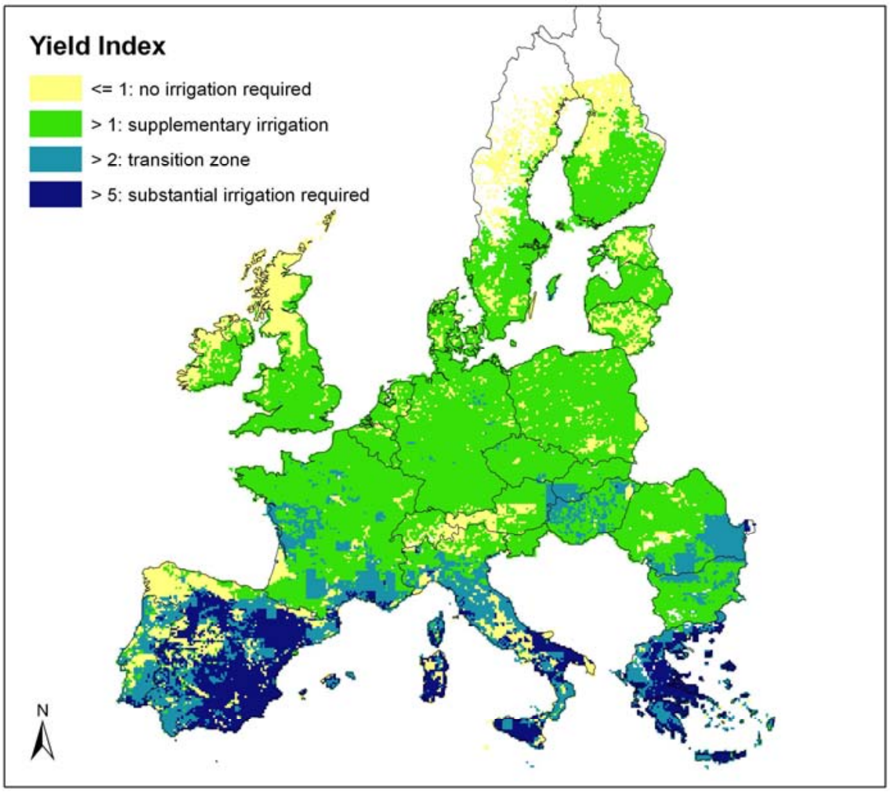


Figure 17: Relative yield-increase of irrigation strategy S2 compared with the no-irrigation strategy SX (Yield index), indicating the dependence of agricultural production on irrigation.

4.3 Comparison with reported national water abstractions

Reported water abstractions, the calculated irrigation demand and the potential abstractions assuming high and low irrigation efficiency for the year 2000 are displayed in Table 10 and Figure 18.

Reported water abstractions were expressed in mm/yr as ‘reported’ irrigation, dividing abstractions by irrigated area. Accordingly, irrigation requirement and potential abstractions were expressed in mm/yr and not as volume. Where countries reported agricultural water abstractions rather than irrigation abstractions, the latter were replaced by agricultural abstractions. This may introduce some bias in regions where irrigation is relatively unimportant and watering livestock accounts for the majority of agricultural water abstractions. National irrigation scheme efficiencies (es) range from 0.41 (low efficiency) to 0.70 (high efficiency). These efficiencies correspond to national multiplication factors (1/es) of 2.42 and 1.26. The resulting difference in irrigation water use ranges from less than 100 mm up to about 800mm. Irrigation requirement and potential water abstractions under high and low efficiency define an uncertainty range to which reported water abstractions should correspond to. The uncertainty ranges reflect the enormous water saving potential of irrigated agriculture that could be achieved by reducing conveyance losses, improved application efficiency, changes in irrigation practices, change of crops and reuse of treated sewage effluent. According to a recent study on EU water saving potential, the saving potential of irrigated agriculture is about 43% (Ecologic 2007). The following countries were omitted from the analysis for obvious inconsistencies in reported data or missing information on water abstractions: Malta, Switzerland, Estonia, Latvia, Lithuania, and Luxemburg, Finland. The countries were ordered with increasing reported irrigation water abstractions. Ideally one would expect that reported abstractions should fall within the uncertainty range defined by irrigation requirement and water abstractions under a low efficiency irrigation infrastructure.

Figure 18 compares reported national irrigation abstractions with calculated irrigation requirements and the corresponding abstraction range. Countries are grouped into EU15-Countries (Western European countries, UK – PT) and new member states (Eastern European countries CZ - BG) sorted according to reported abstractions. For some countries, reported abstractions overshoot calculated irrigation requirements (Sweden, Belgium, and Poland) but typically they undershoot calculated values. Roughly speaking, reported and calculated values are positively related reflecting the high water demands in the Mediterranean and South-East Europe in contrast to Northern, Central and Western Europe. Large discrepancies between reported and calculated values occur. For example, data for Italy seem to correspond reasonably well to simulation results. However, the reported irrigation is about 900 mm higher than in Spain and Greece with comparable or even more severe climatic conditions. Reported data from Spain and Greece, however, are likely to underestimate true abstraction due to lacking data and high percentage of illegal and unrecorded abstractions. The irrigation abstractions reported for Portugal (resulting from dividing water abstractions by irrigated area) are 2.7 times higher than calculated and 3.7 times higher than in the neighboring country Spain, which seems unrealistic and may indicate possible inconsistency of the underlying data on water abstractions and irrigated area. The discrepancies observed for Eastern European countries require further analysis to separate the impact of model uncertainties and limitations of the statistical information.

Generally, several factors can cause discrepancy between reported and calculated irrigation water use. First, reported irrigation abstractions are based on estimates rather than real measurements and are frequently missing or non-existing, as indicated in section 2.2. EU Member States apply different methodologies to assess water abstractions for irrigation and partly no measured data are available. Such methodologies include questionnaires to farms and operators of irrigation systems (Nagy et al. 2007), application of water use coefficients, but also estimations based on water rights (e.g. Spain) and model-based estimations (e.g. Italy, ISTAT 2006). The use of a model-based assessment in Italy possibly explains the relatively good fit between reported and calculated data in Italy. Irrigation water use is rarely measured, although only monitoring can provide reliable data. This is most likely the case when irrigation water is supplied by public networks or in well managed irrigation districts. On the contrary, self supplies are much more difficult to control, especially when abstracted on site (for example from groundwater wells), unless metering (and reporting) is enforced by law. In Italy, for example, in the same areas where public agencies operate, there is irrigation operated with private water supplying (80% of farms in some areas), which can neither be planned nor controlled by authorities (Zucaro and Pontrandolfi 2005). Also illegal abstractions (exceeding legal abstraction rights or undeclared and unauthorized abstractions) can severely bias assessments. Spanish water authorities estimate that about 510000 illegal wells exist in Spain, extracting at least 3.600 hm^3 of water as opposed to legal abstractions of 4500 hm^3 (WWF/Adena, 2006). Thus about 45% of all water abstracted from aquifers is abstracted without legal constraints, providing a clear example of the so-called ‘tragedy of the commons’ (Hardin, 1968). Adding this amount of illegal abstractions to the reported data for Spain would likely approximate the calculated values.

Second, in addition to uncertainty of abstraction data, also data on irrigated areas are an essential input for the assessment. Uncertainties in irrigated area directly affect model results and conversion of reported abstractions to ‘statistical’ irrigation.

Third, simulation results and abstraction data are conceptually different and discrepancies can be attributed to different sources of uncertainty. Irrigation requirements simulated by the model are determined by climatic and edaphic conditions and standardized crops (not taking into account regional varieties and differences in management). Simulation results are subject to uncertainties related to parameterization of crops and management and to uncertainties of input data, such as irrigated areas, crop composition and climatic and edaphic information. The large scale approach required various simplifications (standardized irrigation strategies, averaging soil and climate over spatial units, limiting the number of simulated crops), and therefore a comparison to local observations of crop specific irrigation is difficult. Rice is so far the only crop where results were checked crop specifically and the simulated values were replaced by literature values. This can only be provisional and a more specific sub-model must be developed in future to estimate water use in rice cultivation.

Reported water abstractions include the effects of irrigation systems efficiencies, irrigation practices and restrictions of water use by water shortage, legislation or for economic reasons. Estimating water use and abstractions from simulated irrigation applications is subject to considerable uncertainty due to the broad range of possible losses, return flows, and irrigation scheme efficiencies. As shown, estimated abstractions can be as high as more than twice the irrigation requirement. There are currently no data available at European scale allowing a comprehensive assessment of water losses during transport from abstraction points to fields and allowing a reasonable correction of simulated irrigation requirements.

Fourth, the actual water use in contrast to calculated abstractions or requirements can be affected by additional factors, such as irrigation management, maintenance, economic aspects and legal restrictions. Various studies indicate that irrigation management and maintenance of irrigation systems are key factors determining actual water use, counterbalancing potential water savings of irrigation technology. Lilienfeld and Asmild (2007) conclude from an irrigation study in Kansas, USA that "irrigation system types did not appear to strongly influence levels of water use efficiency/water excess. This suggests that management and field techniques are also important components of water use efficiency at the farm level." They also point out that there is a relation between water use efficiency and the age of farmers, possibly reflecting different management styles. Cancela et al. (2006) report low irrigation efficiencies for sprinkler irrigation of about 36% contrasted by application efficiencies of 45% for normally less effective surface irrigation in an irrigation district in Galicia, Spain. The low efficiencies are referred to poor equipment handling, wind, spacing of irrigation equipment and other management issues. Also economic aspects, such as market prices of crops, water prices and costs for irrigation technology and maintenance affect the marginal income achieved by irrigation and thus feed back on irrigation water use. On the contrary, unlimited access to water or low costs favors inefficient irrigation and excess water use. An important issue is also the legal restriction of water abstractions and irrigation, for example by assigning water rights as in Spain or issuing temporal interdictions as in the Netherlands. Such restrictions are not included in the assessment, but may have a significant impact on the true water use with respect to the (calculated) water requirement.

Consequently the direct comparison of estimated and reported abstractions gives only a rough indication. A model validation on observed data, however, is not possible with the data currently available. Nevertheless, a comparison of reported and simulated data is useful. Discrepancies point directly to inconsistencies in underlying data, model assumptions and real-world irrigation practices and regulations. This can guide future improvement of reported abstraction data, underlying statistics and the modeling approach.

Table 10: Comparison of reported data (Eurostat, 2000) with simulation results given as reported and calculated irrigation requirement (in mio m3/yr and mm/yr) and calculated abstractions (expressed as gross irrigation in mm/yr) respecting low and high efficiency of irrigation systems.

CTRY	Irrigated Area (ha)***	Reported irrigation abstractions (mio m3)	Irrigation demand (mio m3)	Efficiency range (high-low)	Reported irrigation* (mm/yr)	Calculated irrigation requirement (mm/yr)	Calculated abstraction (Low eff.) (mm)	Calculated abstraction (High eff.) (mm)
AT	28277	68	103	1.4-2.2	239	364	797	503
BE	2885	10*	3	1.4-2.3	347	97	220	139
BG	77435	731	634		944	819	1883	1064
CH	44237		6		0	13	29	17
CZ	15896	9*	28	1.4-2.2	59	176	385	243
DE	220270	163*	223		74	101	233	132
DK	201185	165	107	1.4-2.2	82	53	118	75
ES	3206214	21763	35919	1.4-2.2	679	1120	2486	1570
FR	1566535	4872*	6349	1.4-2.2	311	405	905	572
GR	1159281	7600*	12776	1.4-2.2	656	1102	2421	1529
HU	65924	173	760	1.4-2.2	262	1152	2568	1622
IT	2450993	38360	22381	1.5-2.3	1565	913	2136	1349
LU	49				408	28	65	37
MT	332		2	1.3-2.0		627	1252	791
NL	61824	76*	50	1.4-2.2	123	80	177	112
PL	33392	110	17		330	50	116	65
PT	256022	6551*	2427	1.4-2.3	2559	948	2176	1374
RO	393850	513*	2030	1.4-2.3	130	515	1164	735
SE	53044	107	22	1.4-2.2	202	42	93	58
SI	1680	7*	6	1.4-2.2	399	380	821	519
SK	106882	77	409	1.5-2.4	72	382	913	576
UK	146603	106	62		72	42	98	55

*: approximated by total agricultural abstractions
**: reported irrigation abstractions / irrigated area
***: areas finally realized in irrigation map, minor deviations from statistical data possible

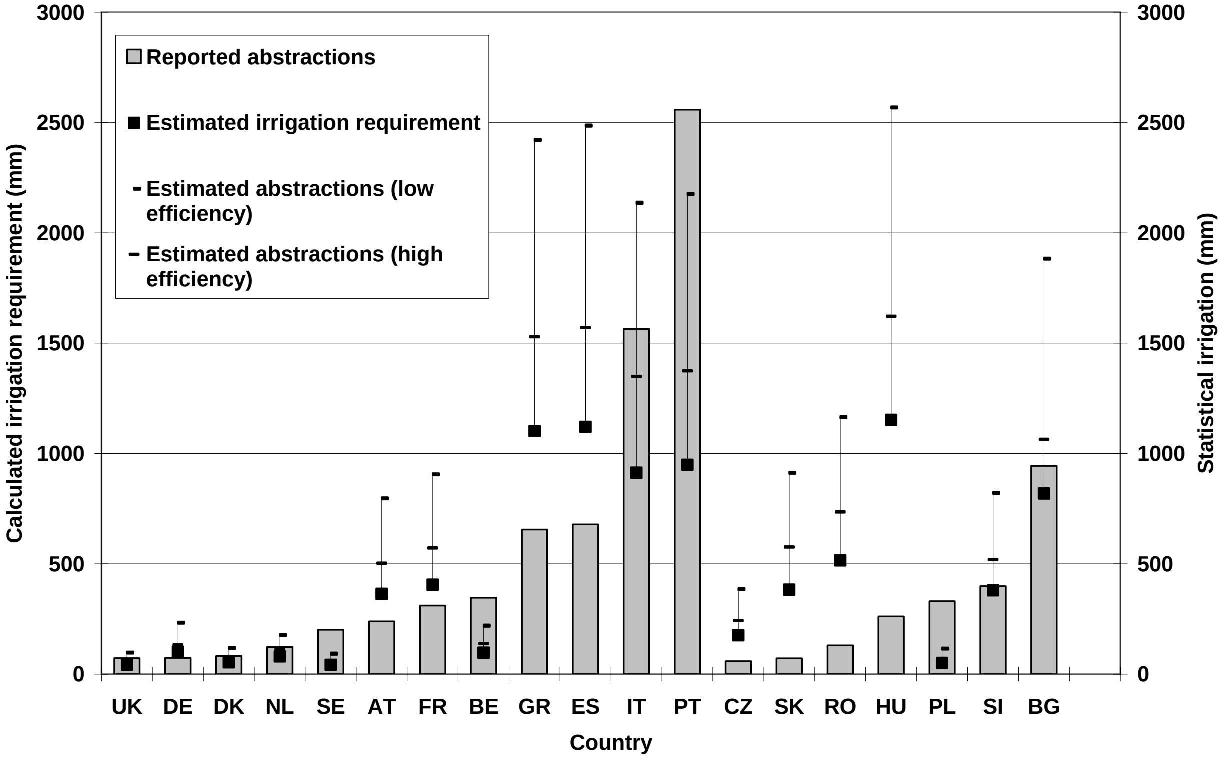


Figure 18: Comparison of reported national water abstractions for irrigation with calculated irrigation requirements and resulting abstractions assuming low and high efficiency of irrigation practices. All units converted to mm/yr.

4.4 Comparison with reported regional water abstractions in France

A second comparison was made with regional water abstraction data from France. The data set covers the climatic transition from the humid Atlantic climate to the summer-dry Mediterranean climate. This comparison was directly based on comparison of water abstractions and irrigation requirement, without taking into account irrigation efficiency (Figure 19). An initial screening suggested two different geographical groups with different relations to simulation results (A and B). We therefore split the data into two regional subsets, separating Southern France (Corse, Languedoc and Provence) from the remaining part of France. Initially, data from southern France indicated high irrigation water use, which was not represented by the model. After correcting model irrigation for rice crops, a better coincidence was achieved. Calculated irrigation and water abstraction underestimate the corresponding statistical data in Provence by a factor of about 0.7. On the contrary, calculated irrigation in Northern and Central France overestimates water abstractions in Northern and Central France by a factor about 1.7. Generally, this grouping is equivalent to the grouping already made when comparing national abstraction data: a separation of i) dominantly rain-fed agriculture with temporary/supplementary irrigation and ii) dominantly irrigated agricultural systems.

The different behavior of these two geographical regions can be explained as follows: According to data from the FSS 2003, groundwater is the major source of irrigation and sprinkler is the dominant irrigation method in Central, Western and Northern France. This suggests dominant on-site abstraction and use of pressurized sprinkler irrigation systems. True abstractions are possibly systematically underestimated by statistics in these regions, as only wells exceeding a certain capacity require authorization (Dubus I.G., 2007, oral communication) and abstractions are not generally measured. In southern France, instead, there is a high share of public irrigation water supply and off-site surface water use, indicating that irrigated areas are organized in an institutional context and irrigation infrastructure exist to distributed water. In this environment, water abstractions are likely to be monitored. Underestimating abstractions by a factor of 0.7 can well be explained by conveyance and application losses in a relatively efficient irrigation system.

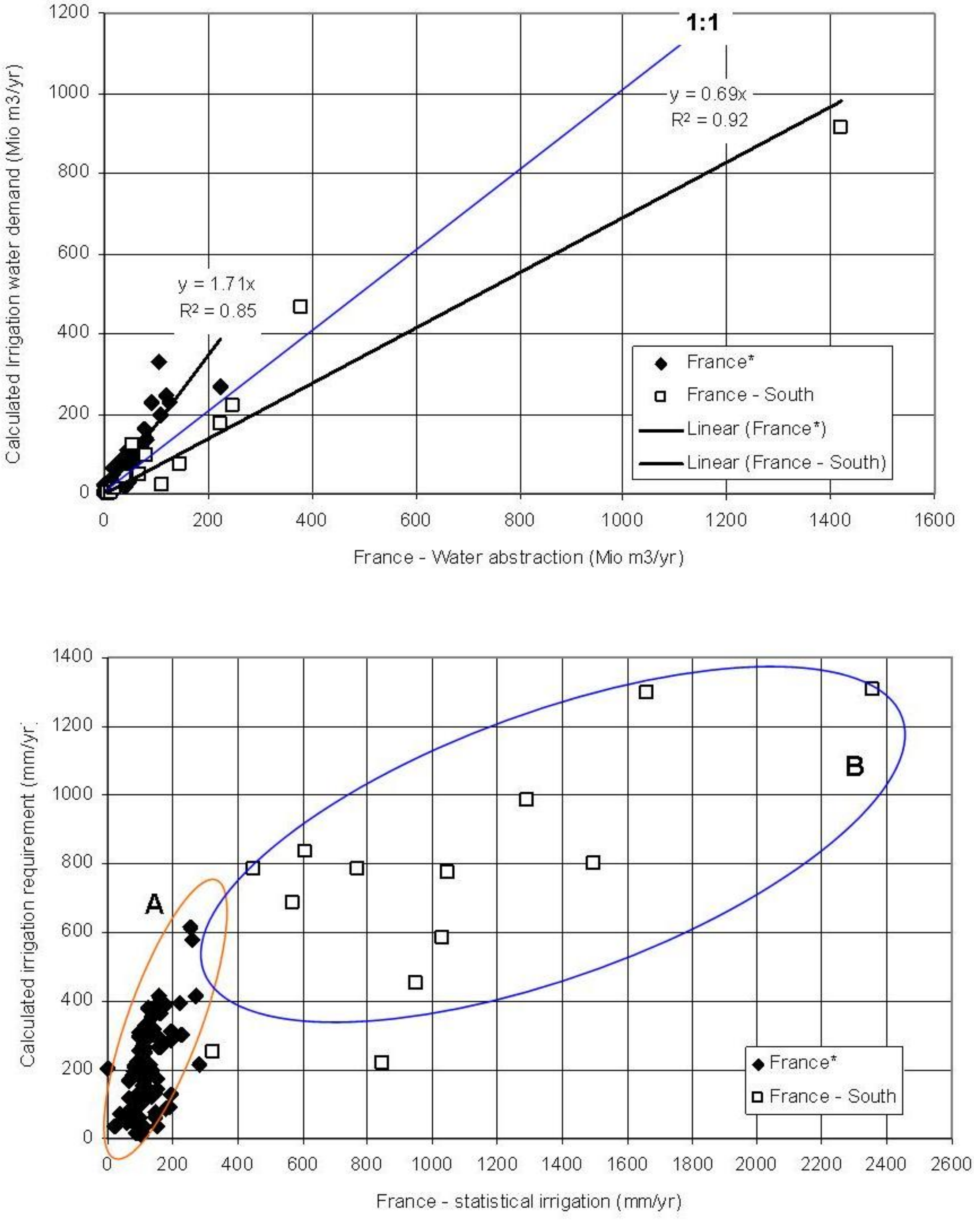


Figure 19: Upper panel: Comparison of regional water abstraction data with calculated simulation volume (in Mio m3) for France, indicative linear regression fits for the two geographical areas (France – South and France –rest). Lower panel: Comparison of average statistical and calculated irrigation (in mm per unit irrigated area) for France. The axis of the ellipsis roughly indicates a potential regression line for the two regions France-rest (A) and France-South (B).

5 Conclusions

Our assessment provides a view on irrigation requirements at high spatial resolution with large geographical coverage (EU27 and Switzerland), accounting for composition of crops, crop management, soil conditions and climate. The spatial patterns of irrigation water use reflect the distribution of irrigated areas and the climatic water requirements at sufficient resolution to support detailed analysis of regional differences in agricultural pressures on water resources. The approach can principally provide reasonable estimates of net irrigation requirements.

A comparison with reported agricultural abstractions revealed discrepancies between reported abstractions and model estimates. These discrepancies require careful interpretation, as not only model uncertainties come into play, but also the quality of reported statistical data has to be questioned. Issues to be considered in this context are the availability of reliable water abstraction data, limitation of irrigation by economical factors and legal restrictions, and the availability of information to correct irrigation requirements to water abstractions. Despite these limitations, it could be shown that relations between available data and model results exist and that a meaningful interpretation is possible. The comparison of reported statistics and calculated results allows evaluating the consistency of statistical information feeding the model. It needs to be stressed here, that the model represents an irrigation demand based on a given land use scenario. The analysis does not include national or regional regulations and restrictions on water use for irrigation.

The compilation of the European Irrigation Map was a prerequisite to perform this analysis, integrating and taking advantage of different available data and information sources. As it is a complementary product to the European land use map developed at JRC (Grizzetti et al. 2007), its application in an operational context (i.e. regular updates according to land use statistics) requires a prior update of the land use map as well. The crop specific assignment of irrigated areas requires further improvement and collection of country specific information on irrigated crops and irrigation practices. This is, however, less relevant for the estimation of regional irrigation requirements, which is always based on a crop mix and total irrigated area, leveling out the effects of individual crops.

Future improvements of the assessment can be made by more detailed consideration of legislative aspects and water availability (requiring a comprehensive water resource assessment at European scale) allowing a better approximation of actual water use. The results of this study rely directly on the quality of the underlying data sources (irrigated areas, land use). The future improvement and development of the statistical information will therefore also improve the model assessment of irrigation water requirements and needs.

The work presented in this paper contributes to the development of agri-environmental indicators carried out in the European Commission. A previous indicator on water use intensity (IRENA Indicator 10, EEA 2005) was based on the distribution of irrigated areas at sub-regional level (NUTS3), but did not include quantitative information on water use. The assessment of water use via the OECD/Eurostat Joint Questionnaire does currently not provide the spatial detail for regional comparisons. Ongoing activities aim at overcoming these limitations and further developing agri-environmental indicators on irrigation and water abstraction in agriculture. In this context, the modeling approach provides an independent estimate not biased by problems of unrecorded water abstractions or by national differences in accounting and reporting. Instead, it focuses on the water needs based on the reported crop areas and irrigated areas applying official data and a unique methodology. This reference information supports evaluation and comparison of national and regional statistics which are typically based on different methodologies and helps to identify inconsistencies or to modify assessment strategies. The bottom up approach allows aggregating results from the site-scale (10x10km) to regional and national estimates. The data sets created are therefore also useful identifying hot spots of irrigation water use at various spatial levels and communicating the findings across different administrative levels.

Especially in southern Europe, irrigation is a key driver of water use. Quantitative and qualitative degradation of water resources is frequently observed, providing an example of the so-called ‘tragedy of the commons’ (Hardin, 1968) and demonstrating the need for appropriate water management. The approach presented here will facilitate various spatially distributed analysis, including water needs of agriculture, quantitative pressures on water resources (in combination with assessment so f water availability), water saving potentials (as discrepancies between abstractions and water needs), leaching of nutrients and pesticides and salinisation risk. Also impacts of land use change and climate change on agricultural water needs and agricultural pressures on the environment can be assessed. Information-driven policy will benefit from this analysis allowing for better targeted policies or measures.

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Abstract

Agriculture is an essential driving force in the management of water use. Especially in Southern European countries, irrigation is an essential element of agricultural production and agricultural water use has a substantial share in total water use (exceeding 50%). The presented work contributes to the assessment of impacts of irrigated agriculture on water resources at European scale. We developed a modeling approach to estimate irrigation water requirements and regional irrigation water demands in the EU at high spatial resolution. The modeling approach was applied for a first assessment of irrigation water requirements.

A prerequisite of the analysis was the compilation of a European Irrigation Map (EIM), providing information on the distribution of irrigated areas in EU25 for modeling studies. The EIM complements the underlying European land use map (Grizzetti et al. 2007), combining FSS statistics on irrigated area and crop area and information from the Global Map of Irrigated Areas (Siebert et al. 2005). The map was used to derive irrigated areas (as total and per crop) for spatial modeling units.

To estimate irrigation water requirements we applied the soil water and crop growth model EPIC that was implemented in a European agricultural modeling system EAGLE and calculates water and nutrient flows at a spatial resolution of 10x10 km raster cells. Different irrigation strategies were defined to analyze the effect of application rates and irrigation intervals on water requirement. The final results were given per raster cell and per crop, based on the most efficient irrigation strategy (maintaining optimum yield with lowest irrigation).

We show that allowing higher soil water deficit does not automatically lead to non-tolerable reduction of crop yields and soil moisture. Irrigation requirements (irrigation per unit irrigated area) in Europe range up to 2368 mm/yr in average per cell. Water demands (volume for defined spatial units) are calculated subsequently based on the irrigated area within each cell.

Resulting water abstractions were calculated using rules-of-thumb values of irrigation efficiency and conveyance efficiency. A comparison with reported national statistics on water abstraction data showed considerable discrepancies for many countries, indicating not only model uncertainties, but also illustrating shortcomings of national statistics. Such a comparison is a useful tool to check the consistency of both, model assumptions and underlying statistical information.

The results provide a spatial overview on irrigation water demands in Europe and allow analysis of agricultural pressures on water resources in Europe at a considerable high spatial resolution. Being based on a single methodology applied to official data sources, the estimation supports inter-comparison of national statistics, which are based on different methodological approaches. This pilot assessment was based on irrigation and land use statistics from the years 2000 and 2003. The methodology was designed for application in an operational context, allowing future updates of the assessment corresponding to statistical data. The approach can therefore principally be applied and extended to track ongoing development or run future scenarios of land use and climate. Future improvements will rely on the development of the underlying statistical information and on the incorporation and improvement of crop specific information.

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