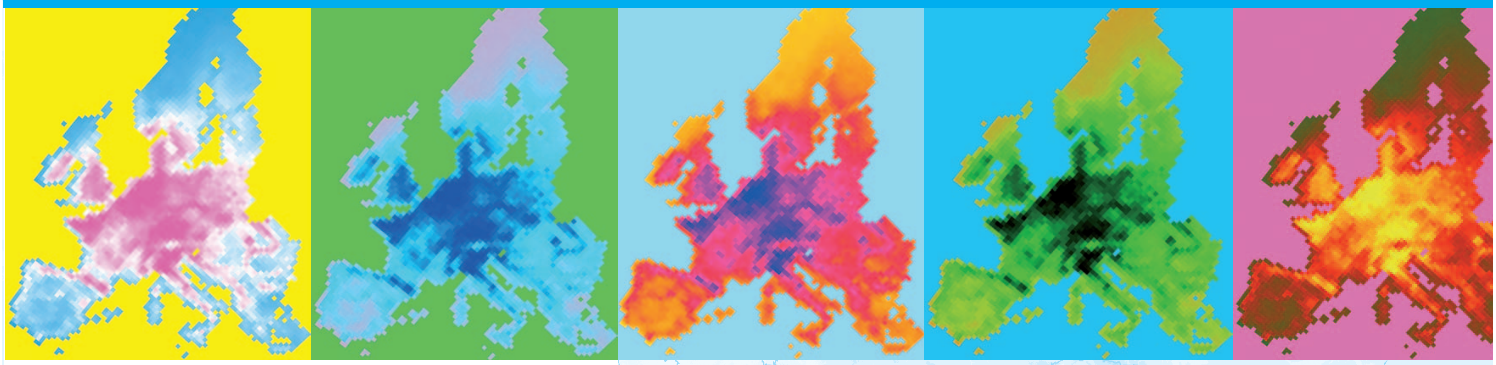
European Agrochemicals Geospatial Loss Estimator: Model Development and Applications

Fayçal Bouraoui and Alberto Aloe



Institute for Environment and Sustainability

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1 INTRODUCTION

The CAP reform by decoupling subsidies from production levels and liking them to the protection of the environment is promoting a cleaner agriculture and a more sustainable use of resources. Agricultural subsidies are now linked to application of statutory minimum requirements (SMR) and cross compliance. Farmers willing to go beyond SMR can get additional payments through Rural Development Programs by implementing “Good Farming Practices”. Modelling tools to help managers decide appropriate strategies in reducing the impact of agriculture on soil and water resources are needed. These models must be responsive to management practices, and should be flexible enough to allow the evaluation of the environmental and the crop production response to various forcing functions including policy (set aside, compliance with the nitrates directive), farmer personnel initiatives such as the implementation of best management practices, but also to uncontrollable factors such as climate change.

The purpose of this research was to develop a versatile tool allowing the assessment of the fate of agrochemicals at EU level (EU25) using readily available data. The tool developed, EAGLE (European Agrochemicals Geospatial Loss Estimator), is composed of the following three distinct components:

- **EPIC model**. EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally a field-sized area, up to 100 ha (weather, soils, and management systems are assumed to be homogeneous). The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control. Within the

EAGLE context, EPIC represents the logic tier where data input are processed to obtain relevant information for the specified study area.

- **Database**. The EAGLE European geodatabase holds all the necessary data (soil, meteorological, crop management, etc.) to perform EPIC simulations. A specific data model was designed, using the ESRI ArcGIS geodatabase environment, in order to structure all the relevant data (geographic and tabular) to perform EPIC modelling at European scale.
- **GIS Interface**. This is an ESRI ArcMap customization that allows the use of EPIC using data stored in the previously described geodatabase through an intuitive GIS interface.

The EPIC model (Williams, 1995) was selected as it runs on a farm (field basis) and includes most of the aspects linked to farming practices and operations. It allows the simulation of the fate of nitrogen, phosphorus, and pesticides as affected by farming activities such as timing of agrochemicals application, tillage, crop rotation, etc., while providing at the same time a basic farm economic account. In addition EPIC has been thoroughly evaluated and applied from local to continental scale (Gassman et al., 2005). Furthermore most of the parameters required to run EPIC are readily available at EU level (Mulligan et al., 2006).

This report will start with a brief description of the theory behind the EPIC model will be provided. Then the following section will present the geodatabase put together in order to run EPIC at the European level. The next part will detail an application of the EPIC model to evaluate the impact of potential climate change on crop water and nutrient requirements. Finally a brief application to evaluate the fate of pesticides will be given to illustrate the versatility of the developed tool.

2 MODEL DESCRIPTION

2.1 HYDROLOGICAL CYCLE

The EPIC (Erosion-Productivity Impact Calculator; Williams et al., 1995) is a field scale model, originally developed to simulate the long-term effects of soil erosion on soil productivity. A nutrient cycling and pesticide fate routines were added later on. The various developments of EPIC are given by Gassman et al. (2005).

The hydrological model is based on the water balance equation in the soil profile where the processes simulated include surface runoff and infiltration (SCS curve number), evapotranspiration, lateral flow, and percolation. Surface runoff, Q(cm), is related to daily precipitation, P (cm), based on the SCS curve number (U. S. Department of Agriculture, 1972) as follows:

$$Q = \frac{[CN(aP + 2) - 200]^2}{CN[CN(aP - 8) + 800]} \tag{1}$$

CN is the curve number, and *a* is a unit conversion factor equal to 0.3937. The curve number for a watershed depends on the antecedent soil moisture content, land use and treatment practices, the hydrologic surface conditions and the hydrologic soil group. The EPIC model uses a daily curve number based on a soil moisture accounting procedure developed by Williams and Laseur (1976) and goes from a minimum value when the soil is at wilting point to a maximum value when the soil is saturated.

Potential evapotranspiration can be computed, based on data availability, using one of the following methods: Penman (1948), Penman-Monteith (Allen et al., 1989); Priestley Taylor (Priestley and Taylor, 1972), and Hargreaves (Hargreaves and Samani, 1985). Evapotranspiration is determined using the Ritchie's approach (Ritchie, 1972). Potential soil evaporation and plant transpiration are partitioned based on the leaf area index (LAI) and the above ground biomass (CV, kg/ha). Potential soil evaporation, E_S, (cm) is determined as:

$$E_S = E_0 e^{(-5.10^{-5} CV)} \qquad (2)$$

where E_0 is the potential evapotranspiration (cm). The potential plant transpiration, E_{P0} (cm), is determined as a function of E_0 and LAI (Ritchie, 1972):

$$E_{P0} = \frac{E_0 \ LAI}{3} \qquad \text{for} \quad 0 \le LAI \le 3 \qquad (3)$$

If LAI is larger than 3, potential plant transpiration is taken as the potential evapotranspiration. For any given day, the sum of plant transpiration and soil evaporation cannot exceed E_0. The potential transpiration rate is then distributed in the soil profile based on root distribution.

2.2 NUTRIENT CYCLE

EPIC divides the nitrogen into active organic, stable organic, fresh organic, nitrate and ammonium pools. The model simulates mineralisation (transformation from organic to ammonia) from the fresh organic pool associated with crop residue and microbial biomass and from the active organic pool. The contribution of the fresh organic N pool to mineralisation is estimated as:

$$RMN = 0.05 \, CNP \sqrt{\frac{SW}{FC} TF} \;\; FON \qquad (4)$$

where RMN is the mineralisation rate (kg/ha/d), FON is the fresh organic N present in the soil (kg/ha), CNP represents the impact of the carbon to nitrogen and carbon to phosphorus ratio on the decomposition rate, SW is the soil water factor, TF is the temperature factor, and FC is the field capacity (mm/mm). The organic N associated with humus is divided into active and sable pools which are in dynamic equilibrium. The mineralisation from the active pool is calculated as:

$$HMN = CMN\ ON\ (SWF\ TF)^{0.5}\left(\frac{BD}{BDP}\right)^{2} \qquad (5)$$

where HMN is the mineralisation rate (kg/ha/d), CMN is the humus degradation rate (d^{-1}), BD and BDP are the settled and current bulk density as affected by drainage (t/m^3).

The second stage of mineralisation is based on a first order kinetics and is a function of soil moisture, soil temperature and soil pH. Volatilisation of applied ammonia at the soil surface is determined simultaneously with the nitrification and is a function of air temperature and wind speed. Volatilisation of ammonia in lower soil layers is function of soil temperature and cation exchange capacity. Denitrification is considered to be a first order process, and is based on the amount of soil organic carbon content and is function of soil temperature and soil moisture.

The cycling of organic P is similar to that described for nitrogen with mineralisation occurring from the fresh organic P and organic P associated with humus. Mineral P is divided into a labile P pool, an active mineral pool, and an inactive mineral pool. Fertiliser P is labile at application and then is transferred rapidly to the active mineral pool. The active and stable inorganic P pools are dynamic, and at equilibrium, the stable mineral P pool is assumed to be four times larger than the active mineral P pool (Sharpley and Williams, 1990).

2.3 CROP GROWTH

EPIC uses a daily time step to calculate crop potential growth and crop growth limitation stress factors which include the following constraints: water stress, temperature stress, and nutrient stress. Maximum crop yield is based on the radiation use efficiency. The daily potential biomass increase is calculated as:

$$\Delta B_p = 0.001\ BE\ PAR \quad (6)$$

where B_p is the potential biomass production (t/ha), BE is energy to biomass conversion parameter (kg/ha/MJ/m^2) (function of atmospheric CO2 level), and PAR is the intercepted photosynthetic active radiation (MJ/m^2) estimated based on Beer's law as:

$$PAR = 0.5\ RA\left(1 - \exp^{-0.65\ LAI}\right) \quad (7)$$

where RA is the solar radiation (MJ/m^2), and LAI is the leaf area index. LAI is calculated daily based on heat units. The daily change in LAI is calculated as follows:

$$\Delta LAI = LAI_{\max}\ \Delta HUF\ \left(1 - \exp^{(5(LAI_{i-1} - LAI_{\max}))}\right) REG \quad (8)$$

where LAI_{max} is the maximum leaf area index, HUF is if the heat unit factor, and REG is the minimum of the water, nutrient, temperature, aeration and radiation stress factors. Heat units (HU) on a particular day are calculated during the phenological development of the crop as the average daily temperature in excess of the crop base temperature, and the heat unit index (HUI) as the ratio of the cumulative heat unit divided by the potential heat units:

$$HU_i = \max(0, T_{av} - T_b)\ ; \quad HUI_i = \frac{\sum_{k=1}^{i} HU_i}{PHU_j} \quad (9)$$

where T_{av} is the average daily temperature (°C), T_b is the base crop growth temperature (°C), *i* is the day, PHU is the potential heat unit for crop *j* (obtained as the sum of heat units from normal planting to maturity). The yield is calculated as the product of the harvest index and above ground biomass. The harvest index can however be reduced by water stress, or a shortened growing season and it is thus adjusted accordingly. Perennial crops maintain their root system through cold-induced dormancy, and growth restarts when average air temperature exceeds the base temperature for the crop.

2.4 GROWTH CONSTRAINTS

EPIC adjusts the daily potential growth by constraints including the influence of the following limiting factors: nutrients, water, temperature, aeration and radiation. This stress can impact not only biomass production, but also root development and yield. A stress is estimated for each of the limiting factor and the actual stress is taken equal to the minimum stress calculated for each of the constraints. Water stress (WS) is evaluated as follows:

$$WS = \frac{WU}{EP_0} \tag{10}$$

where WU is the water use. The temperature stress (TS) is estimated as:

$$TS = \sin\left(\frac{\pi}{2}\left(\frac{T_s - T_b}{T_o - T_b}\right)\right) \tag{11}$$

where T_o is the optimal growth temperature (°C), and T_s is the surface average soil temperature (°C). The nutrient stress (NS) is based on the ratio between the actual and the optimum N and P plant content. The stress factor varies non-linearly between 1 (actual N and P content at optimum level) to zero when N and P contents are at half the optimum level. The nutrient stress factor (NS) is calculated as:

$$NS = \frac{SN_s}{SN_s + \exp^{(3.52 - 0.026\, SN_s)}} \quad and \quad SN_s = 200\left(\frac{\sum_{k=1}^{i} UN_k}{C\, B_i} - 0.5 \right) \qquad (12)$$

where SN_s represents a scaling factor, UN_i is the cumulated nutrient uptake for day i (kg/ha), B_i is the cumulated biomass (kg/ha), and C is the nutrient (N or P) optimal concentration of the crop.

Aeration stress is estimated from the top meter of the soil and is a function of the soil moisture content and porosity. It varies from zero to one when the total soil porosity is filled with water. EPIC also considers pest as a constraint to crop growth. The pest factor is used to adjust the crop yield at harvest. The pest factor is a function of temperature, soil moisture and ground cover. The pest index grows rapidly during warm moist with ground cover and is reduced during cold months. EPIC keeps track of all stress factors and computes a daily sum for each of the factor allowing to monitor the number of stress days (sum for all previous days of the stress factor).

2.5 FARMING PRACTICES

The major function of tillage is to mix nutrients and crop residues in the plough depth. The impact of tillage on soil bulk density is also taken into account by considering between tillage operations the settling effect of rainfall events. Bulk density settling is also function of the sand content of the soil. Tillage operations will also affect the ridge heights and also will convert standing residues to flat residues, both processes impacting surface runoff and erosion.

EPIC allows irrigation to occur as sprinkler or furrow irrigation. Application timing and rate may be calculated automatically based on the plant requirement and pre-specified application and timing criteria (such as the minimum numbers of days between two irrigation applications, minimum rate to be applied) or can be specified as exact amount and exact dates of application.

Fertilisation management is similar to irrigation and can be fixed for each crop of can be calculated automatically (timing and quantity) based on pre-specified criteria. Other operations incorporated in the EPIC model include liming to raise the pH to optimum levels.

2.6 MODEL STRUCTURE AND DATA REQUIREMENT

EPIC3050 is written in FORTRAN and processes the input files as ASCII text files. The model relies on several input files, some of which are proposed as default and can be modified or amended, and others which are site (location specific) which have to be developed by the user. A scheme of the major input and output files used in the present study are illustrated in Figure 1. EPIC requires a description of the soil properties, land use and land management, and climate (daily data and monthly statistical information). The soil properties required include textural information and geochemical composition. Land use data include the crop (crop rotation) used on a specific field and all operations associated including planting, harvesting, nutrient application, irrigation, soil operation. Then daily meteorological data is needed in order to run the model. If data is lacking, then EPIC uses monthly statistical data to generate daily climate time series. All required data to perform EAGLE simulations were stored in a personal geodatabase as detailed in the following sections.

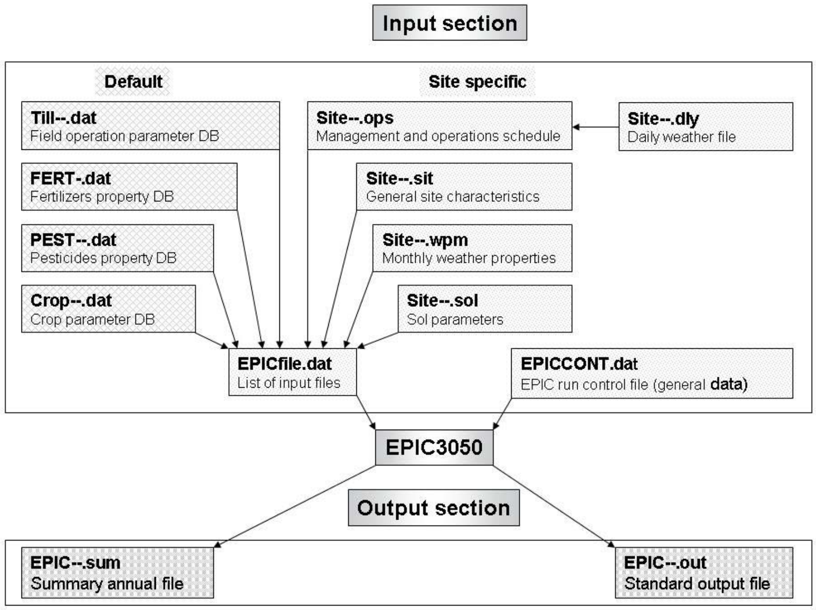

Figure 1. Flowchart of the structure of the EPIC model

3 EAGLE EUROPEAN GEODATABASE

3.1 OVERVIEW

The most relevant aspects that drove the EAGLE database design can be listed as follows:

- it should store all the necessary data for EPIC modelling, and in particular meteorological, soil and landuse data,
- it should be based on a data model that stores geographic data (spatial database), and
- it should have a wide geographic scope in order to allow EPIC simulations for the EU25 territory.

Considering the large extent of the simulation area, the fact that EPIC runs on a daily basis, and the amount of data available at European scale, the choice of a proper spatial database resolution emerged as a key design issue. It was decided to adopt the following strategies in order to conceptualise spatial areas that constitute the discrete EPIC modelling units (Figure 2):

- geographical bidimensional units supporting EPIC runs should be based on a 10 km grid covering the European territory,
- available input soil data (1 km resolution) should be aggregated to the mentioned grid (10 km resolution),
- available input meteorological data (50 km resolution) should be spatially linked to the mentioned grid, and
- available landuse data (1 km resolution) should be tabulated (class aggregation) based on the mentioned grid to obtain area values of landuse classes as 10 km grid cell attributes.

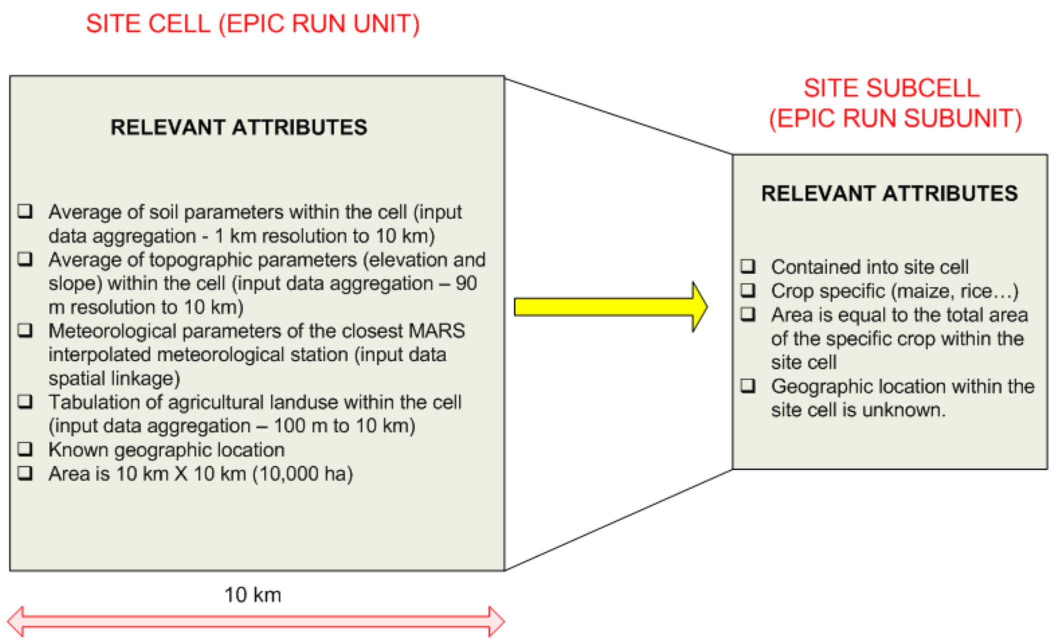

Figure 2. Epic run unit and subunits conceptualisation

Because EPIC runs on a specific landuse type, crop specific EPIC simulation can be achieved by modelling site units based on their crop specific attribute (crop type and geographical extent). As a result, each site unit is composed of crop specific subunits which are the atomic input for EPIC simulation (Figure 2). Subunits can be limited to the most predominant crops, resulting in simulation time saving, or can be used in full to model each crop contained into the specific 10 km run unit.

Figure 3 shows an example of crop specific subunits for a site (10 km square cell) that contains maize, rice, durum wheat and a non agricultural portion where EPIC modelling is not performed. Subunits can be seen as fictitious crop fields of a size which is the total crop area within the 10 km site cell with an undefined spatial location within the site cell having the soil, meteorological, topographic attributes of the whole site cell.

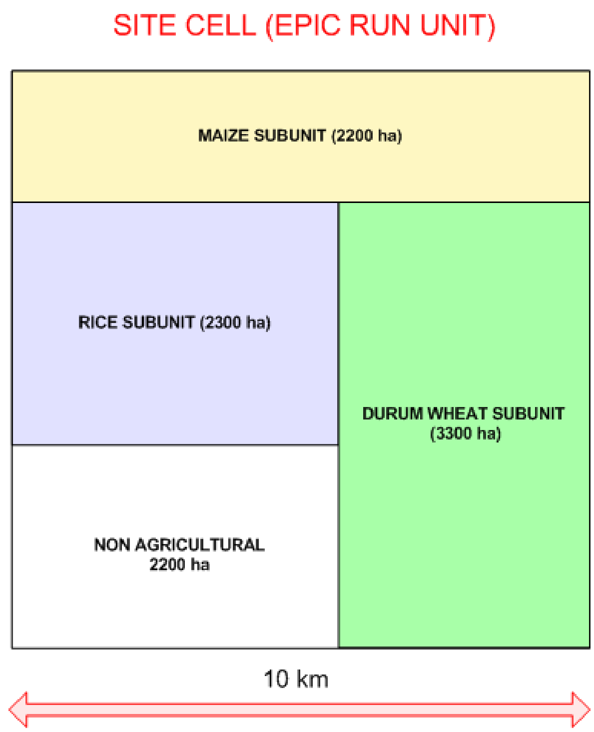

Figure 3. Crop specific run subunit

This conceptual model allows performing EPIC modelling based on the mentioned subunits re-aggregating back the results to run unit level.

The previously illustrated conceptual model was implemented into an object relational data model within the context of the ESRI ArcGIS personal geodatabase.

Various implementation stages of the data model took into account all the rules that are relevant for the sake of EPIC modelling resulting into a final geodatabase data model whose general structure is illustrated in Figure 4.

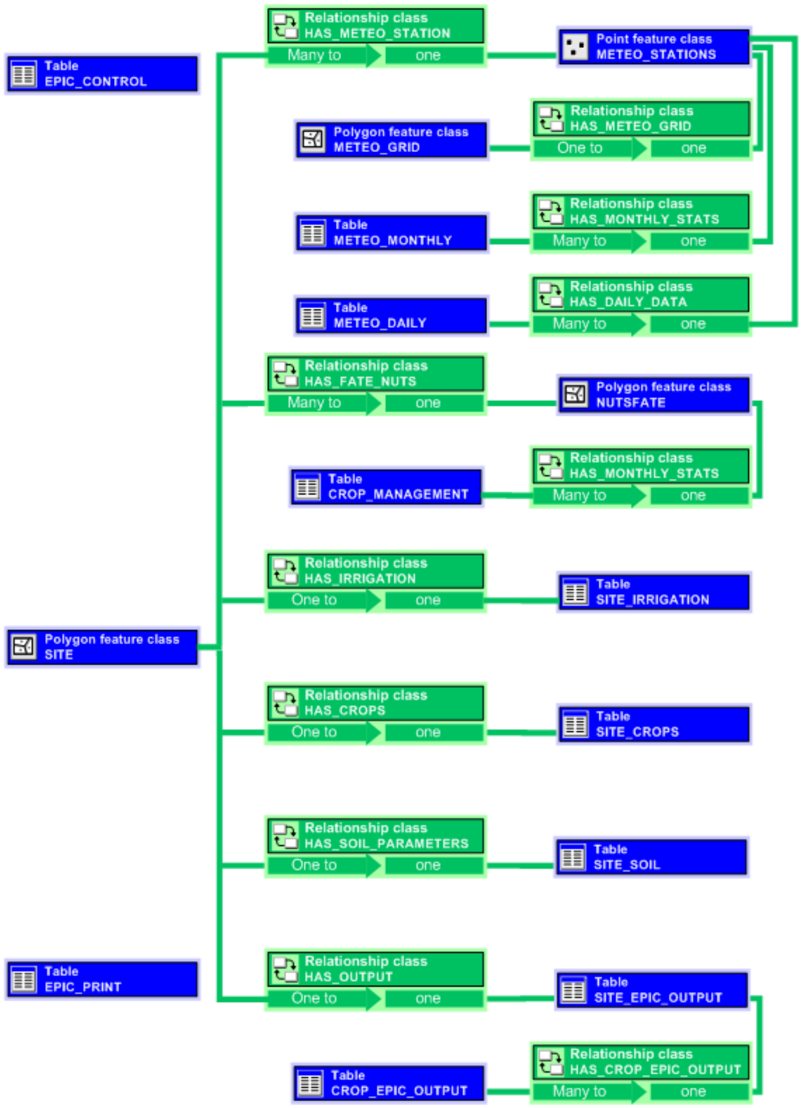

Figure 4. Feature, table and relationship classes of EAGLE geodatabase data model

Within the data model four distinct macro sections can be identified:

- **SITE section**. It is characterised by the SITE feature class and by the following related attribute tables (one to one cardinality) :
  - o SITE_CROPS
  - o SITE_IRRIGATION
  - o SITE_SOIL

- **METEOROLOGICAL section**. It is characterised by METEO_STATIONS feature class (centroids of METEO_GRID feature class) and the following related tables (one to many cardinality):
  - METEO_DAILY
  - METEO_MONTHLY
- **MANAGEMENT section**. It is characterised by NUTSFATE feature class and CROP_MANAGEMENT table
- **OUTPUT section**. It is characterised by SITE_EPIC_OUTPUT table and the related (one to many cardinality) CROP_EPIC_OUTPUT table.

Each section will be detailed in the following pages outlining used input data and pre-processing tasks to fit them into the chosen data model.

3.2 GEODATABASE SITE SECTION

3.2.1 INTRODUCTION

This section is the core part of the EAGLE data model as it contains the EPIC spatial run units with aggregated information about landuse (crop distribution) and soil parameters.

3.2.2 INPUT DATA

3.2.2.1 Soil data

Most of the soil data required to run EPIC was derived from Pan European soil data provided by the JRC's European Soil Bureau Network (ESBN). The European Soil Bureau Database (ESBD) is the only comprehensive source of data on the soils of Europe harmonised according to a standard international classification (FAO) (Jones et al., 2004) and contains:

- Soil Geographical Database of Europe (SGBDB),
- Soil Profile Analytical Database of Europe (SPADE),
- Hydraulic Properties of European Soils (HYPRES) database linked to the SGDBE, and
- Pedo-transfer Rules (PTR) database.

The Soil Geographical Database of Europe (SGBDB) contains the soil-mapping units (SMU) at a scale of 1:1,000,000 that can be related to the Soil Typological Units (STU) that contain soil parameter data. However, as each SMU can be related to one or more STUs, the percentage occurrence of each STU in each corresponding SMU is given within the SGBDB (See Figure 5). The STUs can be linked to the pedo-transfer database that contains class based soil data derived from an expert system for the estimation of several additional parameters needed for environmental interpretations of the soil map.

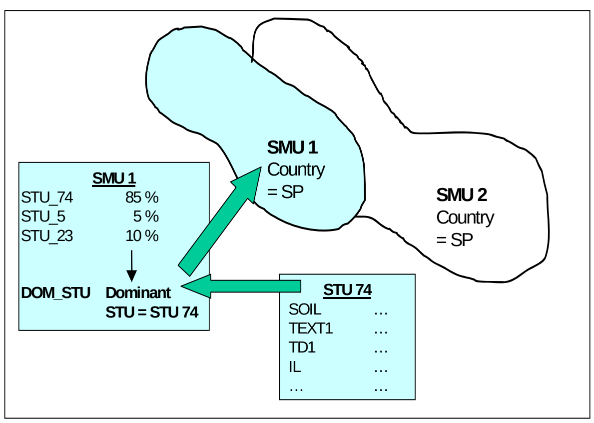

Figure 5. STU and SMU relationship

Soil data for the EAGLE project was derived using the SMUs and 1 km x 1km soil raster data. The ESBN have created a series of 1 km x 1 km soil rasters including topsoil organic carbon content that has been calculated using a refined pedo-transfer rule derived from the European Soil Database, an extended CORINE land cover dataset, a digital elevation model (DEM) and mean annual temperature data (Jones et al., 2004). Additional data were provided as an ESRI grid raster dataset including the following layers:

- Topsoil sand content (%): SLP_SAND,
- Subsoil sand content (%): SLP_TDSAND,
- Topsoil silt content (%): SLP_SILT,
- Subsoil silt content (%): SLP_TDSILT,
- Topsoil organic carbon content (%): OCTOP_GRID,
- Topsoil cation exchange (cmo /kg soil): SLP_CECTOP,
- Subsoil cation exchange (cmo /kg soil): SLP_CECSUB,
- Topsoil base saturation (%): SLP_BSTOP,
- Subsoil base saturation (%): SLP_BSSUB,
- Topsoil packing density (%): SLP_PDTOP,
- Subsoil packing density (%): SLP_PDSUB.

3.2.2.2 Landuse data

For the construction of a land use map two approaches were used within the FATE project, both based on FSS statistical crop area data and Corine Land Cover 2000 (Mulligan et al., 2006). In the first approach that covers EU15, FSS (Farm Structure Survey / Eurostat) data on crop areas were spatialised using the Corine Land Cover 2000 preserving the surface covered by each crop reported by FSS (Grizzetti et al. 2006). The second approach that was used for the 10 new Member States preserved, only the proportion of crop type reported by FSS. The list of the major crops considered within the FATE project is given below in Table 1.

FATE_CODE	DESCRIPTION	EPIC_CODE	EPIC_NAME
SWHE	Common wheat and spelt	SWHT	Spring wheat
MAIZ	Maize	CORN	Corn
RICE	Rice fields	RICE	Rice
OLIV	Olive plantations	OLIV	Olive trees
DWHE	Durum wheat	WWHT	Winter wheat
RYEM	Rye	RYE	Rye
BARL	Barley	BARL	Barley
OATS	Oats	OATS	Oats
PULS	Pulses - total	GRBN	Green beans
POTA	Potatoes	POTA	Potatoes
SUGB	Sugar beet	SGBT	Sugar beets
ROOF	Fodder roots and brassicas	SPOT	Sweet potatoes
RAPE	Rape and turnip	RAPE	Rapeseed
SUNF	Sunflower	SUNF	Sunflowers
SOYA	Soya	SOYB	Soybeans
OOIL	Other oil-seed or fibre plants	CANA	Canola argentine
OVEG	Under glass:fresh vegetables; melons; strawberries	CRRT	Carrots
OFAR	Forage plants - temporary grass	SGHY	Sorghum hay
MAIF	Green maize:other green fodder:forage plants	CSIL	Corn silage
TWIN	Vineyards - quality wine	GRAP	Grape
APPL	Fruit and berry plantations - total	APPL	Apple trees
GRAI	Pasture and meadow:permanent grassland and meadow	SPAS	Summer pastures
TWIO	Vineyards - other wines	GRAP	Grape
TAGR	Vineyards - table grapes	GRAP	Grape
TARA	Vineyards - raisins	GRAP	Grape
TABO	Olive plantations - table olives	OLIV	Olive trees
GRAE	Rough grazings:permanent grassland and meadow	SPAS	Summer pastures
CITR	Citrus plantations	CITR	Citrus trees
OCRO	Other permanent crops	APPL	Apple trees
OCRG	Permanent crops under glass	APPL	Apple trees
TOBA	Tobacco	TOBC	Tobacco
HOPS	Hops	TOBC	Tobacco
COTS	Cotton	COTS	Stripper cotton
TOMA	Outdoor:fresh vegetables; melons; strawberries	TOMA	Tomatoes

Table 1 Major crops considered in the EPIC runs

3.2.2.3 Topographic data

Digital elevation data were provided by Institute for Environment and Sustainability at the Joint Research Centre as a pan European DEM based on SRTM (Shuttle Radar Topographic Mission) data. Data were obtained in ESRI grid format with a resolution of 90 m in Lambert Azimuthal Equal Area projection based on ETRS 89 datum (ETRS_89_LAEA).

3.2.3 DATA PRE-PROCESSING

3.2.3.1 EPIC spatial run units creation (SITE feature class)

As outlined before, the basic EPIC geographic modelling unit was set as a squared area (10km X 10km) where soil, climate are considered constant. A collection of such units was then required in order to cover the EU25 territory based on precise specifications. To model such situation in GIS terms a feature class was created using the vector data model to represent a geographic grid with the following characteristics:

- based on a projected (bidimensional) space in Lambert Azimuthal Equal Area projection (ETRS_89_LAEA projection),
- spatial extent compatible with current standards adopted within European geographic projects (i.e. CORINE landcover),
- each running unit is a squared shape in the mentioned bidimensional space with a size 10km X 10 km. Units are topologically clean (non overlapping polygons, no gaps between unit boundaries),
- run units non overlapping mainland are excluded.

A master grid vector shapefile was created using “Fishnet Tool”, available in the ESRI Developer Network, as an ESRI ArcMap customisation. The chosen spatial extent in ETRS_89_LAEA (Left bounding 2,400,000, right bounding 6,900,000, top bounding 5,750,000, bottom bounding 1,250,000), was a reduced version of the one adopted by CORINE landcover project. It excludes Canary and Azores islands and some Eastern Europe zones which are outside EU25. Bounding limits assure integer coordinate values at 10k cell corners and proper overlapping with other grids based on original CORINE landcover extent.

The master grid was subsequently cleaned resulting in a total of 49,157 cells covering European EU25 territory. The resulting grid is illustrated below for Northern Italy (Figure 6).

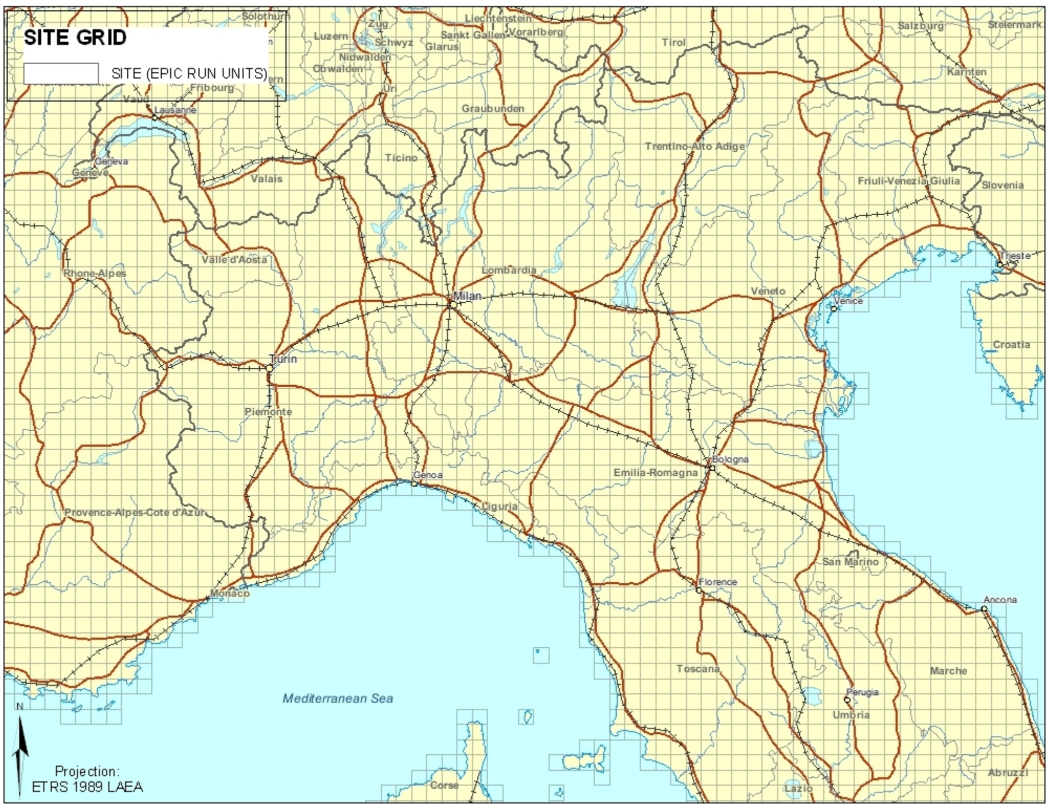

Figure 6. Details of EAGLE SITE feature class for Northern Italy

3.2.3.2 Soil data

Dataset provided by ESBN was initially used to derive two additional soil parameters:

- bulk density data were obtained from packing density using the pedo-transfer function:

$$\rho_b = P_d - (CL \times 0.009) \tag{13}$$

where ρ_b (kg/m^3) is the dry bulk density, P_D is the packing density (g/cm^3) and CL is the clay content (fraction). This calculation was performed using ESRI Spatial Analyst tools on input ESBN grids for topsoil and subsoil resulting in two raster grids containing bulk density data (BD_TOP, BD_SUB)

- base saturation (fraction of CEC occupied by base cations), was used to derive soil pH (see Mulligan et al., 2006 for more details):

$$pH = 0.054 \times \left(B_s + 3.8\right) \tag{14}$$

Two pH grids for topsoil and subsoil (PH_TOP, PH_SUB) were obtained as processing outputs.

Available soil data (1 km resolution) were then aggregated to run unit resolution (10 km) calculating the mean value. This was done using ESRI Spatial Analyst tool “Zonal Statistic as Table” against each input soil parameter grid. Geoprocessing scripts (Python/Vbscript) and models were created in order to overcome data size limitations into available tools. Run units (sites) were grouped into sectors to be processed separately for each soil parameter. Sector outputs were then recomposed into a single final table for each soil parameter input raster (Figure 7).

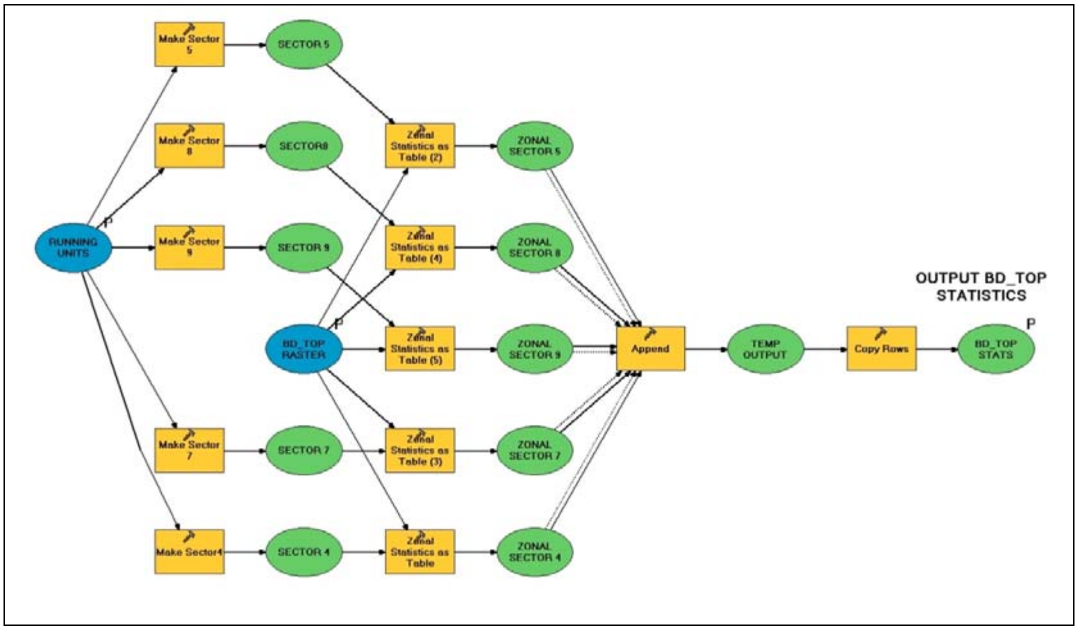

Figure 7 Example of soil parameter aggregation sub-processing model for site cells

To satisfy EPIC inputting needs new soil parameters were calculated based on pedo-transfer functions used with the available aggregated data. Particularly, topsoil organic matter was calculated as follows:

$$OM\_TOP = OCTOP\_GRID \times 1.714 \qquad (15)$$

where OCTOP_GRID ID is the organic carbon content (%).

Two alternatives were used to estimate soil water holding capacity. The first one is based on the Rawls and Brakensiek (1985) model where soil water holding properties are estimated as follows:

$$WP = 0.026 + 0.005\ CL + 0.0158\ OC \qquad (16)$$

and

$$FC = 0.2546 - 0.002\ SA + 0.0036\ CL + 0.0299\ OC \qquad (17)$$

where WP and FC are the wilting point and field capacity (cm/cm), respectively, SA is the sand content (%) and OC is the organic matter content (%).

In addition, the soil functional relationships were also calculated by the van Genuchten (1980) equations according to Mualem theory (1976) and were used to determine among others the saturated hydraulic conductivity. Saturated hydraulic (Ks) conductivity was then used to classify EPIC run units into four hydrologic groups as follows (Arnold, 1999):

1. Group A: minimum saturated hydraulic conductivity in the uppermost 0.5 m Ks > 110 mm/h,
2. Group B: minimum saturated hydraulic conductivity in the uppermost 0.5 m Ks < 110 mm/h and > 11 mm/h,
3. Group C: minimum saturated hydraulic conductivity in the uppermost 0.5 m Ks < 11 mm/h and > 1.1 mm/h, and
4. Group D: minimum saturated hydraulic conductivity in the uppermost 0.5 m Ks < 1.1 mm/h.

Output statistical tables for each soil parameter were then joined together, keeping the mean value field only, resulting in a final soil attribute table with data aggregated at site level.

3.2.3.3 Topographic data

Input providing digital elevation model (SRTM grid) was processed to obtain a slope grid with the same spatial extent and resolution. Values for elevation and slope within site cells were then aggregated using a similar procedure used for soil parameters and were appended, as attributes to the SITE feature class.

3.2.3.4 Landuse data

Input landuse raster grid (100 m resolution) was tabulated against the SITE feature class to obtain area amounts of landuse classes as site (10 km) attributes. This was done by using ESRI Spatial Analyst tool “Tabulate Areas” with a procedure similar to the one adopted for the soil data (sectorial sub-processing). Output table attributes were then limited to 45 crop classes considered into FATE input landuse grid. Through this procedure 5820 sites (running units) were identified as non agricultural (all crop attributes equal to zero). They were kept in the site feature class but they were flagged in order to exclude them from EPIC simulations. Each site is thus characterised by multiple crops having each its own area (Figure 8).

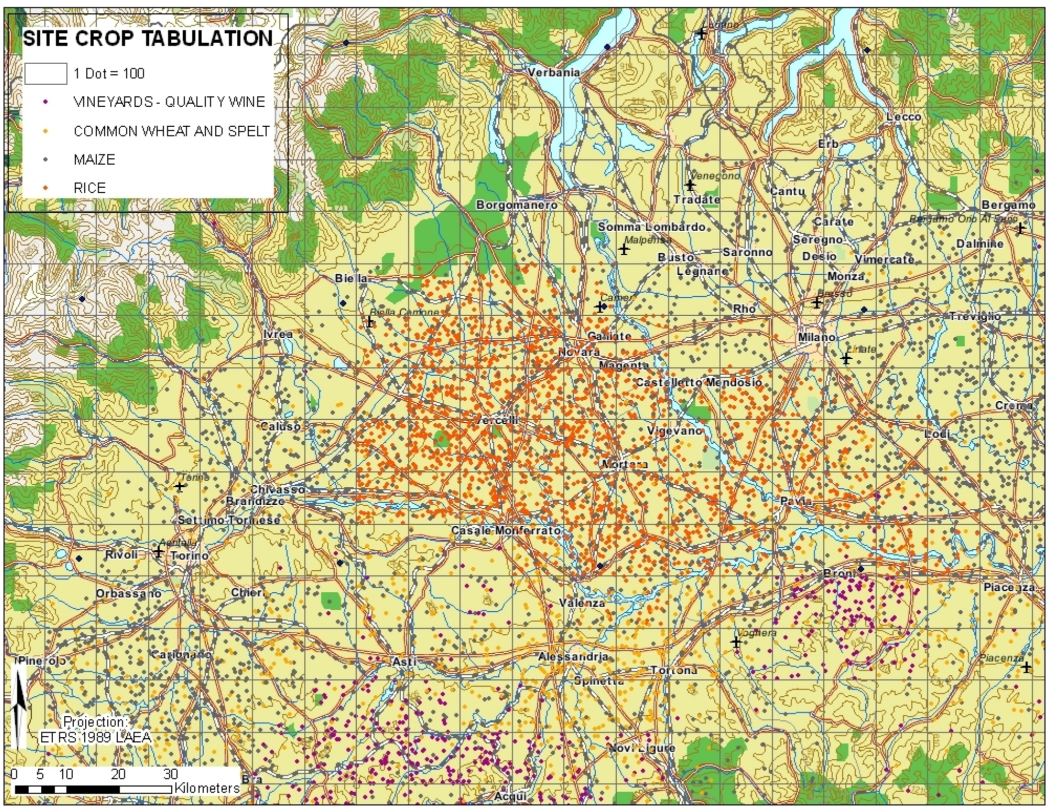

Figure 8 Crop site tabulation for maize, wine, rice and wheat expressed as dot density

3.3 GEODATABASE METEOROLOGICAL SECTION

The meteorological section of EAGLE geodatabase provides EPIC modelling with the required meteorological information. Its database design was mainly driven by:

- **EPIC simulation meteorological needs**. EPIC runs on a daily basis requiring detailed meteorological daily information about various parameters including maximum and minimum temperature, relative humidity, rainfall, solar radiation. Whenever daily data are not available a weather generator creates, based on available monthly meteorological statistics, the required daily information. As a result, such statistics must be provided as input for an EPIC simulation in addition to available daily data.
- **Available data from data provider**. The data set used is the “Meteorological Interpolated Data” of the CGMS system developed at the AGRIFISH (MARS) Unit of The Joint Research Centre of the European Commission. This dataset was pre-processed in order to fit the EPIC modelling requirements.

3.3.1 INPUT DATA

Meteorological interpolated data were created by MARS/AGRIFISH Unit of the Joint Research Centre within the context of the “Crop Growth Monitoring System” (CGMS), (Micale and Genovese, 2004). Measured data, obtained from existing meteorological stations across Europe for the time period 1990/2003, were interpolated into a 50 km square grid. The resulting digital database is composed of a spatial section consisting of the 50 km grid, and a tabular section storing values for meteorological variables. An identifier field allows for direct linking of the tabular data to the related grid cell.

3.3.1.1 CGMS tabular section

This section is composed of a collection of records storing meteorological attributes for each cell of the interpolated grid with a daily temporal resolution (1990/2003). Available attributes, shown in Table 2, describe average conditions over the spatial extent of a grid cell for a specific day but do not necessarily represent meteorological values measured at the cell centroid. Moreover, due to lack of measured data, global radiation and potential evapotranspiration were calculated at station level using other available meteorological parameters. These tabular data were provided by AGRIFISH Unit in form of structured text files containing the mentioned attributes for each grid cell (fictitious meteorological station coming from interpolation process) covering the time period from 1990 to 2003.

MAXIMUM_TEMPERATURE	Maximum temperature (°C)
MINIMUM_TEMPERATURE	Minimum temperature (°C)
VAPOR PRESSURE	Mean daily vapour pressure (hPa)
WINDSPEED	Mean daily winds peed at 10m (m/s)
RAINFALL	Mean daily rainfall (mm)
E0	Penman pot. evap. from free water surface(mm/day)
ES0	Penman pot evap from a moist bare surface (mm/day)
ET0	Penman pot. transp. from a crop canopy (mm/day)
CALCULATED_RADIATION	Daily global radiation in KJ/m^2/day
SNOW_DEPTH	Daily mean snow depth in cm

Table 2. CGMS Available daily meteorological parameters

3.3.1.2 CGMS spatial section

It is composed of a collection of records representing the bidimensional geographic objects (grid cells) used for the spatial interpolation process. Each object (50 km square grid cell) can be linked, through an identifier, to its related meteorological parameters in the tabular section with cardinality of one to many.

The spatial projection of the meteorological grid is the old GISCO (9,48) Lambert Azimuthal Equal Area (Units: meters; Spheroid: sphere; Sphere radius: 6378388 m;

Longitude of origin: 09° 00' 00"; Latitude of origin: 48° 00' 00"; False easting: 0.0; False northing: 0.0).

The collection is composed of 5803 spatial objects (50 km non overlapping grid cells) covering the EU member states, the central European eastern countries, the new independent states and some Mediterranean countries. Data are made available in an ESRI shapefile format containing 5803 grid cells (Figure 9).

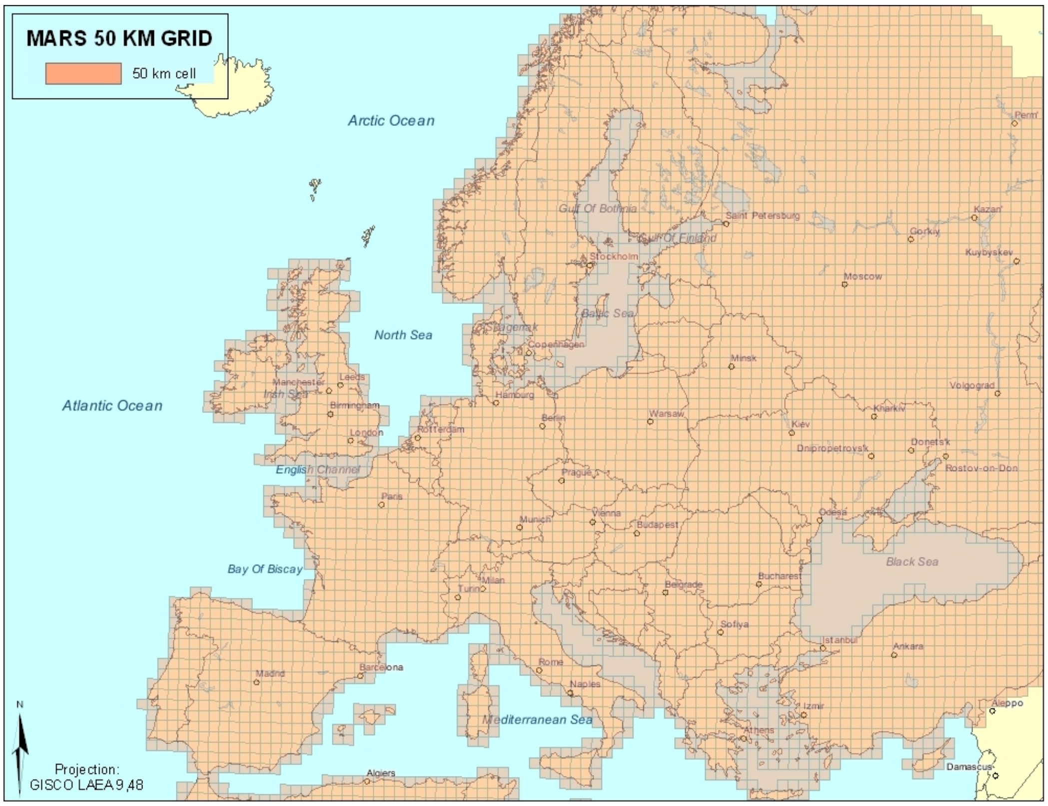

Figure 9. Overview of CGMS/MARS 50 km grid

3.3.2 DATA PRE-PROCESSING

The MARS/AGRIFISH climatic data were pre-processed in order to satisfy EPIC modelling needs. The sections below explain the most relevant pre-processing tasks that were performed on both spatial and tabular input data.

3.3.2.1 Tabular data

Structured meteorological text files were imported into a Microsoft SQL Server 2005 table to benefit from the large data manipulation tools which are available in the database management systems. Attributes of the mentioned table are the same characterising daily records in the original text files, specifying date, meteorological station and meteorological parameters. A total of 12,574,324 records were imported.

Because of EPIC additional input requirements, a new attribute containing a calculated value for the relative humidity (Rh; %) was added. The calculation was performed using the following equation:

$$Rh = \frac{e}{e_s} \tag{18}$$

where e is the actual vapour pressure (hPa; available from input data) and e_s is the saturated vapour pressure (hPa) at a given temperature. The parameter e_s was calculated using the following approximation equation (Chow et al., 1988) that relates air temperature to the vapour pressure over a water surface:

$$e_s = 611 * \exp\left(\frac{17.27 * T}{237.3 + T}\right) \tag{19}$$

where T is the actual temperature (°C), calculated as an average of the available daily maximum and minimum temperatures.

Meteorological monthly statistics were calculated using the WXPM3050 tool that comes with the EPIC toolset (version 3050). A batch processing Visual Basic program was created to prepare WXPM3050 input files for each meteorological stations (grid cell). The batch program reads data from a SQL Server table, runs WXPM3050.EXE via shell and reads output files populating a SQL Server table to store output statistics. The obtained final table (METEO_MONTHLY) stores 30504 records consisting of 12 different statistics (Table 3) for 2542 meteorological stations (months are attributes).

TMX	Average monthly maximum temperature (°C)
TMN	Average monthly minimum temperature (°C)
SDMX	Monthly av. std. deviation of daily maximum temperature (°C)
SDMN	Monthly av. std. deviation of daily minimum temperature (°C)
PRCP	Average monthly precipitation (mm)
SDRF	Monthly standard deviation of daily precipitation (mm)
SKRF	Monthly skew coefficient for daily precipitation
PW|D	Monthly probability of dry day after wet day
PW|W	Monthly probability of wet day after wet day
DAYP	Average number of days of rain per month
RAD	Average monthly solar radiation (MJ/m2)
RHUM	Monthly average relative humidity (fraction)

Table 3. Calculated monthly meteorological statistics

3.3.2.2 Spatial data

The CGMS shapefile containing the meteorological grid underwent the following processing:

- conversion to an ESRI geodatabase feature class with the same attributes. Spatial domain was set as the conversion default,
- reprojection to Lambert Azimuthal Equal Area based on ETRS 89 geographic coordinates system (ETRS_89_LAEA). This projection preserves the area of individual polygons while simultaneously maintaining a true sense of direction from the centre. It is compliant with the European Commission's Infrastructure for Spatial Information in the Community (INSPIRE) guidelines (CEC, 2004). The details of the projection are as follows: Coordinate System: GCS_ETRS_LAEA; Datum: D_ETRS_LAEA; Prime Meridian: 0; False easting: 4321000; False northing: 3210000; Central Meridian: 10; Latitude of origin: 52; Linear Unit: meter,

- all the grid cells without related daily data into the tabular section were erased resulting in a final grid composed of 2542 cells. This was due to the fact that the tabular data were extracted based on EU25 spatial extent ignoring daily records of meteorological stations outside the EU25 territory. The resulting map is shown in Figure 10.

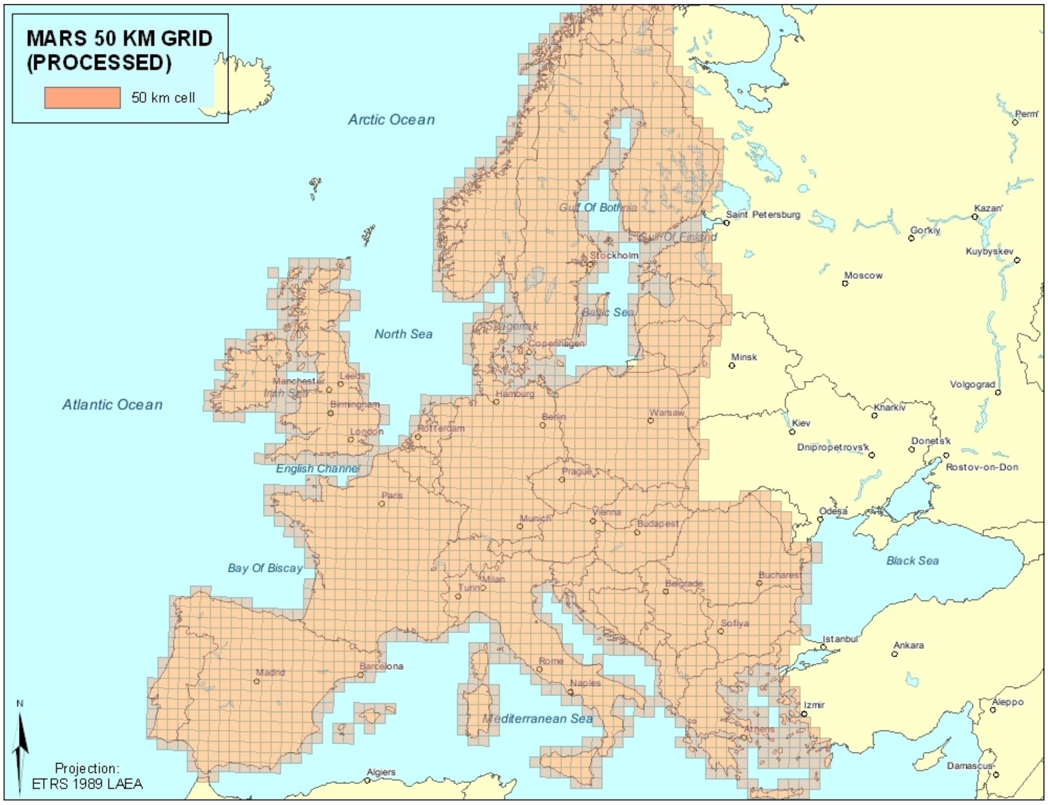

Figure 10. CGMS grid after reprojection to ETRS 1989 LAEA and pre-processing

It has to be noted that the reprojection operation, while preserving cell areas, resulted into a slight grid distortion. The MARS/CGMS grid, reprojected into ETRS_89_LAEA, does not overlap with the 10 km grid of the SITE feature class. Subsequently, the centroids of the output meteorological grid were used to build a linkage between site polygons (EPIC running unit) and meteorological stations. This was done with a spatial join procedure linking each site cell to the closest meteorological station (Figure 11).

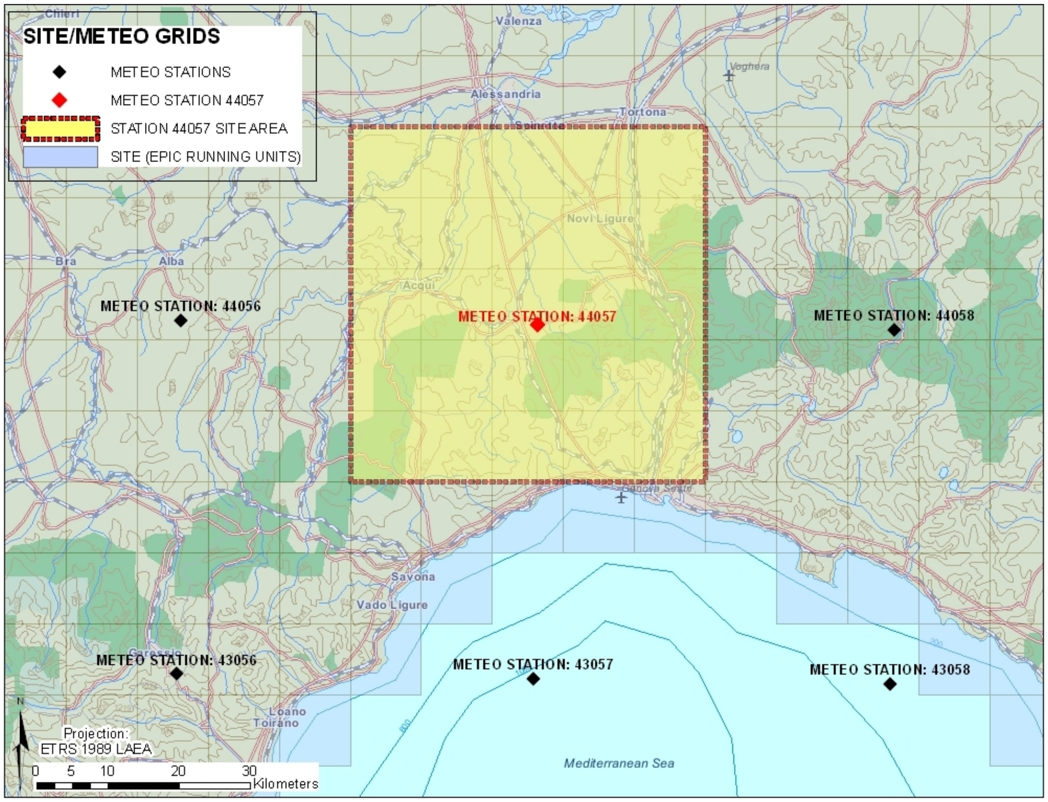

Figure 11. Linkage between meteorological stations and site polygons (10 km EPIC run units)

3.3.3 *GEODATABASE METEOROLOGICAL DATA MODEL*

Taking into considerations all the aspects outlined in the previous sections, the EAGLE personal geodatabase was integrated with a meteorological section to provide the necessary input data for EPIC modelling and to support GIS spatial analysis.

Meteorological daily data were exposed into the geodatabase to assure database completeness outside EPIC sessions. However, for the sake of EPIC simulations, daily data are statically provided as a set of 2542 EPIC meteorological daily files (one for each interpolated meteorological station) permanently stored in the EPIC run directory. They were created once from the METEO_DAILY table through the use of a Visual Basic routine. This option greatly reduces the overhead of the EAGLE GIS interface saving lengthy querying and outputting time. Figure 12 shows a representation of the meteorological section of the geodatabase.

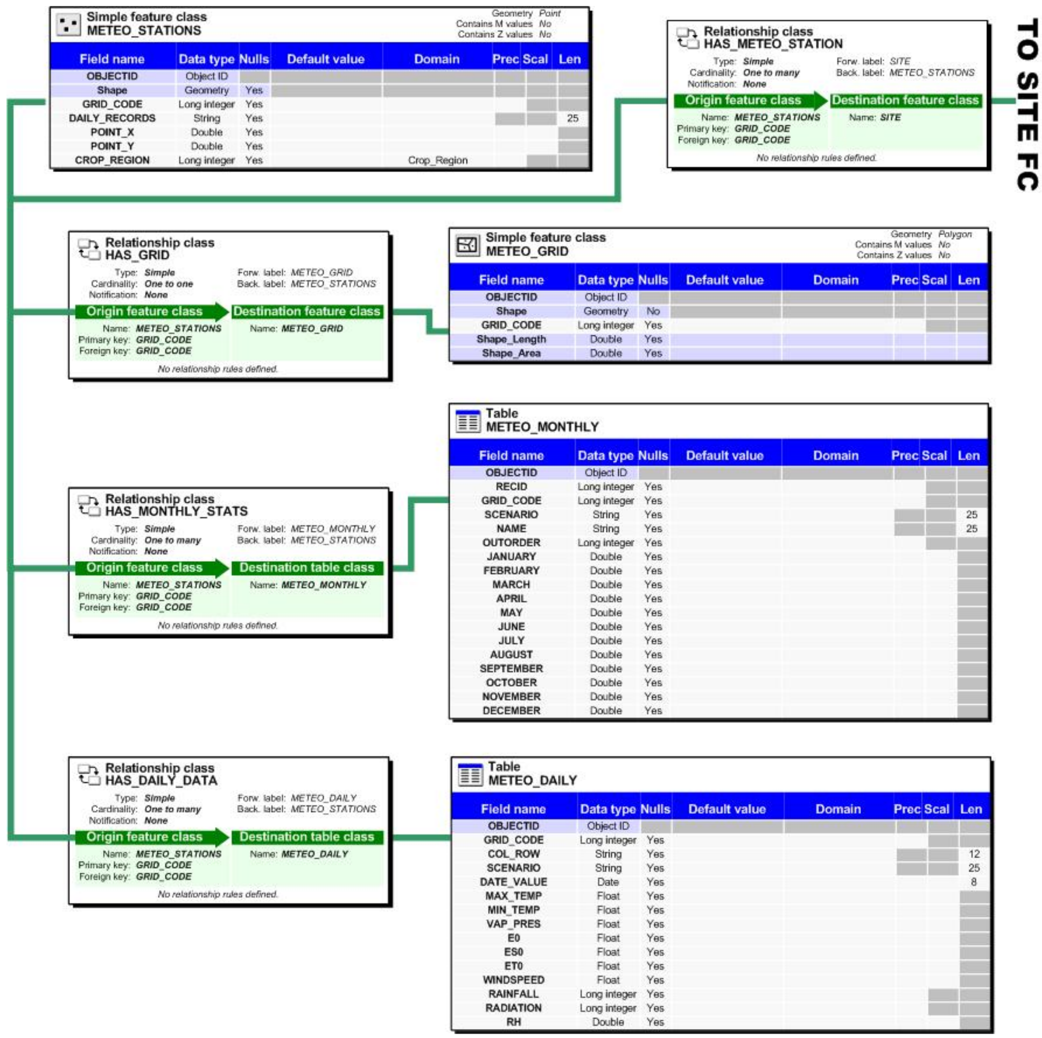

Figure 12. EAGLE meteorological section data model

Particularly, the METEO_MONTHLY table is loaded with the monthly meteorological statistics calculated at pre-processing stage using the entire set of daily records. Relationship classes link the METEO_STATIONS feature class to daily and monthly statistical records with a cardinality of one to many. The relationship class HAS_METEO_STATIONS provides linkage to the SITE feature class in order to associate each EPIC run unit to a meteorological station.

3.4 GEODATABASE CROP MANAGEMENT SECTION

Data about crop management practices are one of the required inputs for EPIC modelling. They consist of detailed schedules of the most common crop operations (sowing, harvesting, tillage, fertilisation) for each crop used for EPIC simulations.

The impossibility to obtain such information at a relevant resolution for the entire EU25 territory lead to the adoption of a specific methodology to model management practices for the 45 crops considered in the EAGLE database. The results were then partially compared and validated against some available data at regional scale.

3.4.1 INPUT DATA

Input data used to obtain crop management schedules include:

- geodatabase polygon feature class containing administrative divisions of countries called Nomenclature of Territorial Units for Statistics (NUTS). Original NUTS polygons (version 8), provided by Eurostat, have been pre-processed to fix some coding inconsistencies when joining them to available tabular data. The modified data stored into a feature class (NUTSFATE), contain 609 NUTS polygons (mainly at statistical level 3) covering EU25,
- parameters for biomass and yield calculations (FAO),
- crop parameters and management data from Blackland Research and Extension Center (Texas Agricultural Experiment Station). Data are included in the modelling applications (including EPIC) distributed by the institute.

- crop scheduling information from Crop Growth Monitoring System (MARS/ AGRIFISH Unit – Joint Research Centre) (Lazar and Genovese, 2004)
- 1990/2003 meteorological daily data from the Crop Growth Monitoring System (MARS/ AGRIFISH Unit – Joint Research Centre)
- data on nitrogen and phosphorous input calculated at NUTS level 2 by the JRC (Grizzetti et al., 2007) and University of Bonn's Common Agricultural Policy Regional Impact Analysis database/model(CAPRI)

3.4.2 DATA PRE-PROCESSING

The key issue of this section was to create a methodology to obtain crop management schedules based on input data. The backbone of this procedure was the identification of sowing dates, for each crop, based on the known time interval between sowing and harvesting dates taking into account meteorological factors and crop specific growth parameters. A scheme of the pre-processing flow is shown below in Figure 13.

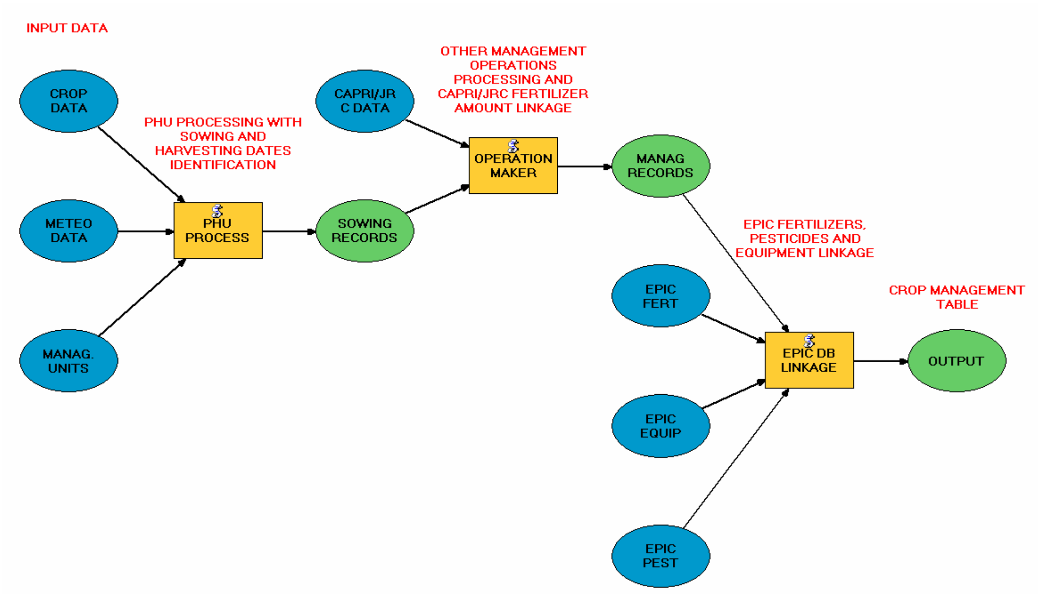

Figure 13. Scheme of the overall management section pre-processing flow

3.4.2.1 Management units

NUTSFATE polygons were used as basic management units. This choice was driven by the fact that management practices and climatic factors (maximum and minimum temperature) can be reasonably considered homogeneous over a NUTS3 administrative unit. An increase in resolution might have dramatically affected database size while not enhancing the level of information.

In order to differentiate crop varieties used in different European regions, it was decided to divide EU25 into 5 main climatic zones: Alpine, Mediterranean, Atlantic, Boreal and Continental (Figure 14). Within a climatic zone, a unique crop variety is considered characterised by a specific time to maturity interval.

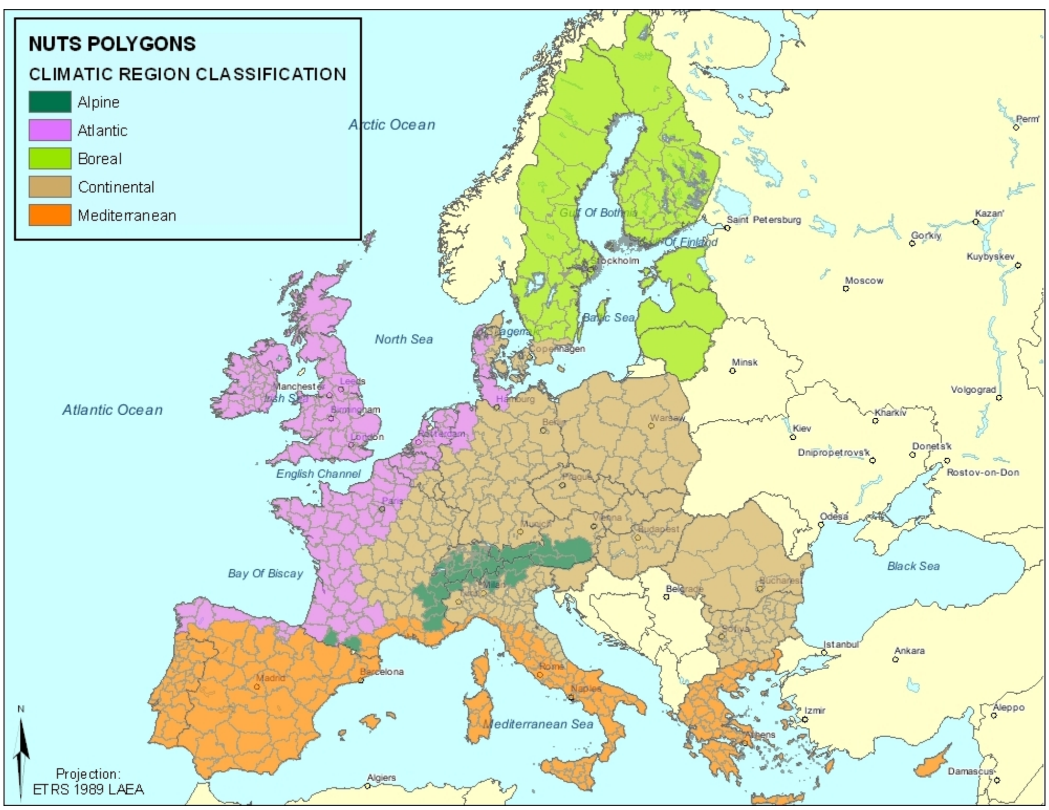

Figure 14. NUTSFATE polygons aggregation into crop regions

Using calculated monthly statistics for the interpolated CGMS stations (see meteorological section), average minimum and maximum monthly temperatures were calculated for the management units spatially joining them to the interpolated CGMS stations (averaging enclosed temperature values).

3.4.2.2 Sowing date evaluation

For this purpose the specific tool "Potential Heat Units" program (PHU), developed at Texas Agricultural Experiment Station, was used. The PHU program calculates the total number of heat units required to bring a plant to maturity using long term minimum/maximum temperatures, optimum and minimum plant growing temperatures and the average number of days for the plant to reach maturity.

The heat unit theory states that plants have specific heat requirements that can be linked to the time to maturity. The portion of the average daily temperature that exceeds the plant's base temperature is the one contributing to plant growth. The heat unit (HU) for a given day can be expressed as follows:

$$HU = T_{av} - T_b \quad ; \quad when \quad T_{av} > T_b \qquad (20)$$

where T_{av} is the average daily temperature (°C) and T_b is the crop base temperature (°C). The total amount of heat units required to reach maturity is:

$$PHU = \sum_{d=1}^{m} HU \qquad (21)$$

where *d* and *m* identify the know time interval for the plant to reach maturity (sowing/planting to harvesting). It has to be noted that, for perennial crops, time to maturity interval is identified by using seasonal crop growing stages like budding and leaf senescence.

For each crop considered in the EAGLE project the following information was used as input for the PHU program:

- crop growing season (winter versus spring crop),
- base growing temperature (°C),
- optimum growing temperature (°C),
- dry down fraction,
- time to maturity (days) which corresponds to the number of days between planting and harvesting. This attribute is related to the climatic zone. Different growing time intervals are provided for each climatic zone.

These data are provided through a structured text file (PHUCRP.DAT) to the PHU executable. Each record has five different fields for time to maturity in order to differentiate among climatic regions. The crop growing season, the base and optimum growing temperatures, and the dry down fraction were taken from the default values provided by the PHU and EPIC crop databases. Specific crop time to maturity intervals were estimated for each climatic region comparing different data sources (FAO, CGMS). Such information was then processed against each running unit (NUTS administrative area) where long term minimum/maximum temperatures are known. An example of result is shown for maize in Figure 15.

A Visual Basic program was developed to batch process management units with the PHU program and writing outputs to a database table. The program manages the entire process from PHU input preparation and PHU execution (via shell) to writing outputs (sowing dates and heat units) to a database table. It has to be noted that all the 45 crops were processed within each management unit without taking into account crop geographic suitability (i.e., olive tree in Scandinavia). Cleaning is performed by the mentioned Visual Basic program by removing crop records that, based on the input landuse, are non existent into the specific management units.

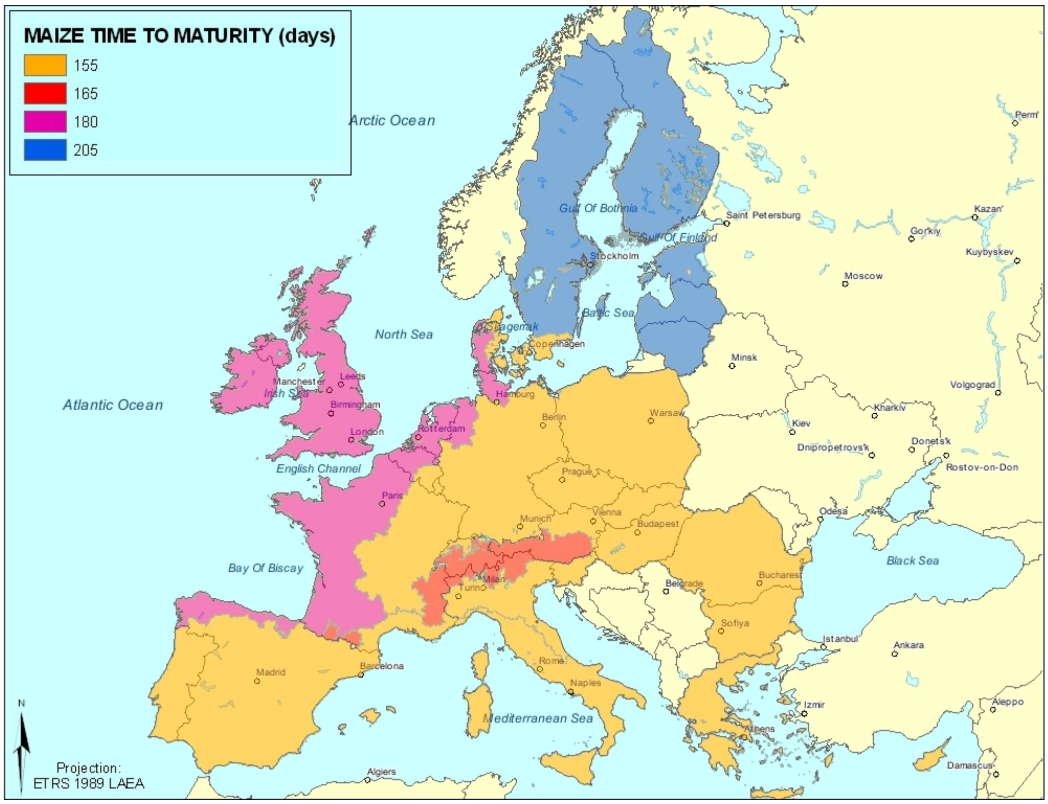

Figure 15. Different time to maturity intervals (days) for maize according to the climatic regions

3.4.2.3 Other operation schedules evaluation

Other relevant crop operation schedules were evaluated relating them to the known sowing/planting dates. The following simple schema was adopted:

- crop harvesting date: calculated by adding the climatic region specific time to maturity to the sowing date,
- crop killing date: calculated as harvesting date + 1. This is the physical removal of the crop from the field,
- crop tillage date: calculated as sowing date -3,

- crop fertilisation date: calculated as sowing date -2.

Results obtained with the adoption of such simplified schema do not reflect real crop schedules. However, crop sowing and harvesting dates obtained from the PHU methodology are a good approximation of the real situation. The map in Figure 16 shows the difference in days for maize sowing schedules between the adopted methodology and data available from MARS /Crop Growth Monitoring System (JRC).

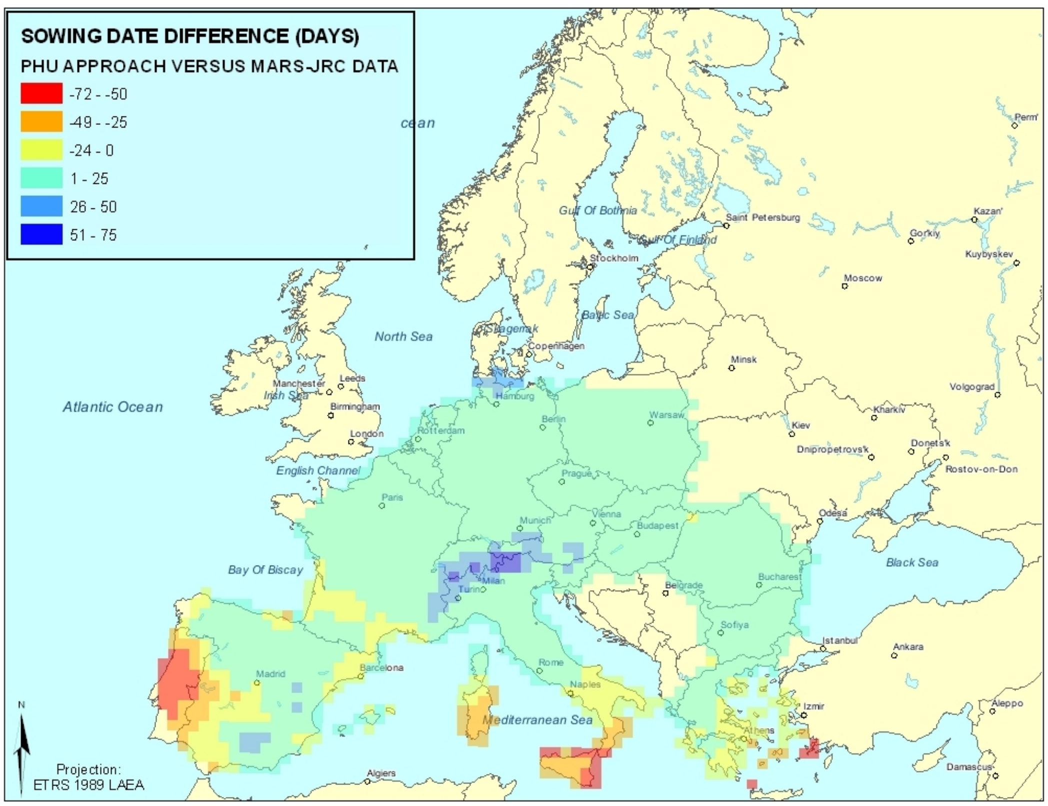

Figure 16. Difference between maize sowing dates with MARS/CGMS data

For perennial crops, an average lifespan of ten years was assumed and the previous schema was iterated for the entire period based on the following specifications:

- for year 1 to 3 harvesting operation was excluded. It was assumed that an early growth stage (first three years) the crop was not productive,

- for year 1 to 9 killing operation was excluded,
- for year 2 to 10 the sowing (planting) operation was excluded.

3.4.2.4 Fertilisation database linkage

Through a linkage between FATENUTS polygons and JRC/CAPRI polygons (mostly NUTS level 2 polygons) fertiliser application amounts were set to those specified in the JRC and CAPRI databases. The fertilising operation previously identified was subdivided into four sub-operations in order to differentiate among the most common fertilisation types. Particularly, the following were considered:

- elemental nitrogen,
- elemental phosphorous,
- hog fresh manure,
- dairy fresh manure.

This choice was driven by the existing EPIC fertilisation data (stored into fert.dat EPIC file). Two manure applications of a different type were considered in order to better approximate manure nutrient amounts which are expressed as mass of organic nitrogen and phosphorus. As a result the amounts of the two manure applications were set to respect the overall balance specified in the JRC/CAPRI databases. These operations are performed together at Julian day sowing – 2.

3.4.2.5 Cleaning data

The Visual Basic pre-processing logic was designed to perform checks on data consistency and cleaning processing mistakes. Particularly:

- PHU output failures were excluded from the processing flow. These failures were exclusively related to geographical/meteorological unsuitability (i.e. growing olive trees in Scandinavia),
- overlaying management units with landuse lead to the deletion of non existing crops within the management unit.

3.4.2.6 EPIC operation equipment database linkage

Existing EPIC operation equipment data (used to specify crop management practices in EPIC simulations), stored into till.dat EPIC file, were preserved and linked to the operation identified before (sowing, fertilisation, tillage, harvesting, pesticide and killing). The linkage was done by importing till.dat into the geodatabase as coded domain to be used within a specific EPIC equipment attribute.

3.4.2.7 EPIC fertiliser database linkage

Existing EPIC fertiliser data describing the nutrient content of each fertiliser type, stored into fert.dat EPIC file, were preserved and linked to the fertiliser operations identified before. EPIC fertilisation data were loaded into a geodatabase coded domain.

3.4.2.8 EPIC pesticide database linkage

Existing EPIC pesticide data, stored into fert.dat EPIC file, were preserved and linked to the pesticide operations of each crop. EPIC pesticide data were loaded into a geodatabase coded domain.

3.4.3 MANAGEMENT DATA MODEL

Designing specifications for the management section of the EAGLE geodatabase were based on the following requirements:

- the data model should depict the conceptual model for management units as described above,
- the data model should be structured around EPIC modelling specific requirements for crop management practices. Particularly, table object storing management records should be characterised by all those attributes that are required to write EPIC modelling management input file (.OPS; see Figure 1)

It was decided to adopt the data model shown below in Figure 17.

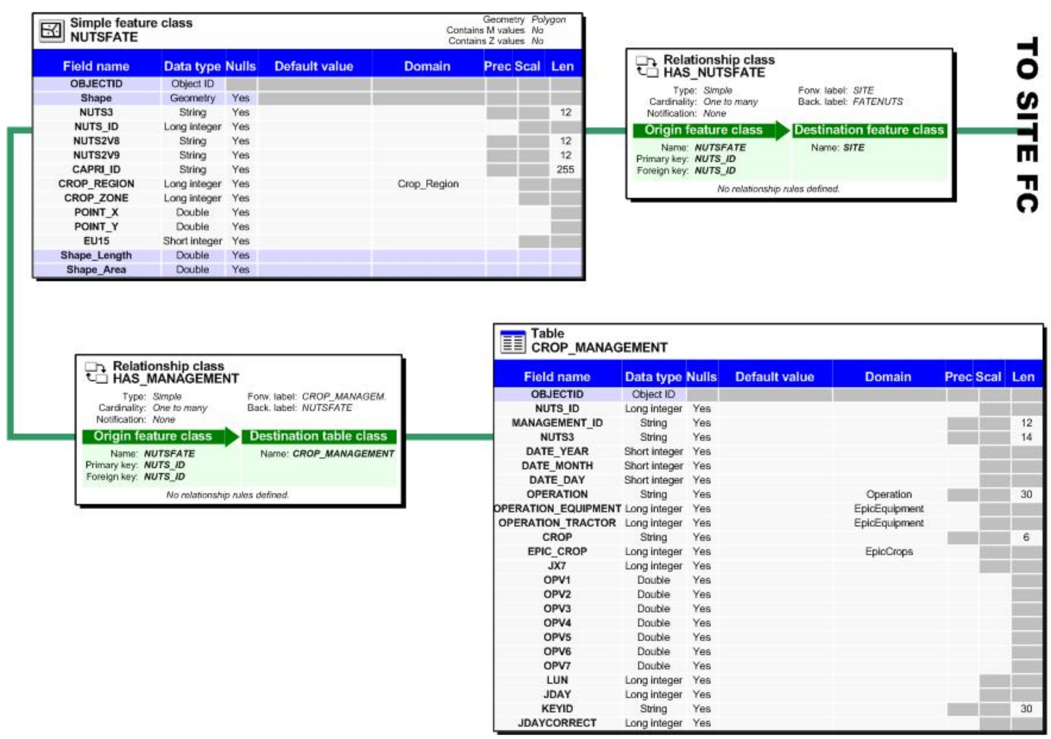

Figure 17. EAGLE geodatabase management section data model

Each NUTSFATE polygon (management unit) has its own management records in the crop management table for each crop within its territory (HAS_MANAGEMENT relationship class). Each crop, within a management unit, has a record for each scheduled operation specifying date and all relevant attributes. Each management unit is then related to its own site polygons (one to many cardinality – HAS_NUTSFATE relationship class).

3.4.3.1 Crop management table

The attribute schema of CROP_MANAGEMENT table is tailored to EPIC ".ops" input file requirements. Particularly, attributes OPVj (j from1 to 7) are EPIC specific management attributes used to specify several attributes like amounts of fertiliser, pesticide, heat unit values and so on (for further information refer to EPIC3050 user manual). Other relevant attributes are:

- EPIC_CROP field provides the mentioned correspondence between EAGLE crops to EPIC crops internally stored into crop.dat EPIC file and used for the simulations. As shown in Figure 17, this field uses a geodatabase coded domain for EPIC crops,
- OPERATION_EQUIPMENT provides a correspondence with existing EPIC operations listed into till.dat EPIC file. A coded domain is used for this field,
- JX7 field is used to specify pesticide or fertiliser (depending on the operation) from those available in the EPIC databases (till.dat, fert.dat)

3.5 GEODATABASE OUTPUT SECTION

The purpose of this section of the EAGLE geodatabase is to store results of EPIC modelling for a particular study area. Each time an EPIC run is called through the GIS interface for a set of site units, the output section is cleared of previous records and loaded with the output of the current model run.

3.5.1 DATA MODEL

The design of this section was driven by the following specifications (Figure 18):

- out section should store yearly general crop outputs as read from EPIC output file labelled EPIC3050.OUT,
- out section should take into account the conceptual schema adopted about running units.

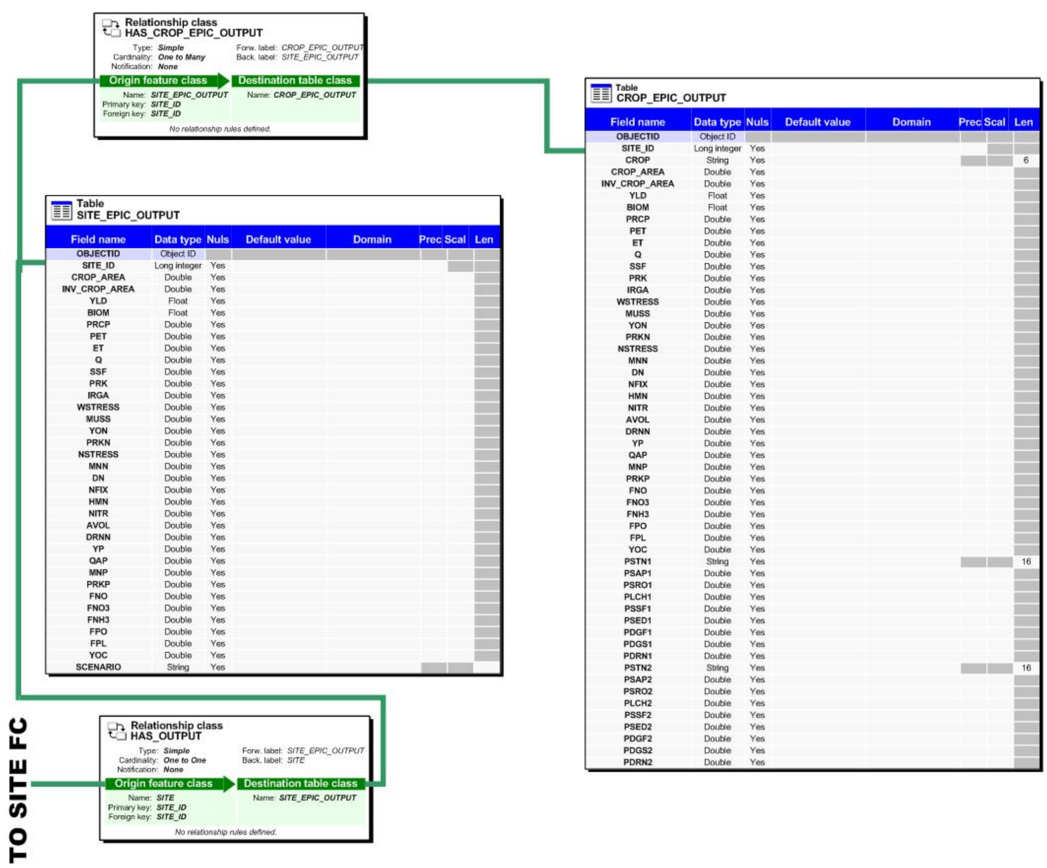

Figure 18. EAGLE geodatabase output section data model

The data model shown in Figure 18 was adopted. CROP_EPIC_OUTPUT table stores outputs of each subunit run within the site unit and SITE_EPIC_OUTPUT stores aggregated data based on the crop specific subunit runs performed within the site. Outputs are aggregated at site level performing output weighted average on site crop area. As a result the SITE_EPIC_OUTPUT table is related with the SITE feature class with a cardinality of one to one (HAS_OUTPUT relationship class in Figure 18) allowing output mapping at site level. Each output site is linked to each crop specific output stored into CROP_EPIC_OUTPUT table with a cardinality of one to many (HAS_CROP_EPIC_OUTPUT relationship class in Figure 18), allowing for crop specific analysis and mapping.

Table 4 lists the EPIC output parameters considered in EAGLE. Parameters related with pesticide practices are stored at a site subunit level (crop specific) into CROP_EPIC_OUTPUT table.

PARAMETER	DESCRIPTION
YLD	Total yield (t/ha)
BIOM	Total biomass (t/ha)
PRCP	Precipitation (mm)
PET	Potential evapotranspiration (mm)
ET	Evapotranspiration (mm)
Q	Surface runoff (mm)
SSF	Lateral subsurface flow (mm)
PRK	Percolation below root zone (mm)
IRGA	Irrigation (mm)
WSTRESS	Water stress [days]
MUSS	Soil erosion-water (t/ha)
YON	Organic nitrogen loss with sediment(kg/ha)
PRKN	Mineral nitrogen loss percolate (kg/ha)
NSTRESS	Nitrogen stress [days]
MNN	Nitrogen mineralized (kg/ha)
DN	Nitrogen loss by denitrification (kg/ha)
NFIX	Nitrogen fixed by leguminous crops (kg/ha)
HMN	Nitrogen mineralized from stable organic matter (kg/ha)
NITR	Nitrification NH3 to NO3 (kg/ha)
AVOL	Nitrogen volatilization (kg/ha)
DRNN	Drnn (kg/ha)
YP	Phosphorous loss with sediment (kg/ha)
QAP	Soluble phosphorous loss in runoff (kg/ha)
MNP	Phosphorous mineralized (kg/ha)
PRKP	Leached soluble phosphorous (kg/ha)
FNO	Organic nitrogen fertilizer application (kg/ha)
FNO3	NO3 fertilizer application (kg/ha)
FNH3	NH3 fertilizer application (kg/ha)
FPO	Organic phosphorous fertilizer application (kg/ha)
FPL	Mineral phosphorus fertilizer application (kg/ha)
YOC	Organic carbon lost with sediment (kg/ha)
PSAP1	Pesticide amount (g/ha)
PSRO1	Pesticide lost in runoff [g/ha]
PLCH1	Pesticide leached [g/ha]
PSSF1	Pesticide lost in subsurface flow [g/ha]
PSED1	Pesticide lost sediment [g/ha]
PDGF1	Pesticide biodegradation in foliage [g/ha]
PDGS1	Pesticide 1 biodegradation in soil [g/ha]
PDRN1	Pesticide 1 lost in drainage [g/ha]

Table 4. EPIC output parameters analysed

3.6 EAGLE GIS INTERFACE

3.6.1 INTRODUCTION

The EAGLE GIS interface is the connection bridge between the geodatabase and the EPIC model. It was designed as a customisation of the ESRI ArcMap environment adding EPIC input/output managing capabilities to the standard GIS interface.

3.6.2 EAGLE ESRI ARCMAP TOOLBAR

The EAGLE GIS interface was designed as an in-process server component (dll), developed into Microsoft Visual Basic 6 environment, to be plugged into ESRI ArcGIS. Main system requirements to use EAGLE server component can be listed as follows:

- Windows XP / Windows 2000/2003,
- ESRI ArcGIS 9.0 or higher,
- Microsoft Access 2000 or higher.

Once the server is properly registered, the ESRI ArcMap user interface is added with a new toolbar representing EAGLE GIS user interface. The toolbar is composed by the following items:

- EAGLE menu (item 1 in Figure 19a). A collection of three subcommands is available:
    - Control Record Settings Command: used to create or edit existing control records,
    - Output Print Settings Command: used to specify output types, and
    - EAGLE Run Settings: used to specify settings that characterise a set of runs.
- EAGLE layer list (item 2 in Figure 19a). A combo box control which lists the available feature layers in the selected Arcmap dataframe,

- A command button to start EAGLE runs (item 3 in Figure 19a),
- A command button for user customised functionality.

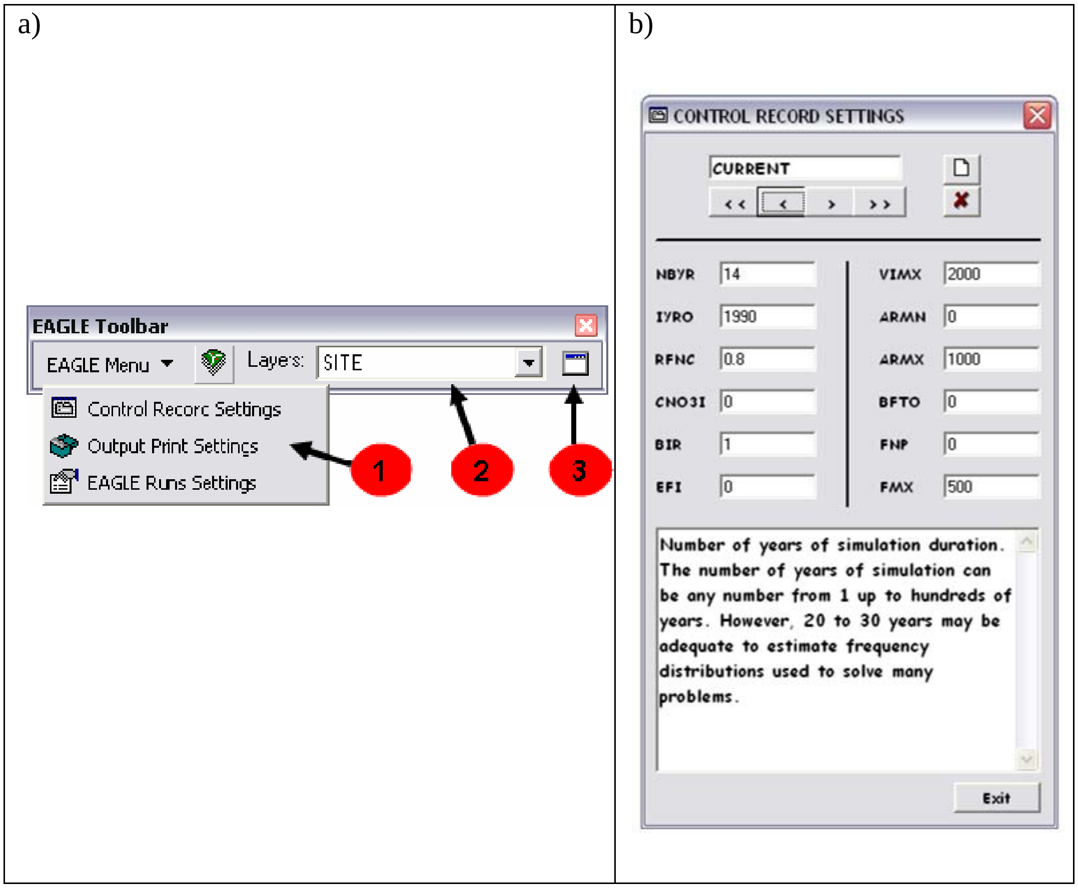

Figure 19. EAGLE tool bar (a) and control record form (b)

3.6.3 PERFORMING AN EAGLE ANALYSIS

3.6.3.1 Selecting the study area

The study area may be identified as follows:

- The entire SITE feature class in the geodatabase;
- A subset of the SITE feature class based on the European region of interest. The subset can be created by exporting a selected set of features from the SITE feature class or by setting EPICRUN attribute, into SITE feature class, in order to exclude

unwanted sites from the simulation. In case of creation of a subset feature class, it must reside in the EAGLE geodatabase and can be named based on the user preferences. The related ArcMap layer may be eventually renamed with a name based on preferences within the dataframe context. As soon as the new layer is added to the dataframe it is listed in the EAGLE layer list.

3.6.3.2 Setting the study area

The study area feature class created as detailed previously (it may also be the entire SITE feature class) is characterised by a set of attributes (fields) that can be classified as follows:

- Readable attributes: they consist of unchangeable attributes like the latitude of the polygon centroid, the related meteorological station, the area , etc.;
- Readable/Writable attributes: they may be modified to allow the creation of different output scenario for the related site polygon.

Readable/Writable attributes in the study area feature class are:

- **IRR-**Irrigation Code. This attribute can be set to the following values:
  - 0 – Dryland,
  - 1 – Sprinkler Irrigation,
  - 2 - Furrow Irrigation.

  Dryland excludes auto irrigation in the simulation. A coded domain (irrCode) simplifies the editing of this field.
- **IRI** - Minimum interval between auto irrigation applications (days),
- **IFA** - Minimum interval between auto fertilisation applications (days). This option must be supported by proper setting in the control record in order to activate the auto fertilisation,

- **IDFO** - Fertiliser used for auto fertilisation. When auto fertilisation is active this field specifies the fertiliser to be used. This field is supported by a coded domain (Fertiliser)
- **SELECTIVE_AUTOIRR –** It controls auto irrigation at crop level. Specific crop auto irrigation can be set into SITE_IRRIGATION table,
- **MNU** – Auto manure application.

3.6.3.3 Setting the control record

The control record stores data that are set, and considered constant, for the entire study area. The user can edit an existing record or create a new one to be later associated to the runs for the study area (Figure 19 b). These functionalities can be accessed from the GisEpic menu and click on "Control record settings" to display the related form. On the form, the navigation buttons allow displaying existing different records. The following actions can be performed:

- EDITING EXISTING RECORD: text boxes can be filled with appropriate data. Pausing the mouse over a text box displays a tip label indicating a range of possible values, clicking the codes beside the text boxes displays useful information about the selected field in the info text box at the bottom of the form. Edits are automatically saved as soon as they are performed. Once the modifications are made it is possible to navigate to different records for further modifications.
- CREATING A NEW RECORD: clicking on the new record button it is possible to create a new record and fill the text boxes with the desired inputs. Whenever it is necessary to get information about an attribute, clicking the field name displays

an explanation text on the text at the bottom of the form. The new record is automatically saved as soon as it is created and edited

- DELETING EXISTING RECORD: using the navigation buttons it is possible to reach the record to be deleted with a click on the delete button (red x icon). The record "CURRENT" cannot be deleted from the database.

The control record can also be edited by accessing the table EPIC_CONTROL where it is possible to modify a larger set of parameters which are not exposed in the previous form.

3.6.3.4 Running EPIC

After the previous steps have been completed the user can launch an EAGLE run over the study area feature class. This can be easily performed by selecting the study area layer on the GisEpic layers list and clicking the "Run Epic" button beside it. In case the user created many control records it should be specified the one to be used in the "EAGLE Runs Settings" section of the EAGLE menu (the default record is 'CURRENT').

It has to be noted that after selecting the layer, ArcMap automatically zooms to the study area feature class extent and checks its compatibility with an Epic run. If the selected layer is not an Epic run compatible feature class the button stays disabled. After launching the run a notification form informs the user about the progress of the operation notifying any error and/or warning that may affect the results. A log file is available in the bin folder.

3.6.3.5 Analysing and mapping results

After a successful run, the results are stored into two tables within the EAGLE geodatabase:

- SITE_EPIC_OUTPUT: this table stores a record for each site (10 km cell) of the study area feature class. Through the relationship class HAS_OUTPUT it can be joined back to the study area feature class for any analysis, statistics and display operation available in the ArcMap user interface.
- CROP_EPIC_OUTPUT: this table stores all the single crop runs (run subunits) that have been made within the related site polygon. EAGLE performs single crop runs based on the five predominant crops within a site. As a result there is a one to many relationship between SITE_EPIC_OUTPUT and CROP_EPIC_OUTPUT that can be navigated using the HAS_CROP_EPIC_OUTPUT relationship class.

4 EAGLE Application to Assess the Impact of Climate Change

4.1 CLIMATE CHANGE SCENARIOS

Eighteen high-resolution grids on monthly climate coming from the combination of five Global Climate Models (GCMs) and four emission scenarios (based on assumptions of demographic, industrial, technological developments) were obtained from Tyndall Centre for Climatologic Research (Mitchell et al, 2004). The combinations available for the GCMs and emission scenarios are summarised in Table 5.

SRES / GCM	A1FI	A2	B1	B2
CGCM2 (Flato and Boer, 2001)	X	X	X	X
CSIRO2 (Gordon and O'Farrell, 1997)	X	X	X	X
ECHAM4 (Roeckner et al., 1996)	Same as A2	X	X	Same as B1
HadCM3 (Mitchell et al., 1998)	X	X	X	X
PCM (Washington et al., 2000)	X	X	X	X

Table 5. Combination of GCMs and scenarios used

All scenarios derive from the Special Report on Emission Scenarios (SRES; IPCC, 2000) and are a major improvement from the previous IS92 scenarios. Based on an extensive literature review of global and regional scenarios, a set of four families (A1, B1, A2, B2) with 40 emission scenarios based on potential population, economic and structural and technological changes were developed, covering from the 5th to the 95th percentile of the global energy related greenhouse gas emission reported in literature (Figure 20).

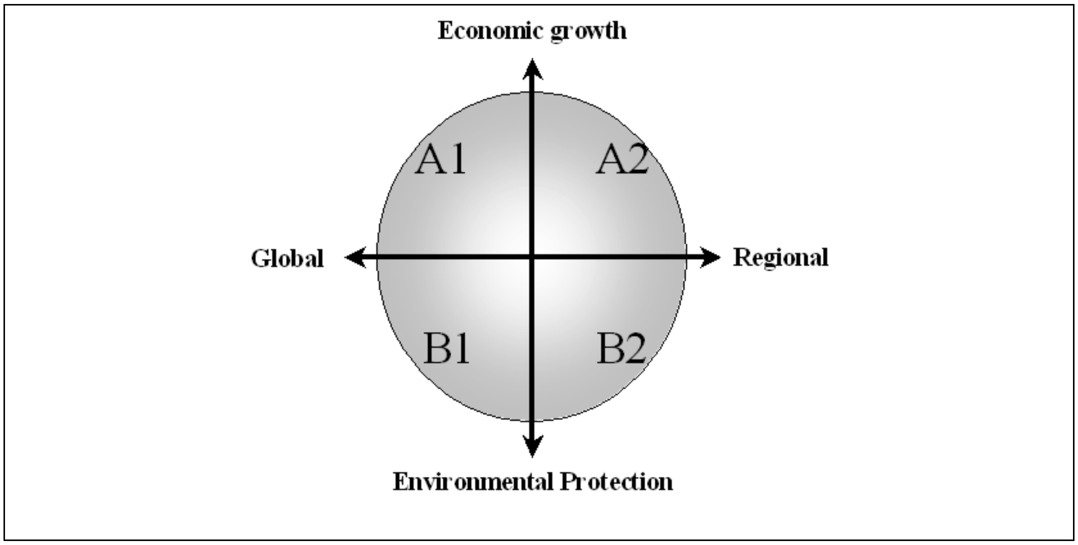

Figure 20. Characteristics of the various climate change scenario storylines

The A scenarios are more economical growth driven, while in the B scenarios the emphasis is put on the protection of the environment. The “1” scenario assumes more globalisation while the “2” scenarios are based on regionalisation.

- The A1 family of scenarios is based on rapid economic growth, an increase in population until the mid-century and a decrease thereafter and the introduction of new and more efficient technologies. The scenario A1F1 puts more emphasis on fuel intensive energy source.
- The A2 scenario is characterised by a heterogeneous, market-led world with high population growth. Economic development is oriented regionally and income growth and technological changes are regionally diverse and slow.
- B1 has the same low growth population as A1 but is characterised by global cooperation and regulation leading to a converging world. Clean and efficient technologies are introduced.

- B2 scenario puts emphasis on environmentally, economically and socially sustainable locally oriented pathways. The technological changes are slower and more diverse than in the A1 and B1 scenarios.

Additional details about the scenarios are given by Arnell et al. (2004).

4.2 CLIMATE CHANGE DATA MODEL EXTENSION

The meteorological data model is normally loaded with MARS/CGMS data from years 1990 to 2003. The METEO_DAILY table stores daily meteorological records and METEO_MONTHLY stores monthly statistics derived from daily data. In such situation, EPIC modelling is based on 14 years of observed data. Alternatively, those tables can be loaded with modified data reflecting a particular meteorological scenario to study how climate changes may affect crop water and nutrient requirements. The EAGLE geodatabase can be set for a specific meteorological scenario through the GIS interface. This results into the following actions:

- 2542 EPIC daily meteorological files are prepared for the specific scenario,
- METEO_DAILY is loaded with scenario specific daily data, and
- METEO_MONTHLY is loaded with scenario specific monthly meteorological statistics.

Meteorological scenario data loading is done through the support of a database management system (Microsoft SQL Server 2005) to handle the large amount of data.

4.2.1 INPUT DATA

Climate change scenario input data were provided by the “Tyndall Centre for Climatologic Research” (University of East Anglia, Norwich UK) as part of the dataset labelled TYN SC 2.0 (Mitchell et al, 2004). The data is supplied on 0.5 degree grid covering the entire global land surface. The data grid can be seen as a rectangle with boundaries at the poles and the International Date Line. Data is only supplied at a monthly time step for only the land boxes for a total of 67,420 cells out of a total of 259,200 cells. The available files can be listed as follows:

- 18 files representing the precipitation change pattern (in the 2080s, relative to 1961-1990) for all the permutations of four CGMs (HadCM3, CSIRO2, CGCM2, PCM) with four SRES scenarios (A1FI, A2,B1,B2) (ECHAM4 runs are available only for the scenarios A1 and B2) (see Table 5),
- 18 files representing the temperature change pattern (in the 2080s, relative to 1961-1990) for all the permutations of four CGMs with four SRES scenarios,
- 1 file of observed precipitation for 1961-1990.

4.2.2 DATA PRE-PROCESSING

4.2.2.1 Tabular TYN SC 2.0 data

The first objective of data pre-processing was the storage of the TYN SC 2.0 data in a tabular format within a SQL Server 2005 database. For this purpose a simple Visual Basic program was created to read the input files and interact with the DBMS via Active X data object technology (ADO).

Precipitation data (18 scenario files) were loaded into a table where each record provides a value for a specific month and a 0.5 grid box (input files, instead, have months as attributes of the grid box). This operation added 14,562,720 records resulting from 67420 grid boxes for 18 scenarios and 12 months. The same operation was performed for temperature data whereas imported observed precipitation data produced 809,040 records (67420 grid boxes for 12 months). The two precipitation tables were linked together in order to calculate the monthly variation that each scenario produces on the observed values. The entire process lead to the creation of two tables:

- PRECIPITATION: containing observed and scenario precipitation,
- SCE_TEMP: containing scenario temperature.

4.2.2.2 Spatial TYN SC 2.0 grid

Based on the TYN SC 2.0 specifications a world grid geodatabase feature class was created (Figure 21) as follows:

- Geographic coordinate system: WGS_1984,
- 720 columns (ranging from -180 deg to 180 deg at 0.5 deg step), 360 rows (ranging from -90 deg to +90 deg at 0.5 deg step),
- Grid cell identifier based on relative cell position to the lower left corner. For example the cell identified by 360,180 is located at the intersection of Greenwich meridian and the equator.

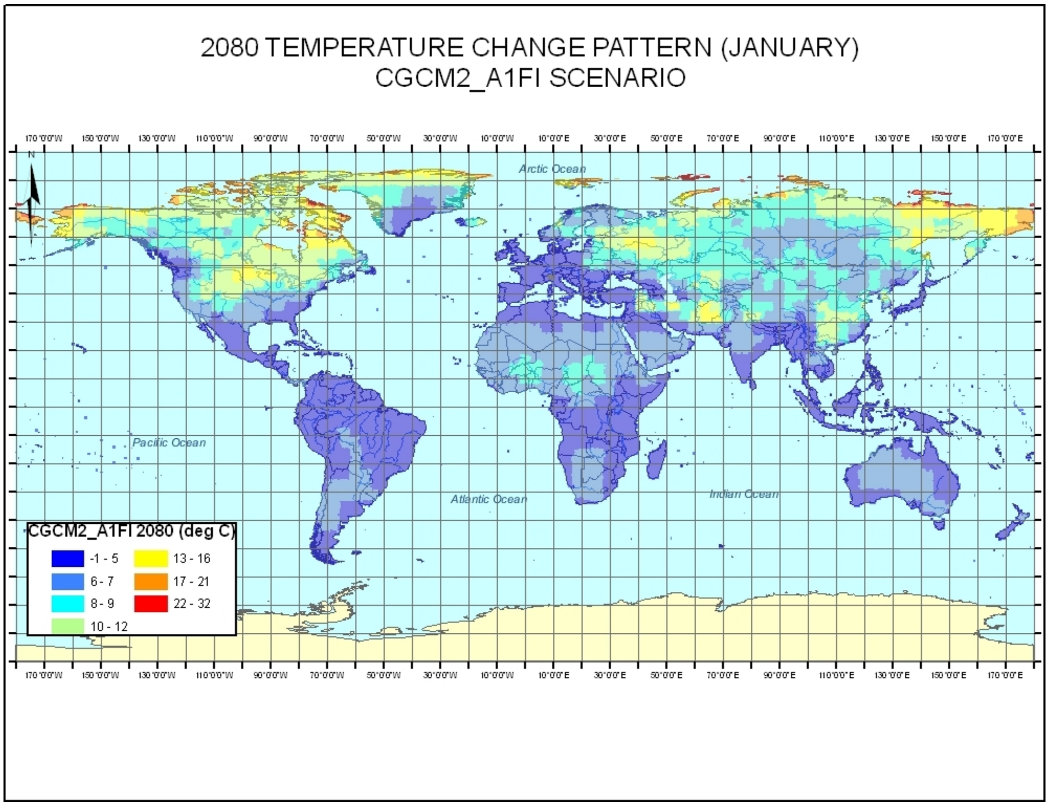

Figure 21. TYN grid showing temperature change for CGCM2_A1FI scenario

Cells which do not have data have been deleted obtaining a final count of 67420 cells. Through the grid box identifier the created grid can be linked to data extracted from the previously created tables for precipitation and temperature change (see Figure 21 for an example). Subsequently, a link was created between the TYN SC 2.0 grid and the MARS/CGMS by spatially joining their centroids. Each interpolated MARS/CGMS station links to a specific TYN SC 2.0 cell box covering the whole EAGLE study area.

4.2.3 CLIMATE SCENARIO DATA MODEL

To support climate scenario simulations within the EPIC modelling framework, a SQL Server database was created to integrate the EAGLE personal geodatabase. The design was driven by the following specifications:

- temperature change pattern (absolute change, °C) from TYN SC 2.0 (2080) should be added to the available MARS/CGMS daily maximum and minimum temperature data (1990/2003) on a monthly basis,
- variation of the precipitation pattern versus the observed TYN SC 2.0 values (relative change) should be applied to daily precipitation data when different from zero. Such approach increases/decreases precipitation amounts on a monthly basis by modifying the rain amount falling on rainy days.

Other variables potentially affected by climatic changes (like solar radiation, wind speed) were not modified.

The design goal was to produce a new daily meteorological table for each scenario by modifying maximum temperature, minimum temperature and precipitation of the original MARS/CGMS data, as indicated above, and recalculating vapour pressure and relative humidity values (which are temperature dependent). This was achieved by creating a set of SQL SERVER views (one for each scenario) able to perform the required calculations using the original MARS/CGMS daily data and the new information coming from TYN SC 2.0 dataset stored in the previously created tables (PRECIPITATION, SCE_TMP). Each view has the structure illustrated in Figure 22.

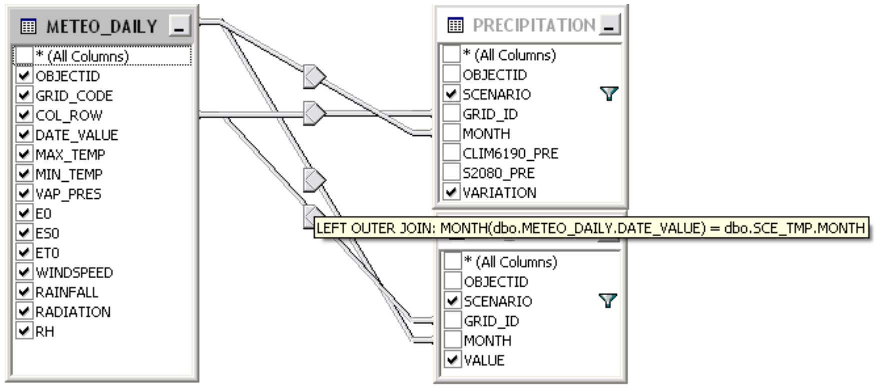

Figure 22. Server meteorological scenario view

Left outer joins link the base table (METEO_DAILY) to PRECIPITATION and SCE_TMP on a monthly basis (note MONTH date function on join relationship) with a filter for the specific scenario on scenario tables.

Joined data are then used for recalculating the relevant parameters as follows:

- maximum and minimum temperature (MAX_TEMP and MIN_TEMP fields) are added to corresponding VALUE into SCE_TMP table to obtain new values,
- precipitation (RAINFALL) is multiplied by variation (VARIATION) into PRECIPITATION table,
- vapour pressure (VAP_PRES) is recalculated based on the new average daily temperature,
- relative humidity (Rh) is recalculated using new value for vapour pressure and temperature according to the relationship shown before (Equation 18)

Each view returns 12,574,324 records (as the original METEO_DAILY), modified as indicated above, and can be used to output scenario specific EPIC daily files and load scenario specific meteorological data into the EAGLE personal geodatabase. The ArcMap GIS interface provides a tool to set EAGLE geodatabase for the required scenario downloading the necessary data from SQL server.

4.3 CO2 ABUNDANCE ADJUSTMENTS

EPIC considers the effects of CO2 on crop growth by modifying the radiation use efficiency based on CO2 concentration in the air (Stockle, 1992). This impact is crop specific with larger positive effects on photosynthesis for C3 crops (wheat, alfalfa, soybeans) and on much lesser scale on C4 crops (maize, sorghum). Negative effects were observed on evapotranspiration for both C3 and C4 crops. A crop specific non linear equation is thus used in EPIC based on experimental results obtained by Kimball (1983) to simulate the impact of CO2 enrichment on the biomass production. Concerning evapotranspiration, the impact of CO2 enrichment is simulated by decreasing linearly stomatal conductance between 330 and 660 ppm. It is important to note that even though EPIC offers four different alternatives to calculate PET, only the Penman-Monteith approach is affected by CO2 abundance in the atmosphere. A doubling of CO2 could result in a probable increase of crop biomass/yield by 33% with values ranging from 24% to 43%. For this study, the CO2 abundance in the atmosphere was set to 330 ppm for the baseline scenario and to 532 and 567 ppm for the A2 and A1FI climate scenarios, respectively.

4.4 BASELINE VALIDATION

The EPIC model has been validated throughout the world and was found accurate in predicting the yield for the major crops (Gassman et al., 2005; Tan and Shibasaki, 2003). In this study, the model predicted yields were compared to available national data, and it was found that EPIC results compared favourably with data reported by EUROSTAT.

4.5 CLIMATE CHANGE MODEL RESULTS

To avoid the impact of initial conditions on model runs, the results will be analysed only in relative way (deviation from the baseline scenario). The results will be presented as absolute changes (calculated as the difference between climate scenario and the baseline results), relative change (calculated as the absolute change divided by the baseline value). One last analysis consisted in determining for each climate change scenario the GCMs agreement expressed as the number of GCMs inducing the same level of deviation,notably the number of GCMs inducing an increase or decrease by more than 10% of the considered model output. The agreement varies from 1 to 5 for both the increase and the decrease predictions. The outputs analysed included precipitation, potential evapotranspiration, crop yield, water stress, and nitrogen application (auto-fertilisation was set a default for all crops). Even though all 18 climate change scenarios were run, only the results for the A1 and B2 will be illustrated as they represent the lower and higher extremes of the potential changes.

4.5.1 PRECIPITATION

The results for annual precipitation are shown in Figures 23 to 28. Concerning annual precipitation, according to the A1 scenarios Europe will face a decreased annual precipitation in the south. It is also predicted that Northern Europe will be wetter. CGM2 and HadCM3 are the most extreme in predicting a dryer southern Europe. The B2 scenarios are somewhat similar to the A1s however in a lesser extreme extent. In relative terms the HadCM3 scenario predicts a reduction in precipitation by more than 30% in Southern Spain and Portugal. ECHAM4 and CSIRO2 predict variations of 10% (-9 to +10%) of the annual precipitation for large parts of Europe, and an increase by 11 to 30% in Northern Europe. Again the B2 scenarios predict similar relative pattern with less relative change. Concerning the variability among the A1 scenarios, the strongest agreements are found in Sweden, and Finland, with four to five GCMs predicting an increase of precipitation of 10% or more. A similar pattern in observed for the B2 scenarios with a general agreement about an increase of precipitation by 10% or more in Sweden and Finland. There is also an agreement for the A1 scenarios about a decrease of precipitation by 10% or more for Greece, the Castilla region in Spain and the bottom tip of Italy. This analysis only focused on the annual amount of precipitation. There are also some seasonal changes (even though some regions show no change in annual precipitation, they exhibit a shift of rainfall between months).

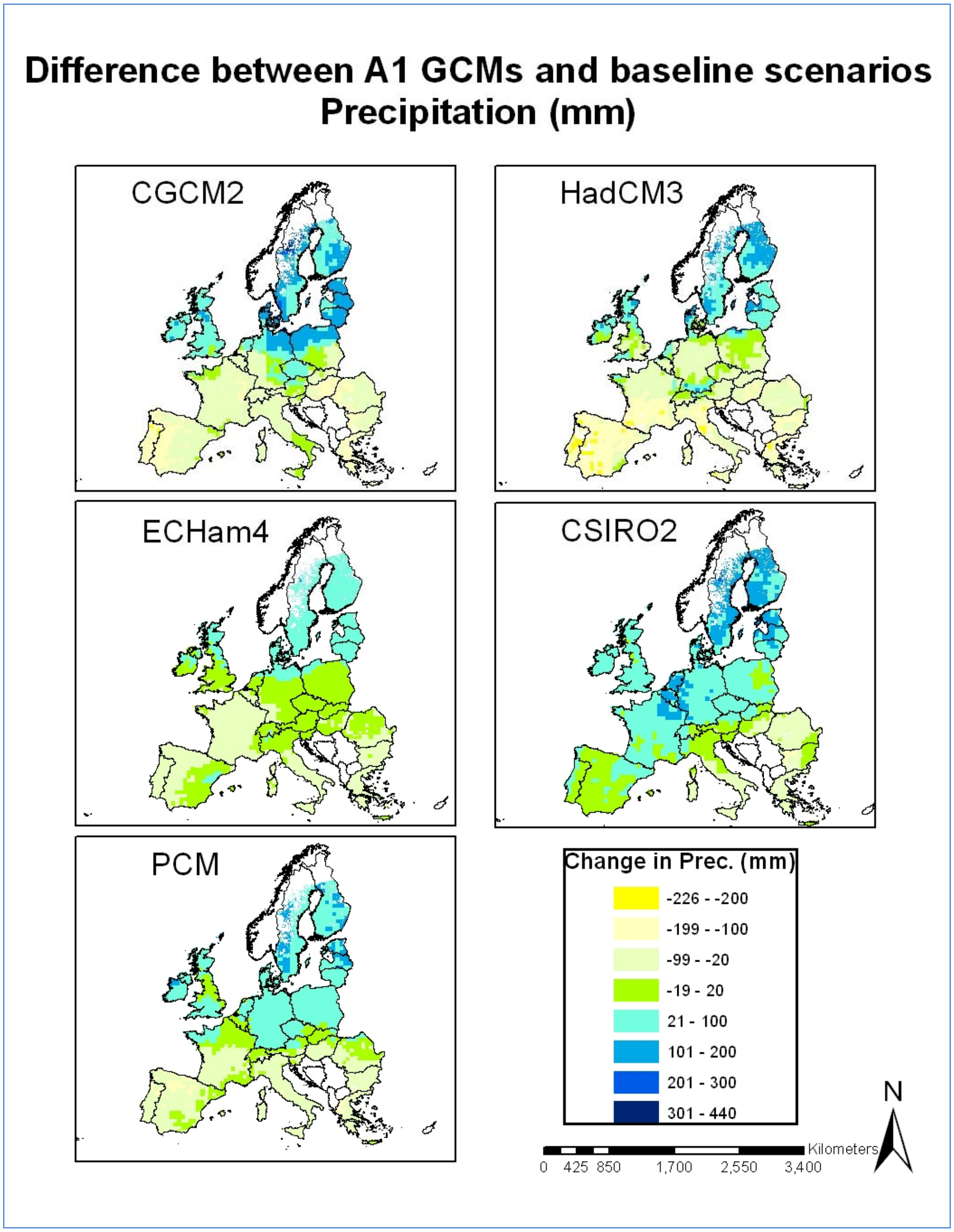

Figure 23. GCMs predicted absolute change in annual precipitation for the A1 scenarios

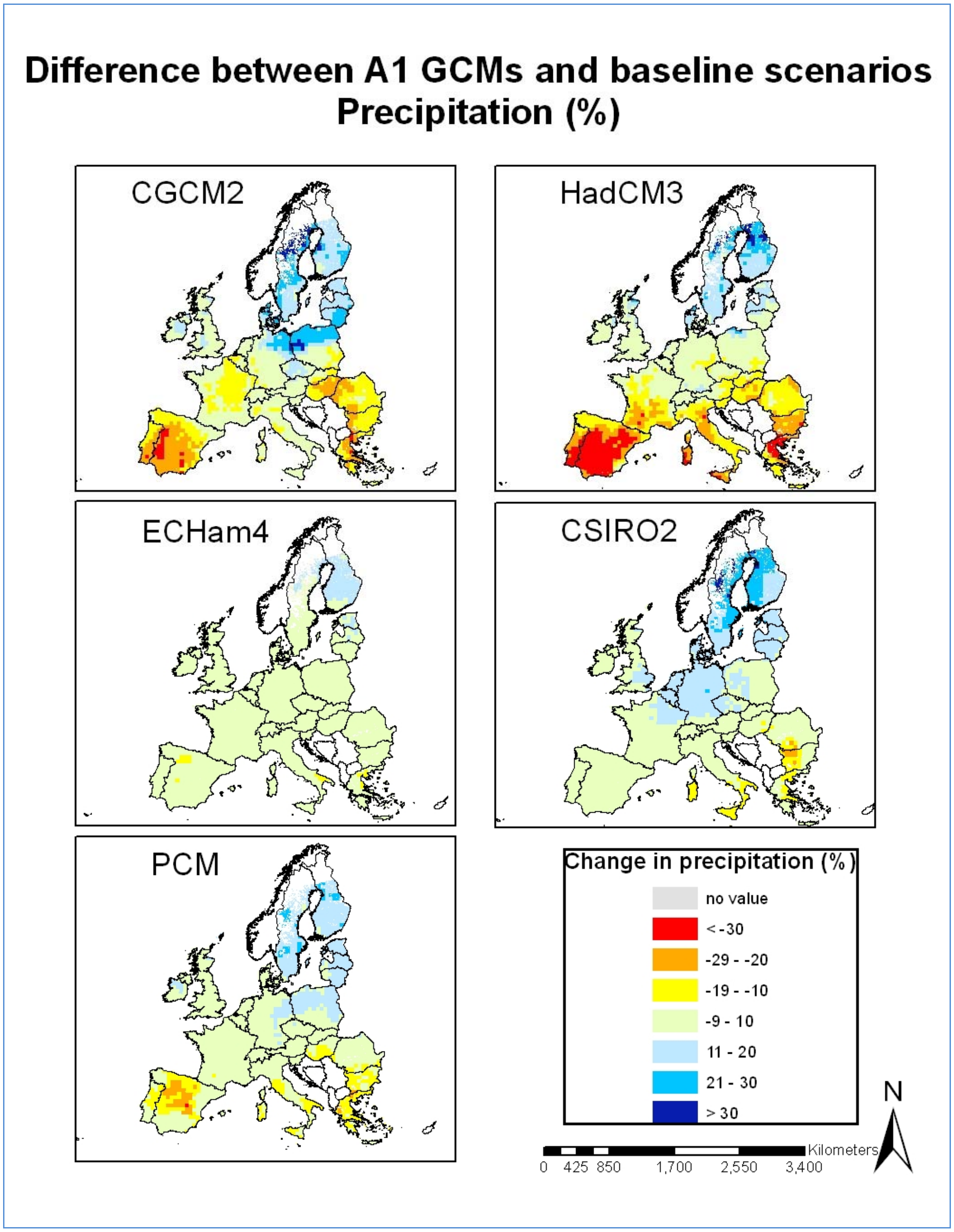

Figure 24. GCMs predicted relative change in annual precipitation for the A1 scenarios

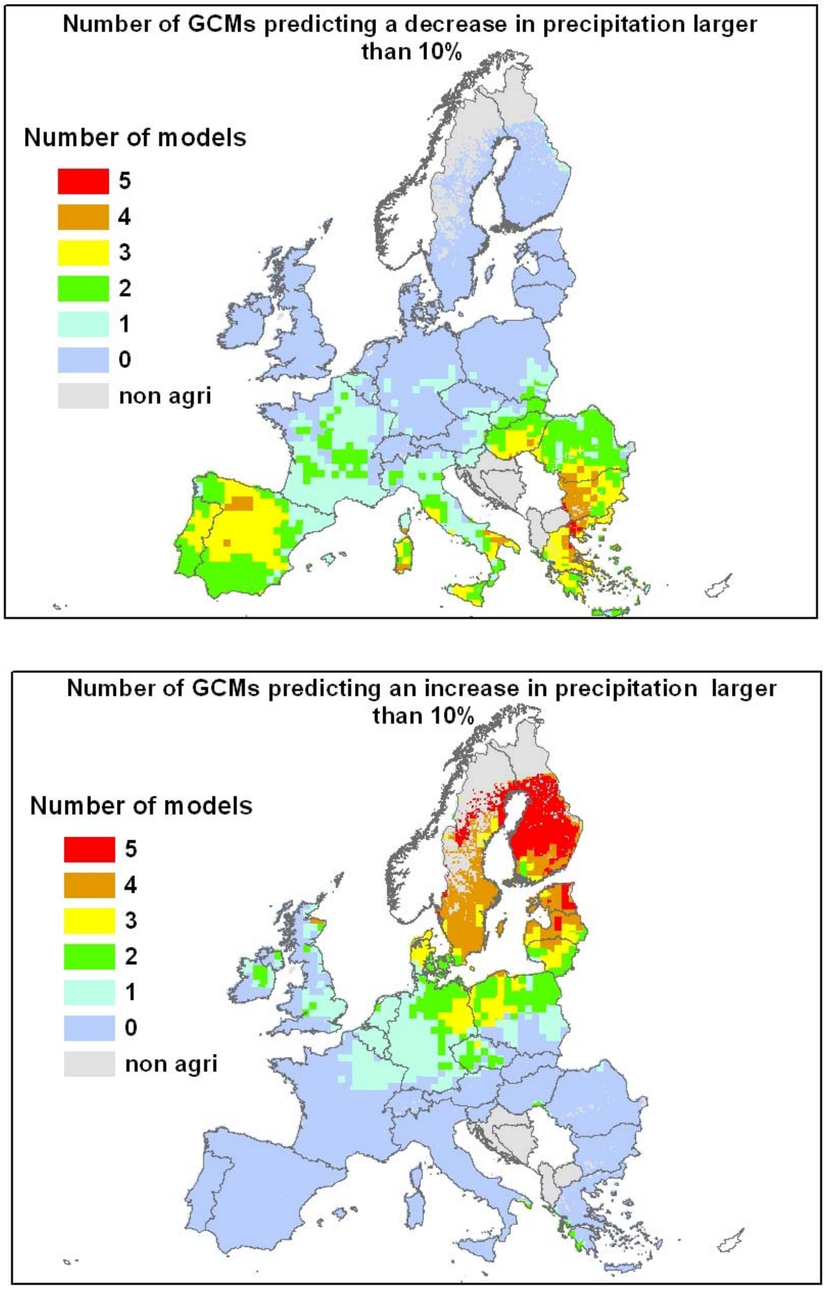

Figure 25. GCMs agreement for predicted changes in annual precipitation for the A1 scenarios

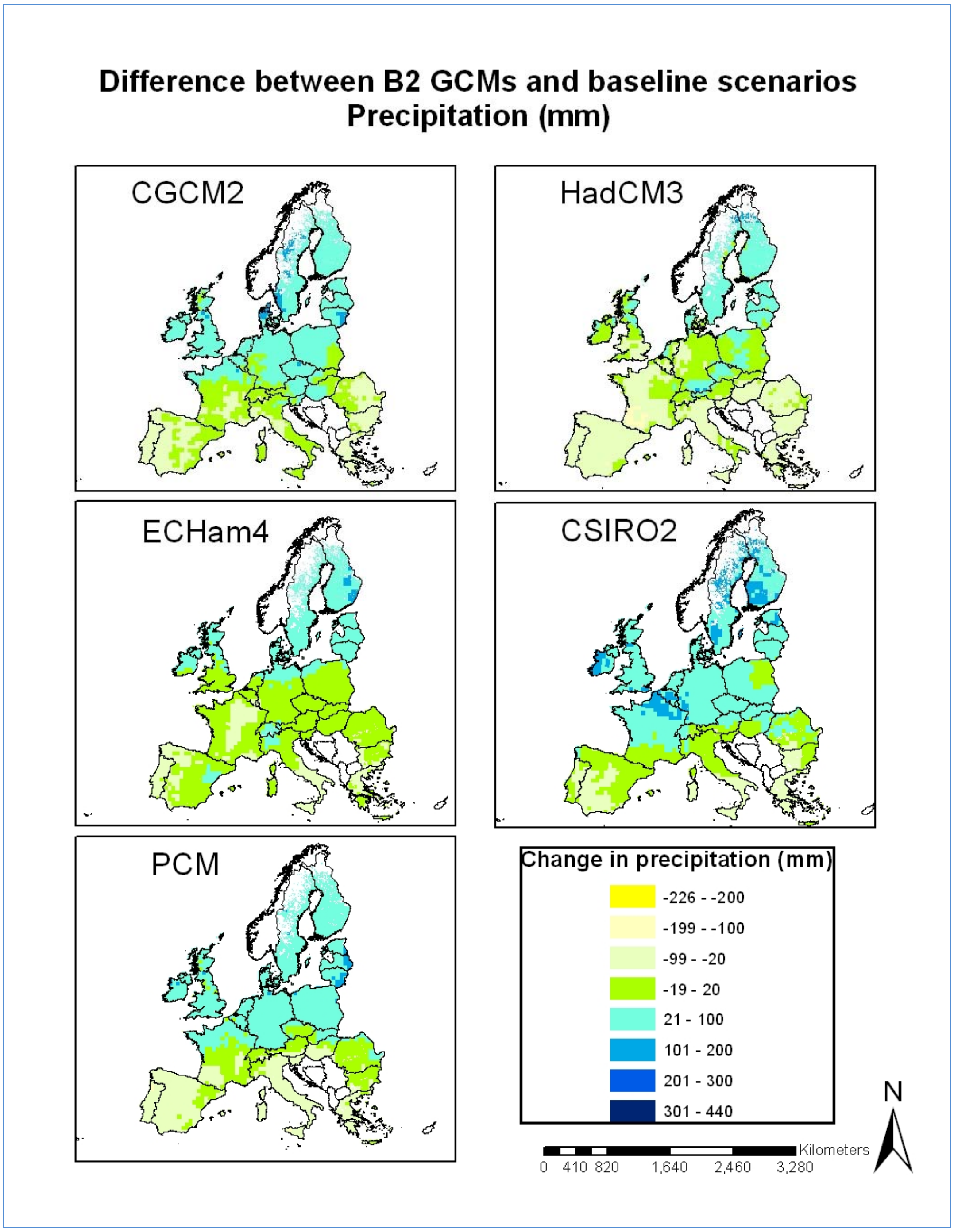

Figure 26. GCMs predicted absolute change in annual precipitation for the B2 scenarios

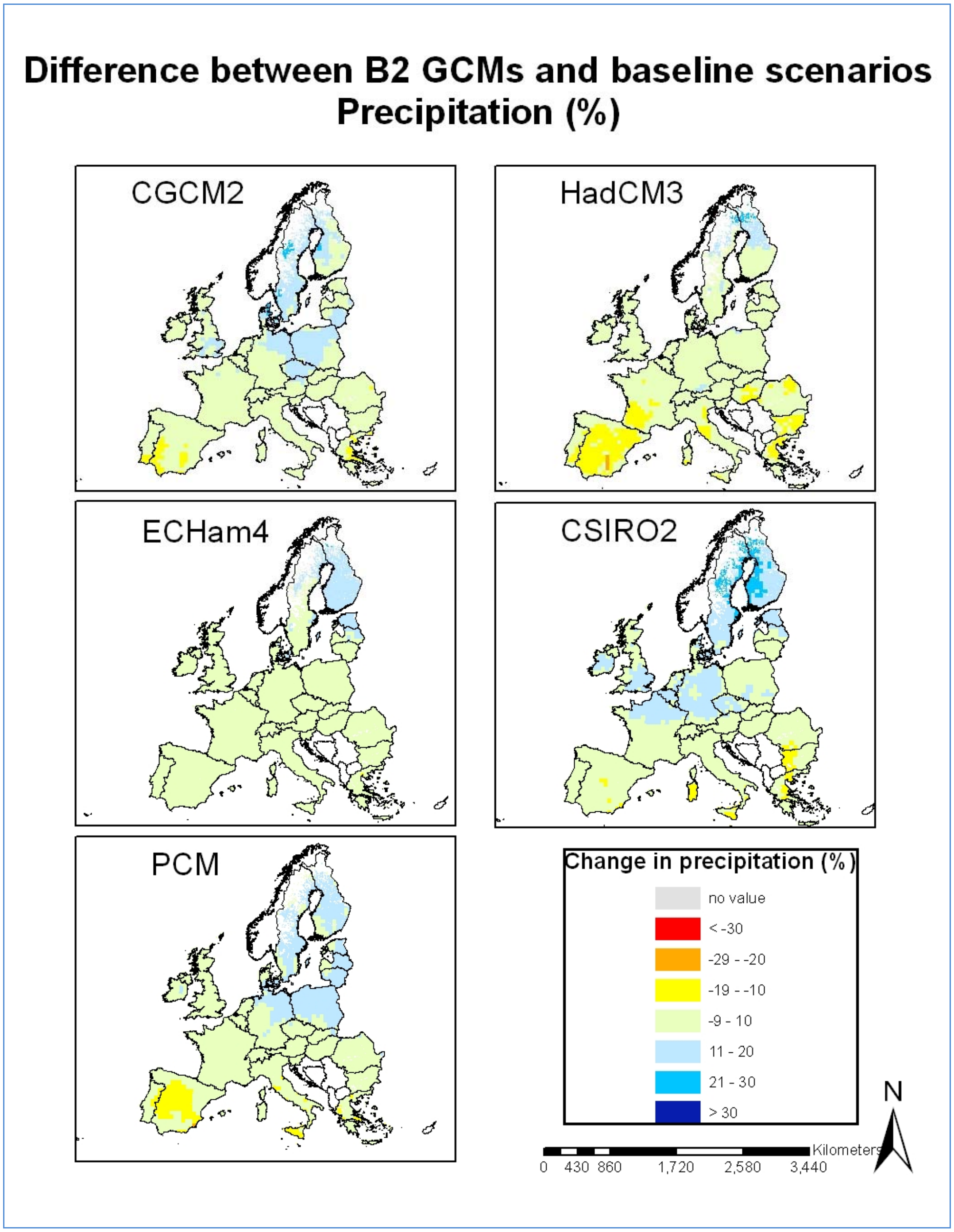

Figure 27. GCMs predicted relative change in annual precipitation for the B2 scenarios

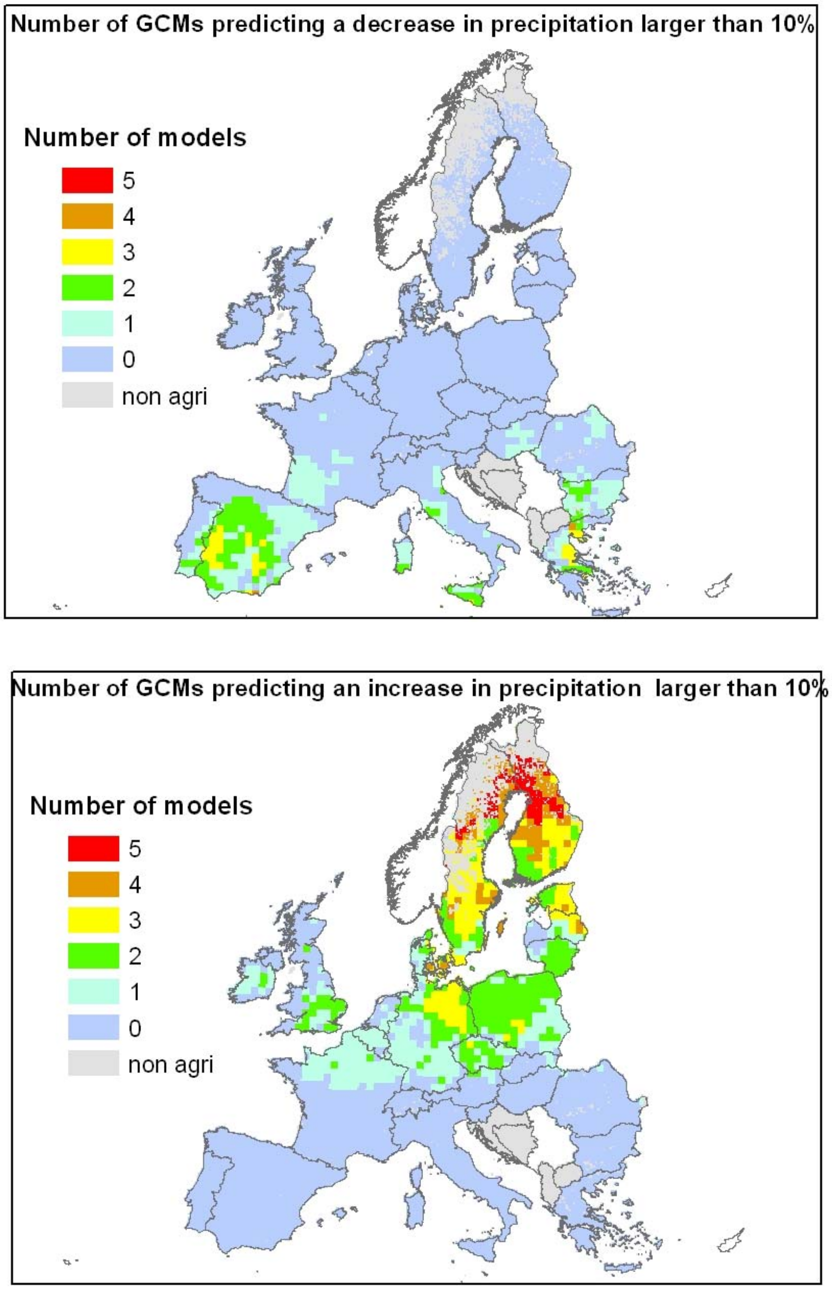

Figure 28. GCMs agreement for predicted changes in annual precipitation for the B2 scenarios

4.5.2 POTENTIAL EVAPOTRANSPIRATION

The results for annual potential evapotranspiration are shown in Figures 29 to 34. The picture for the impact of climate change on PET is clearer as all scenarios predict an increase of PET however with large variability between the scenarios. Again for the A1 series, CGCM2 and HadCM3 are the most extreme ones, while for B2 HadCM3 and CSIRO2 are the most extreme. Absolute changes could exceed in large areas of Europe 300 mm. In relative terms for the A1 scenarios (excluding ECHAM4) it is predicted that Northern Europe will face an increase of PET by more than 30%, while these changes will not exceed 20 % in Southern Europe. According to the B2 scenarios, the absolute change should not exceed 10%. Concerning the agreement between the various GCMs, they all agree in predicting an increase of PET by more than 10%. For the B2 scenarios there is a mild agreement that Northern Europe will face an increase of PET by more than 10% (3 GCMS agreements).

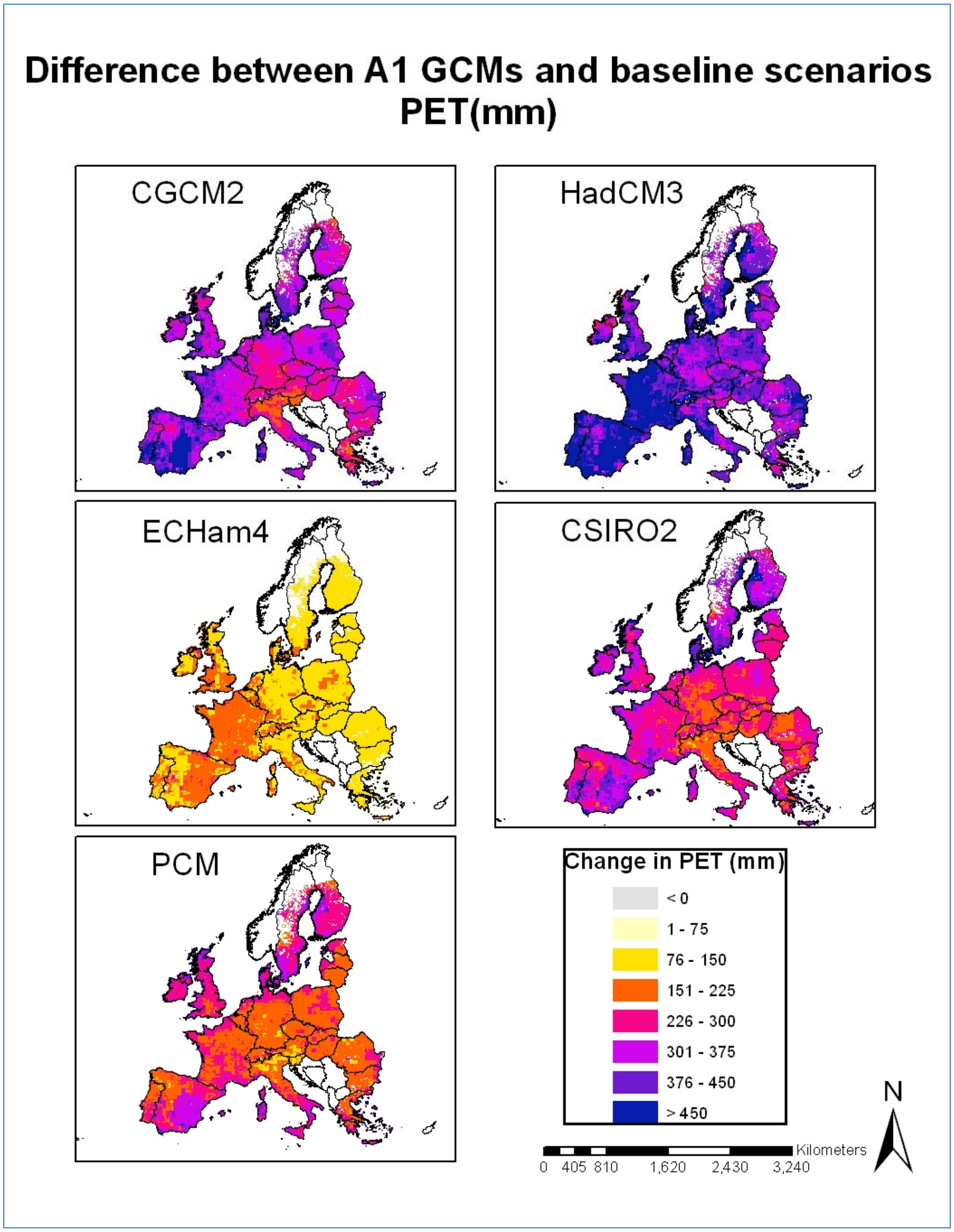

Figure 29. GCMs predicted absolute change in annual PET for the A1 scenarios

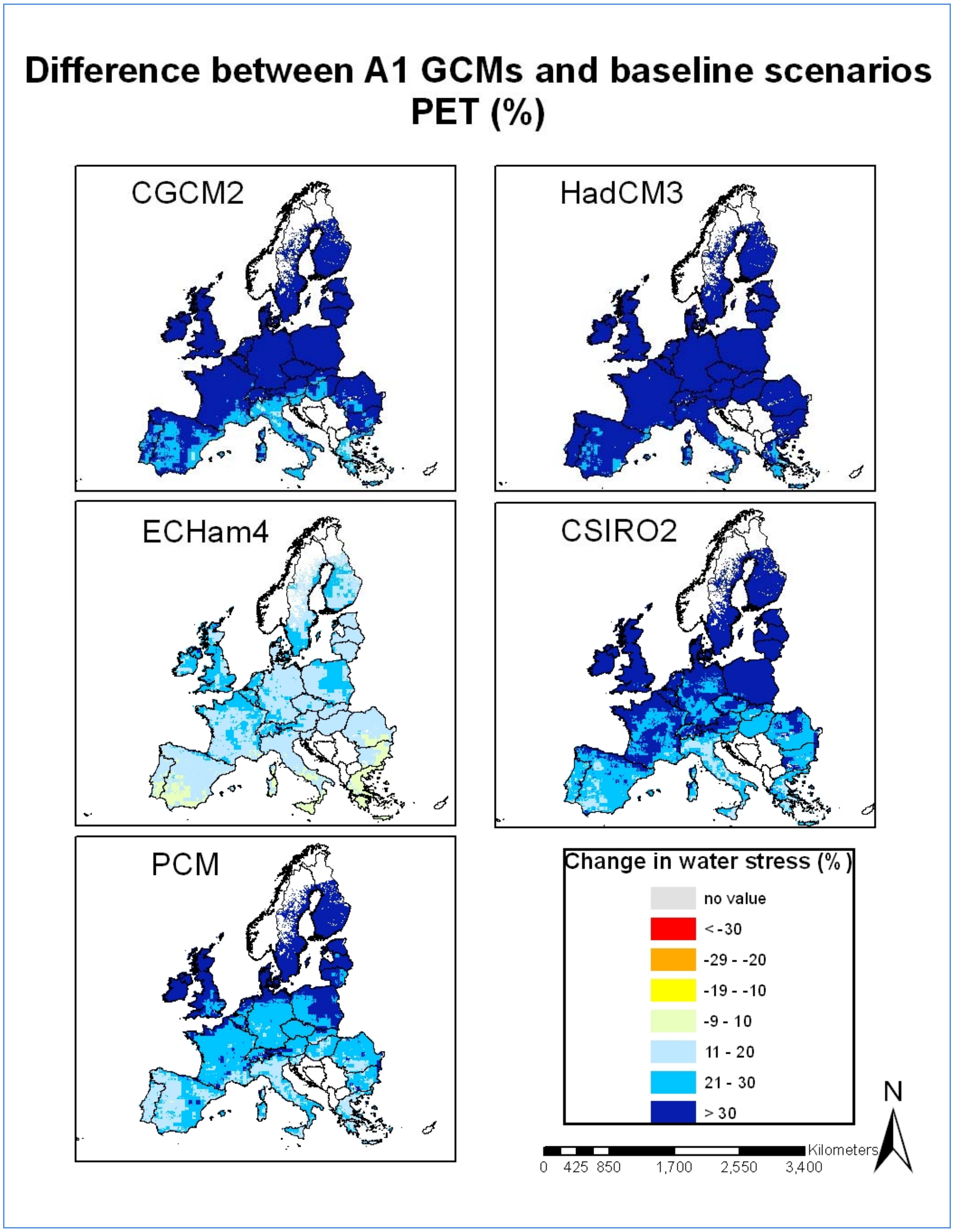

Figure 30. GCMs predicted relative change in annual PET for the A1 scenarios

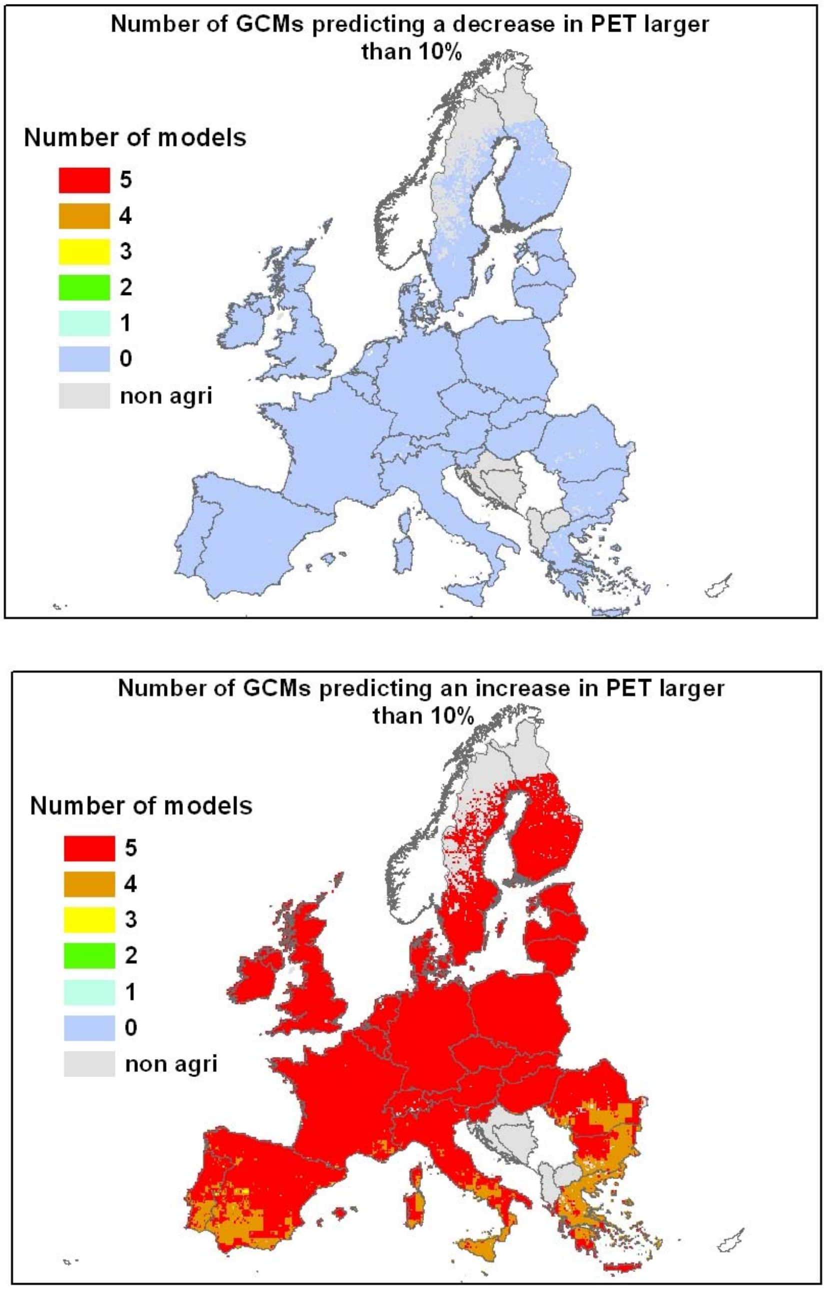

Figure 31. GCMs agreement for predicted changes in annual PET for the A1 scenarios

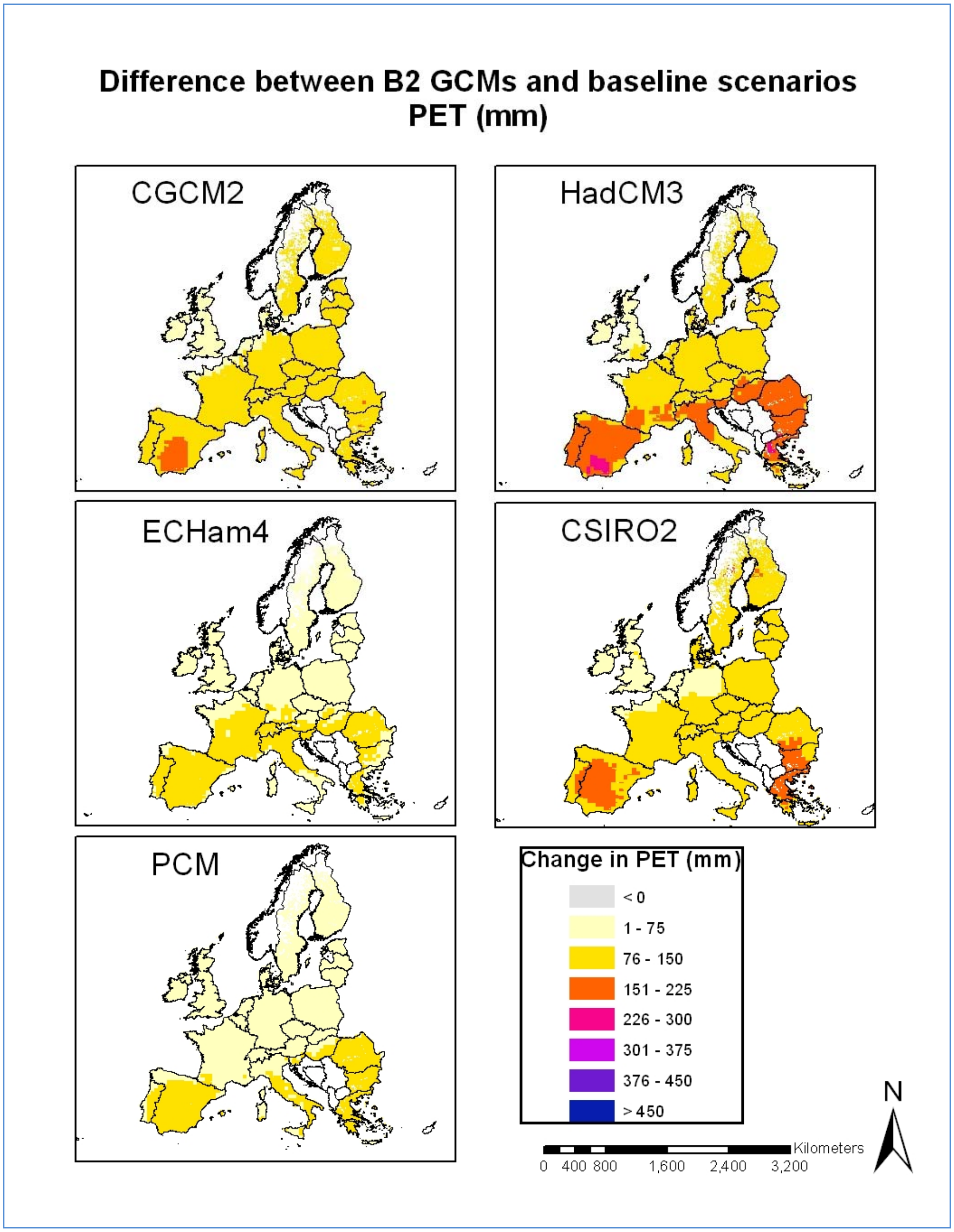

Figure 32. GCMs predicted absolute change in annual PET for the B2 scenarios

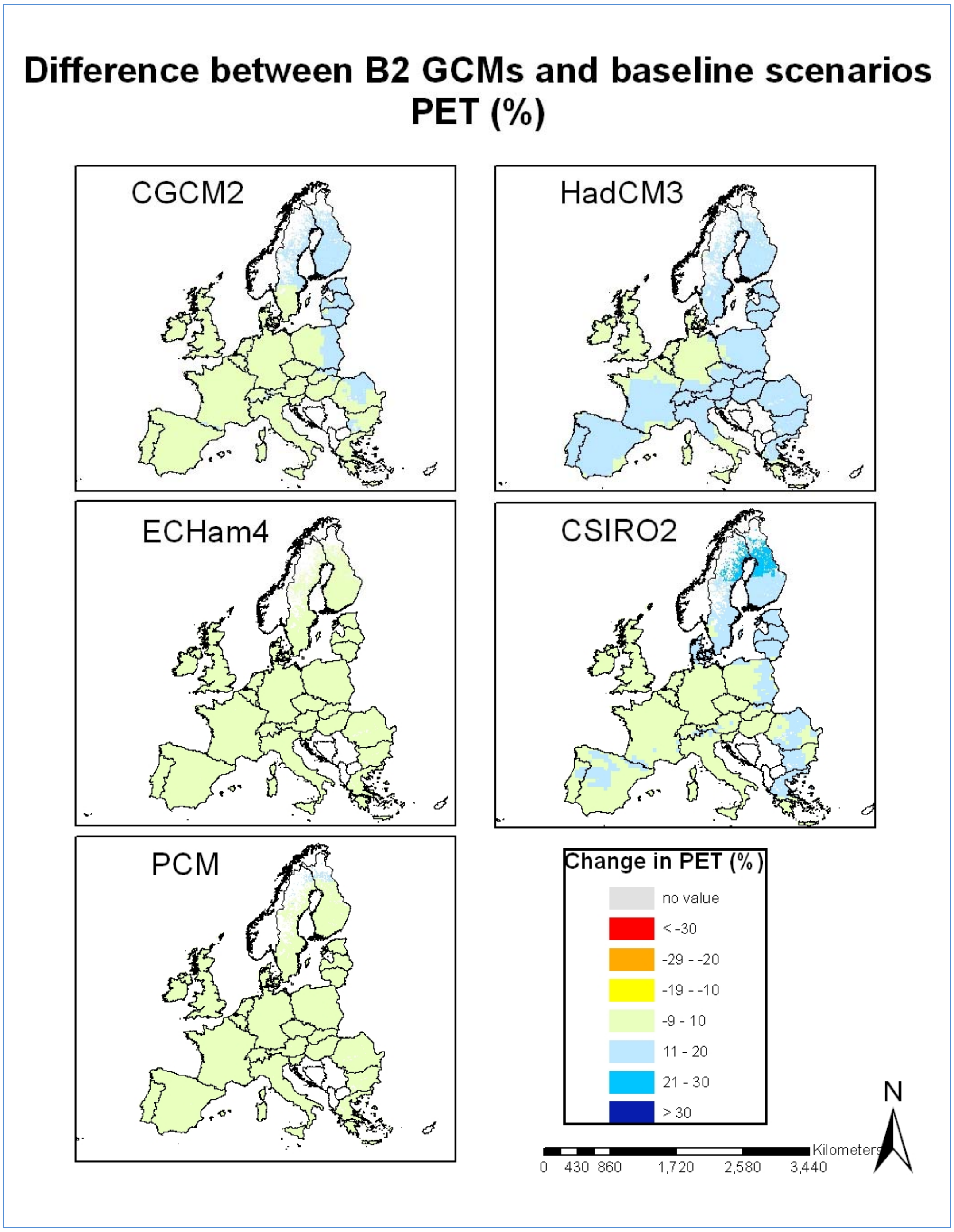

Figure 33. GCMs predicted relative change in annual PET for the B2 scenarios

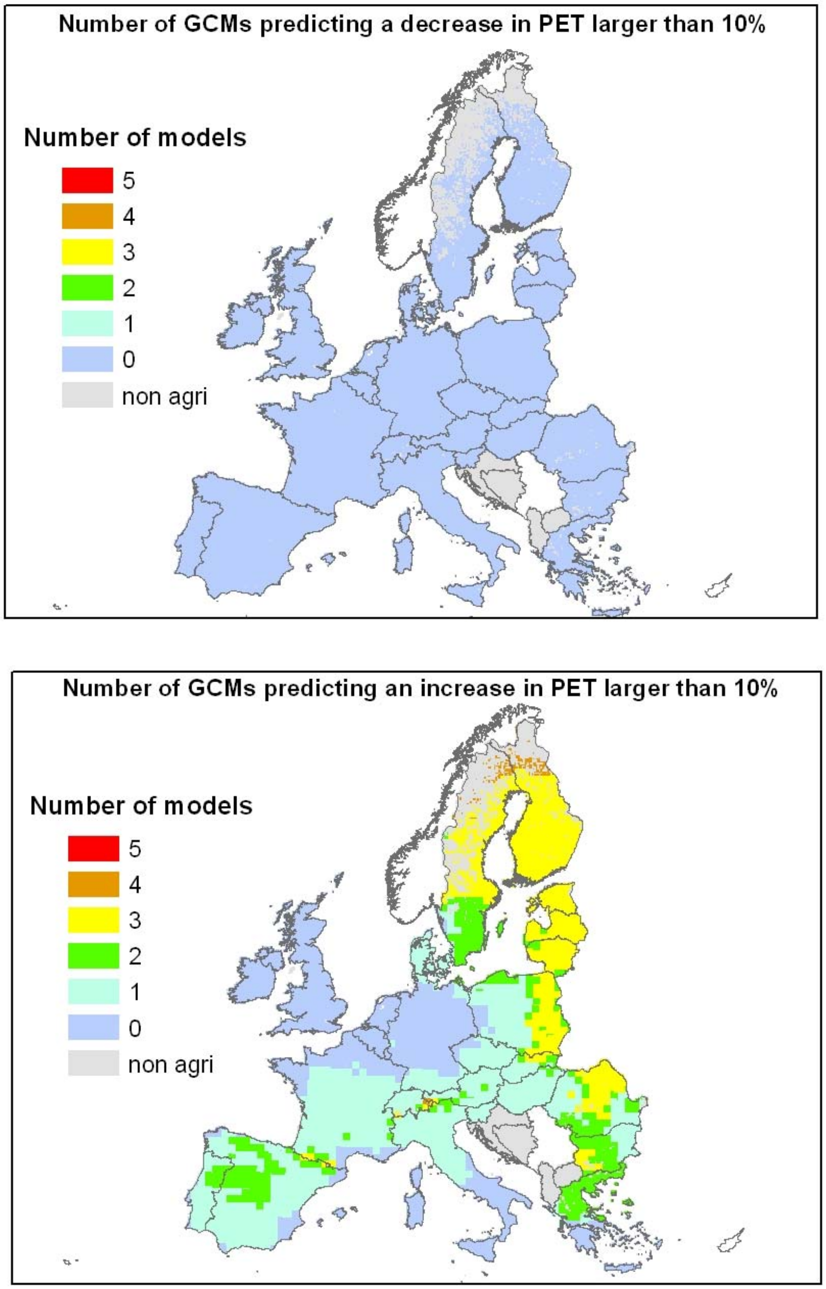

Figure 34. GCMs agreement for predicted changes in annual PET for the B2 scenarios

4.5.3 CROP YIELD

The results for annual crop yield are shown in Figures 35 to 40. It is important to remember that the results reported for crop yield are a weighted average of the five dominant crops present in each grid cell. All A1 scenarios predict an increase in crop yield by 2 to 4 t/ha in Sweden, Finland Denmark, Estonia and Latvia. This is a combined effect of CO2 fertilisation and more favourable crop growing conditions in Northern Europe. On the other hand, areas dominated by maize cultivation will see a drop in crop yield from 2 to 4 t/ha including the Po valley in Italy, Aquitaine region in France, and large portions of Hungary and Romania. The predicted effect for the B2 scenarios is similar but less extreme. Regions dominated by maize production will see a decrease in crop yield, while most part of Europe will see an increase crop production. In relative terms HadCM3 (A1 series) is the most extreme one with predicted losses in crop yield by more than 30% for large portions of Europe, only Sweden, Finland Ireland and Northern England benefiting from the climate change with an increase in yield by more than 30%. The agreement between the GCMS for the A1 scenarios for a decrease in crop yield by more than 10% is localised in areas with a large extent of cultivation of irrigated maize, while there is also an agreement for an increased crop yield in Sweden, Finland, Ireland, Scotland and Brittany. A similar agreement is found for the B2 scenarios.

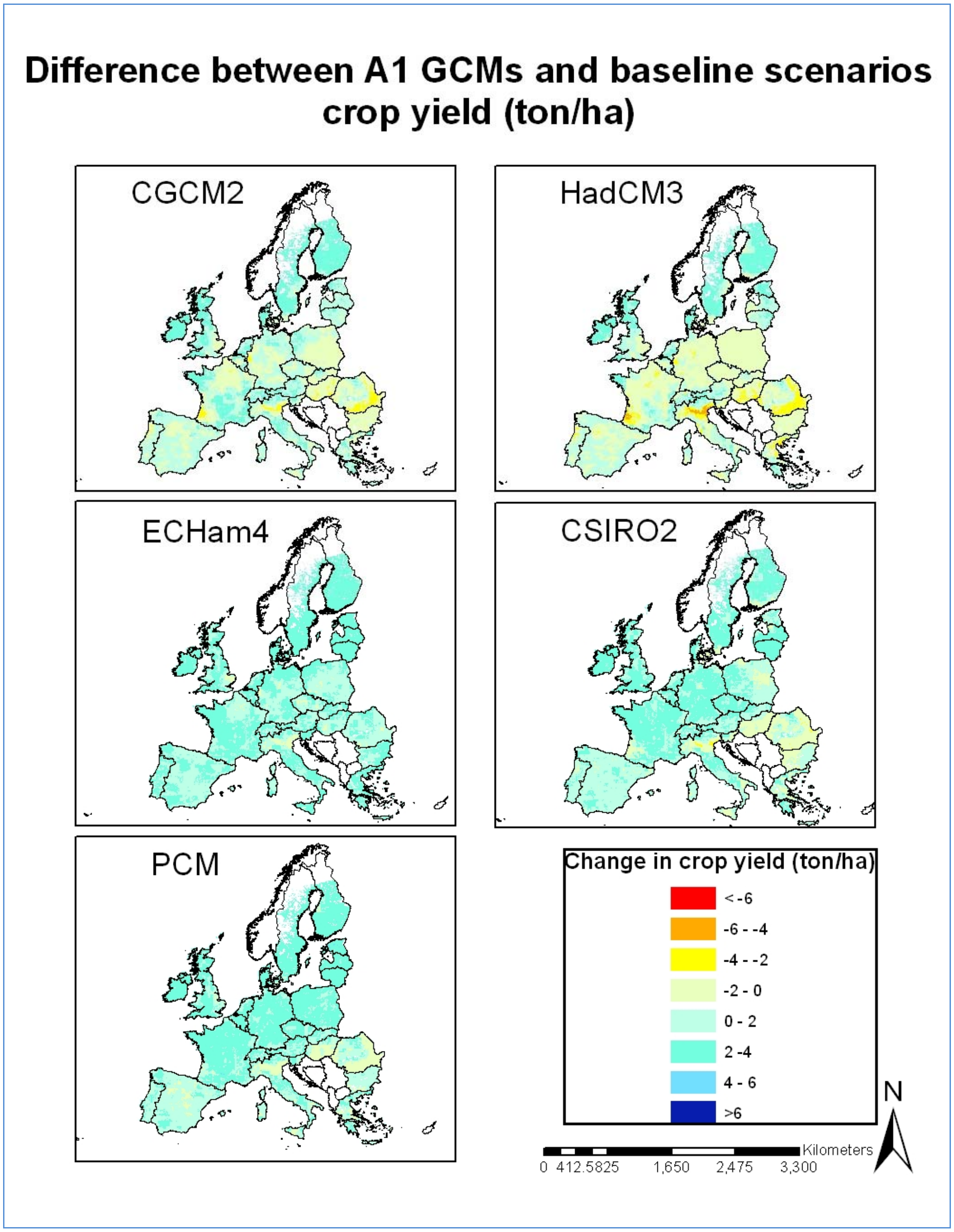

Figure 35. GCMs predicted absolute change in annual crop yield for the A1 scenarios

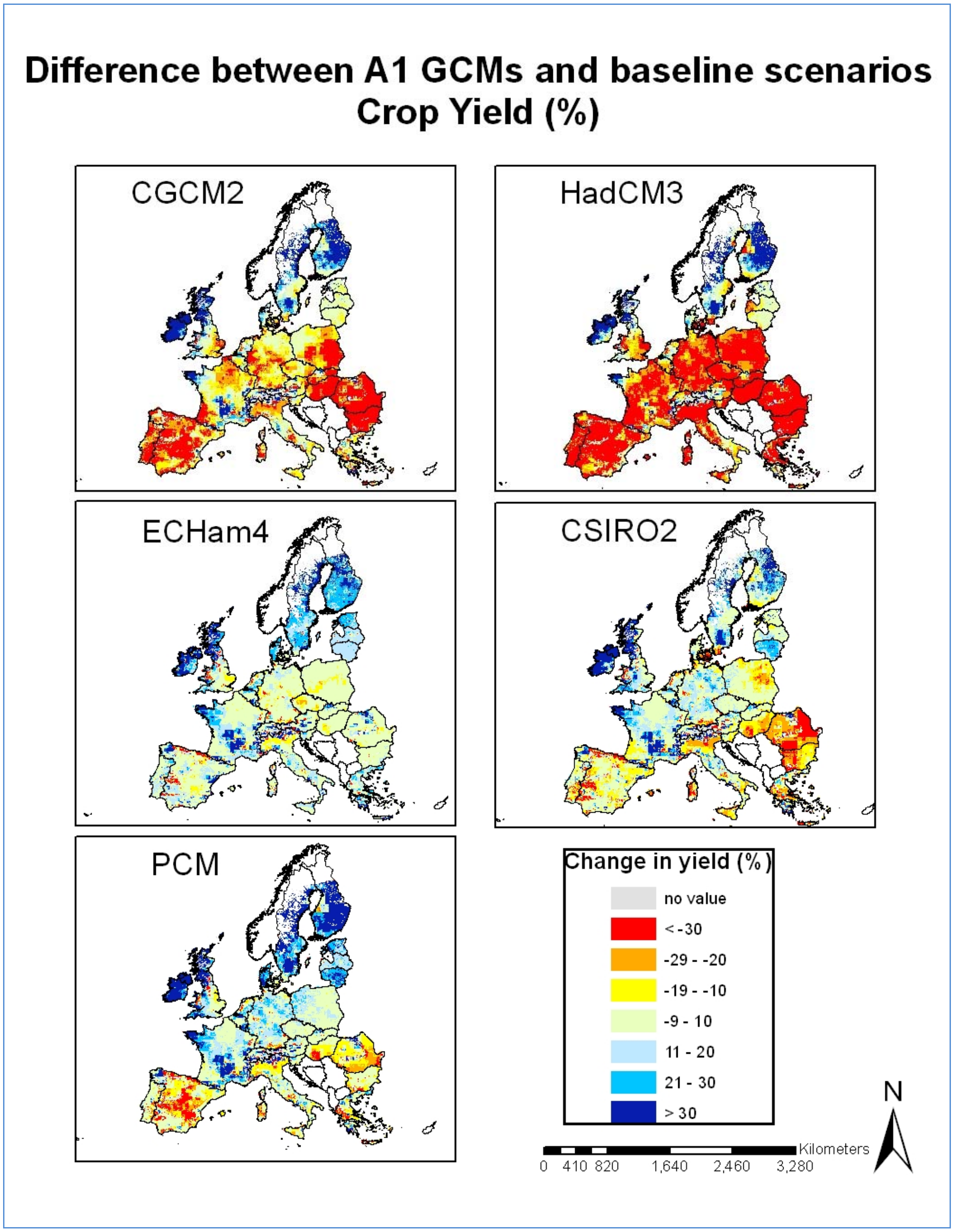

Figure 36. GCMs predicted relative change in annual crop yield for the A1 scenarios

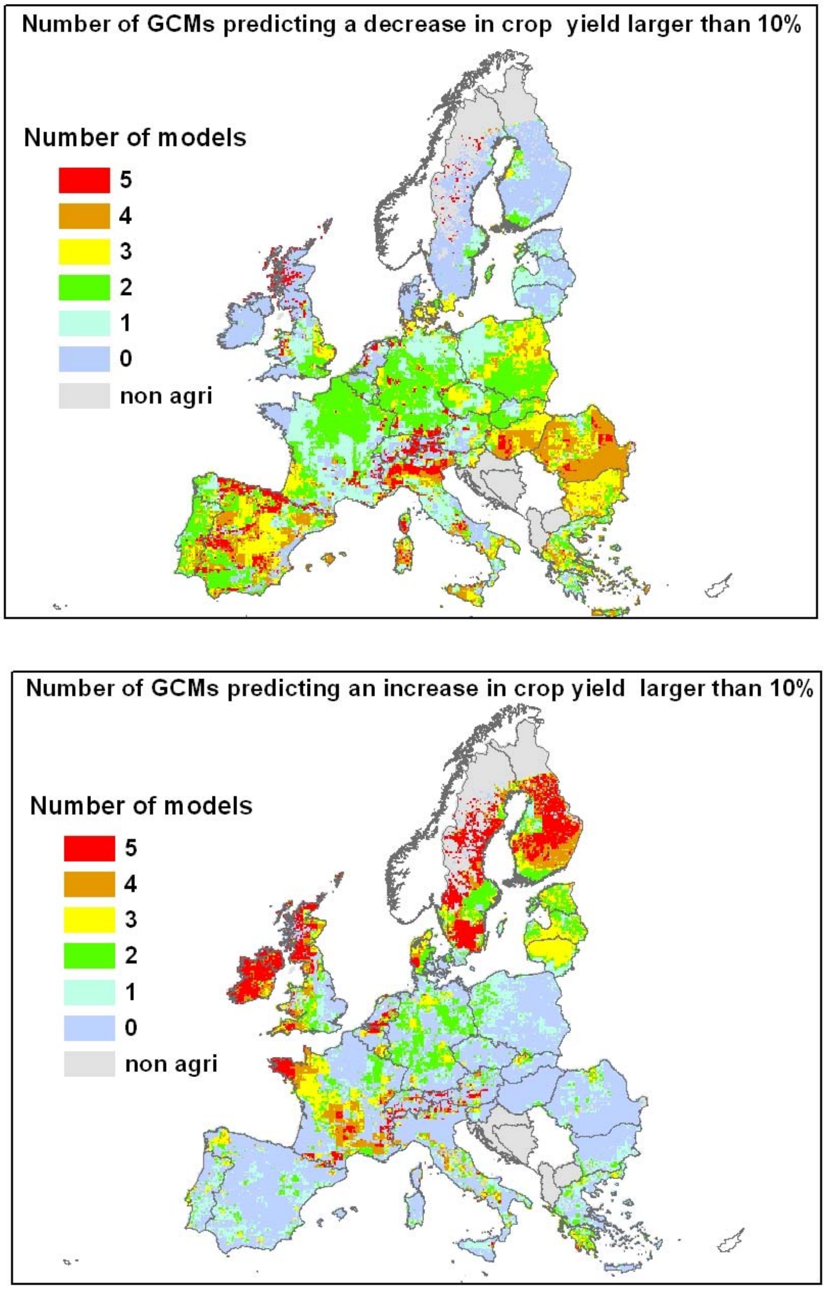

Figure 37. GCMs agreement for predicted changes in annual crop yield for the A1 scenarios

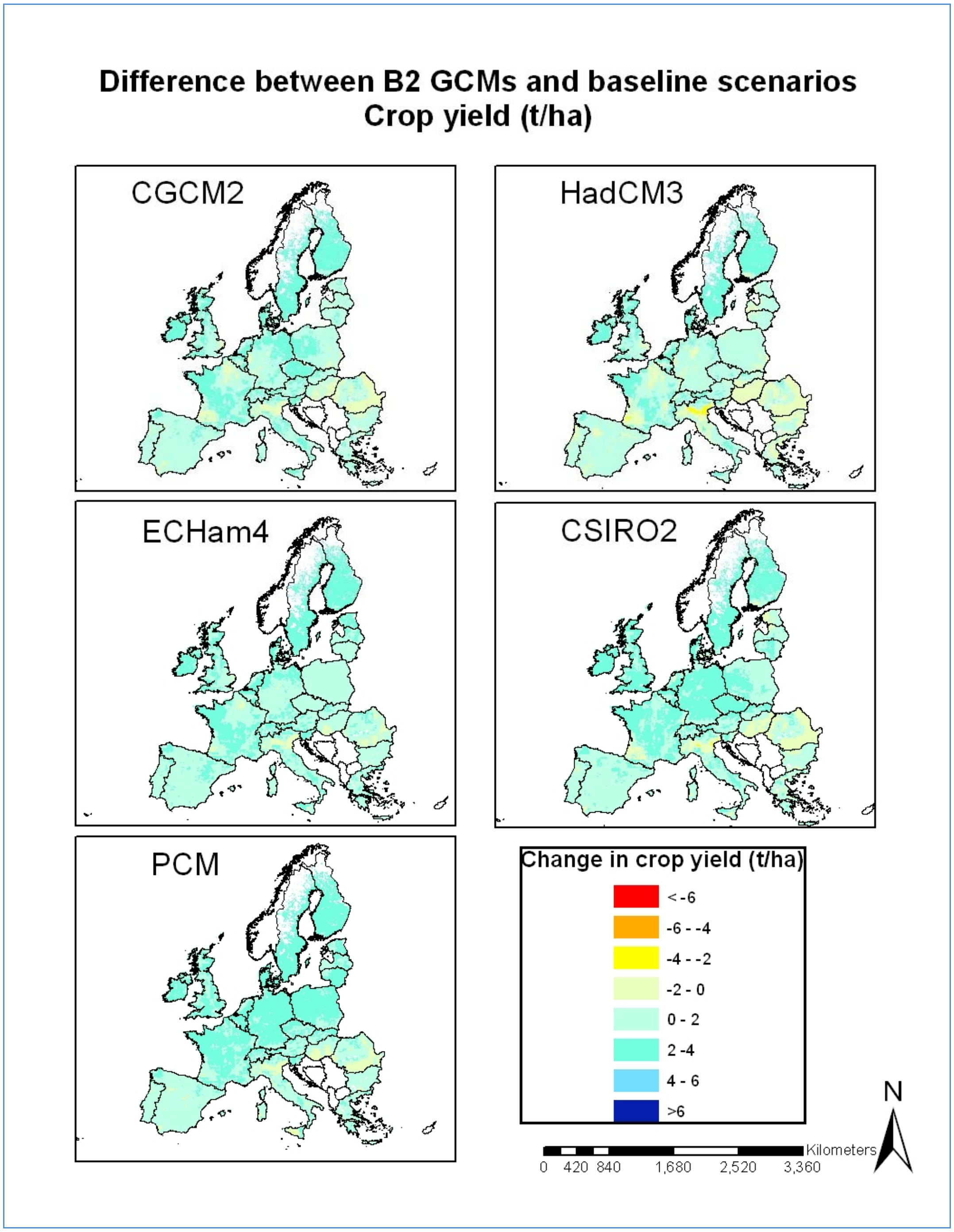

Figure 38. GCMs predicted absolute change in annual crop yield for the B2 scenarios

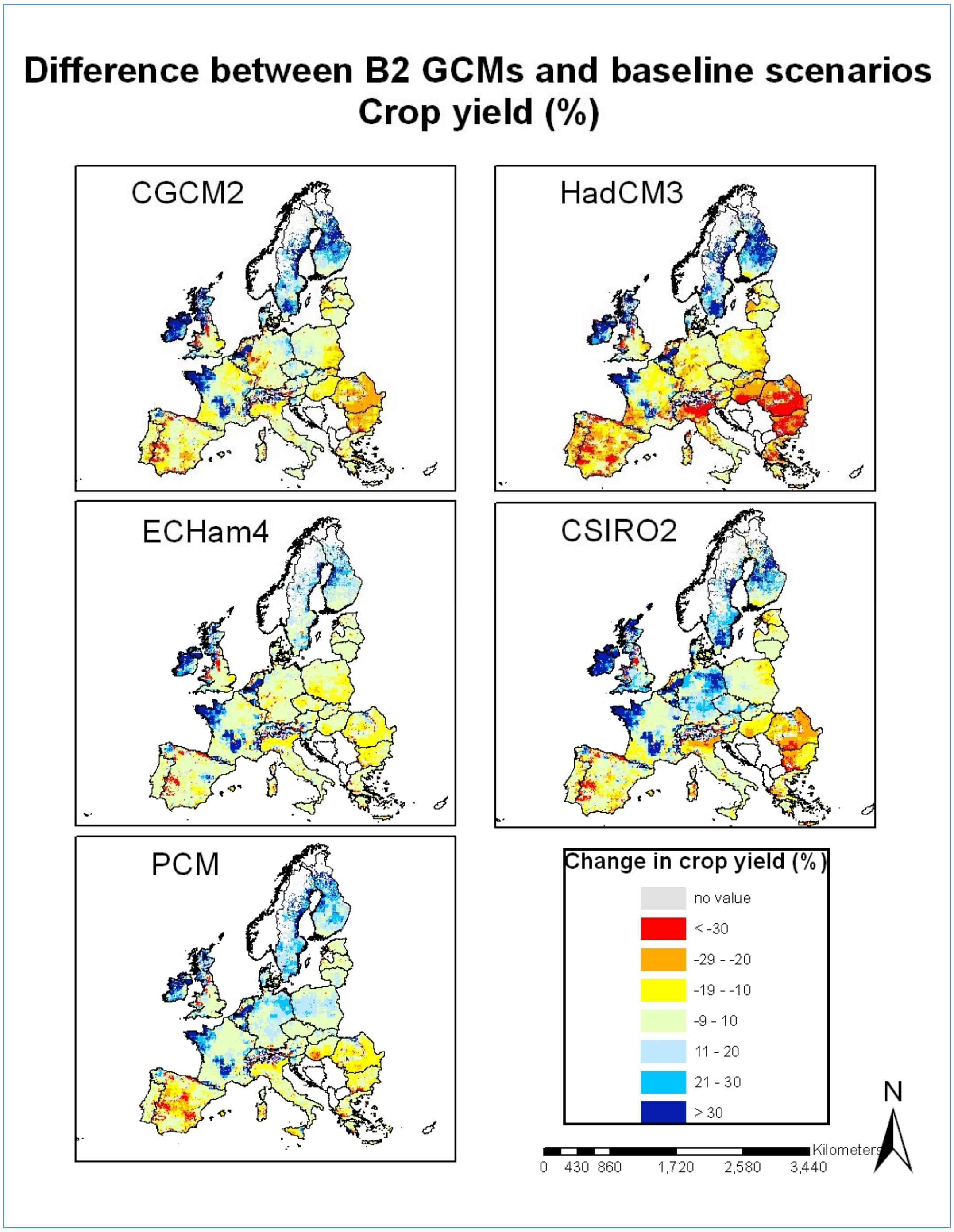

Figure 39. GCMs predicted relative change in annual crop yield for the B2 scenarios

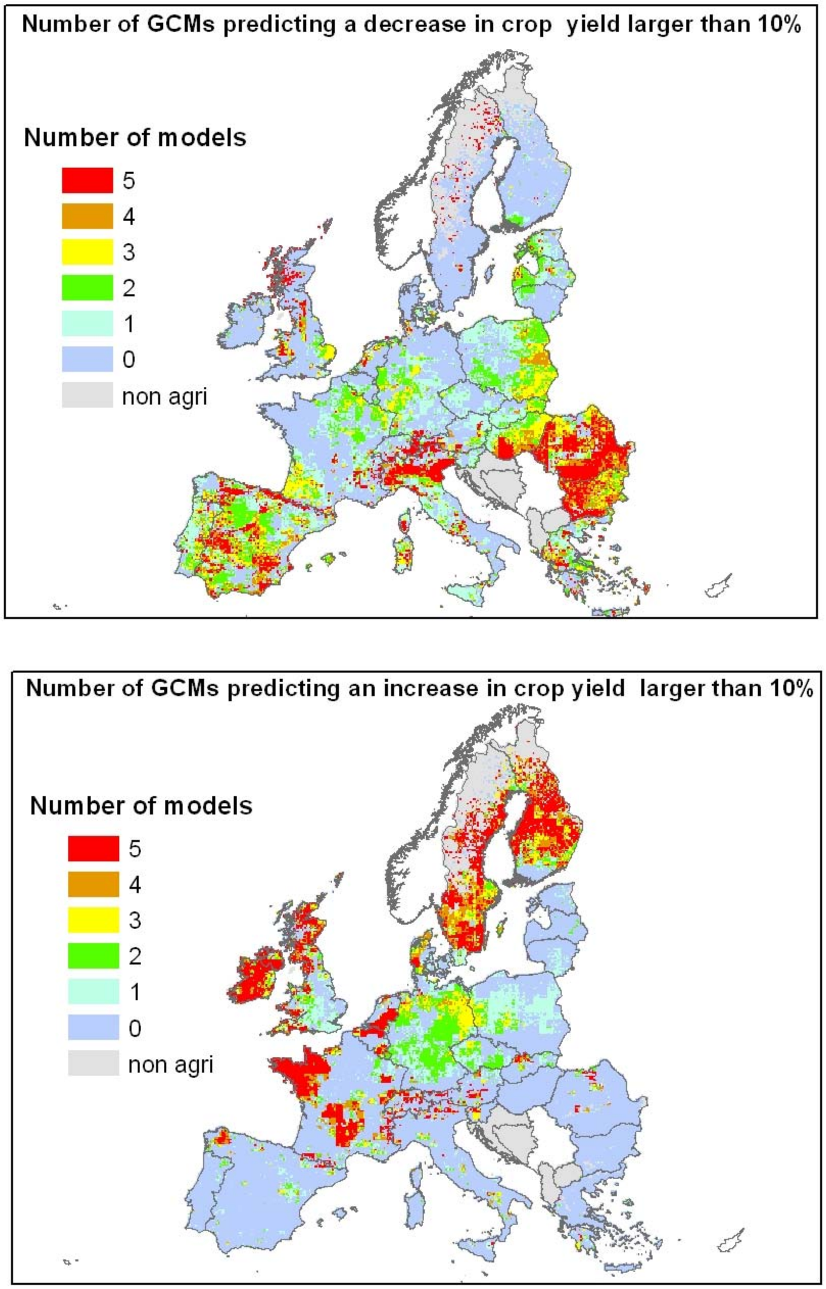

Figure 40. GCMs agreement for predicted changes in annual crop yield for the B2 scenarios

4.5.4 WATER STRESS

The results for annual water stress are shown in Figures 41 to 46. The change in temperature and precipitation affected greatly the water stress (proxy indicator for irrigation water requirement). During all runs it was decided not to auto-irrigate all the crops in order to make comparable runs between the baseline and climate change scenarios results. The same irrigation schedule implemented in the baseline was kept for the climate change scenarios. Large portions of Europe will see an increase in water stress from 1 to 50 days for the mildest A1 scenario (ECHAM4 A2 scenario used as A1). The most extreme scenarios (GCM2 and HadCM3) predict an increase in water stress larger than 50 days for a large part of Europe. Only northern countries will face a smaller increase of water stress. As expected the changes in water stress days are milder for the B2 scenarios with the north part of Europe exhibiting a decline in water stress days while all scenarios do not predict a change larger than 50 days. This increase in water stress days for CGCM2 and HadCM3 is partly responsible for the crop yield decrease under some of the A1 scenarios. These two GCMs predict an increase in water stress by more than 30% for about the whole Europe. Milder scenarios such as ECHAM4 predict fewer changes in the southern part of Europe. This is explained by the fact that these regions are irrigated, and that the current management scheme could mitigate somewhat the effect of climate change. Under the most extreme scenarios, not enough water is available under the current irrigation scheme to fulfil the additional crop water requirements. Under the B2 scenarios, changes in water stress exceed 30% along the UK and Irish Atlantic coasts, in the Alps and along the Massif Central in France. Concerning the agreement of the different GCMs, there is an overall consensus under the A1 scenarios that all Europe (but parts of southern Spain and Portugal, Greece due to auto-irrigation) will see an increase in water stress by more than 10%. It is predicted that the Atlantic coast of

Scotland will see a decrease in water stress. For the B2 scenarios, there is less agreement concerning the extent of the changes. However, all models agree that the Alps region, southern France, Ireland, western England and part of the Castilla regions (Spain) will also see an increase in water stress by more than 10%.

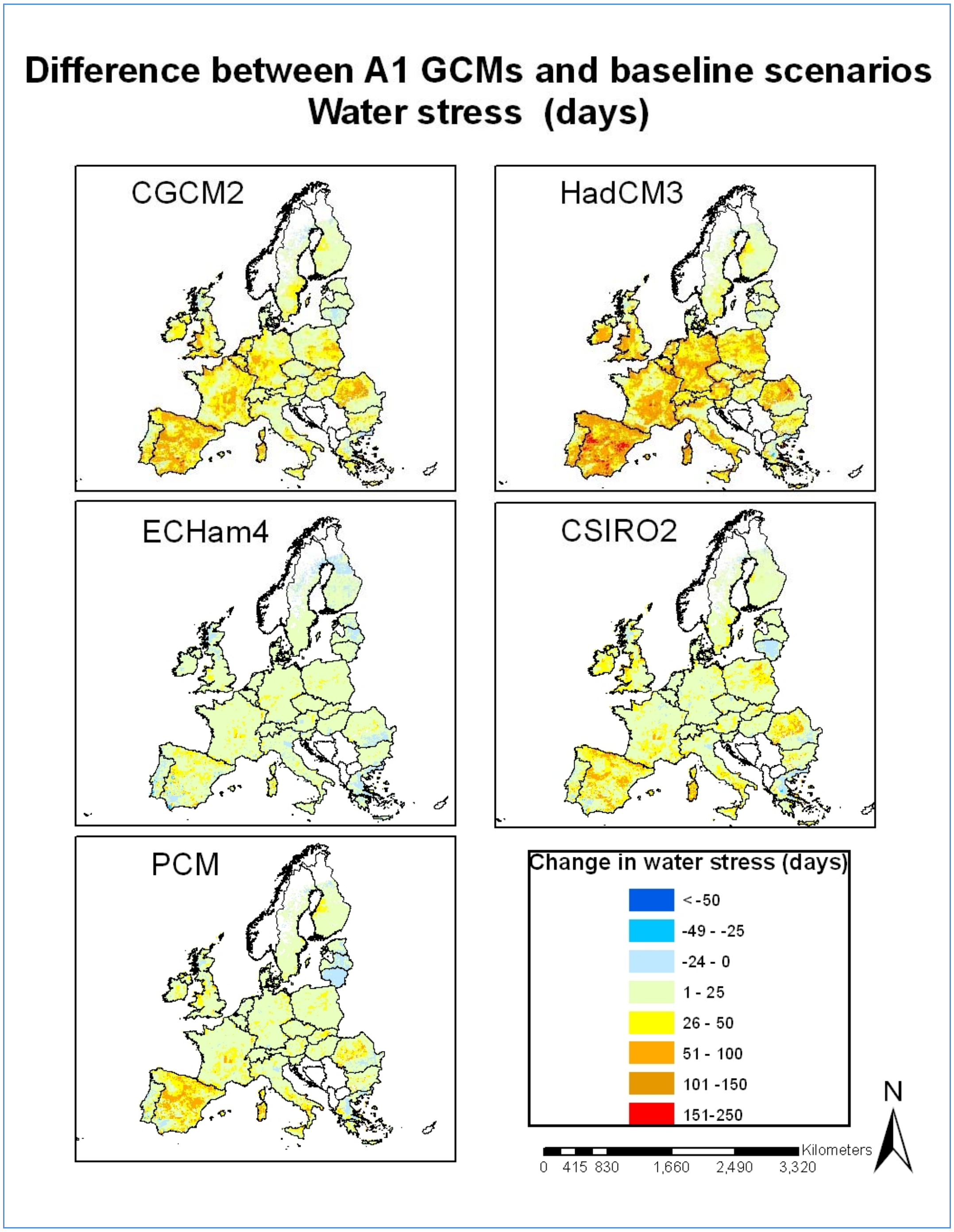

Figure 41. GCMs predicted absolute change in annual water stress for the A1 scenarios

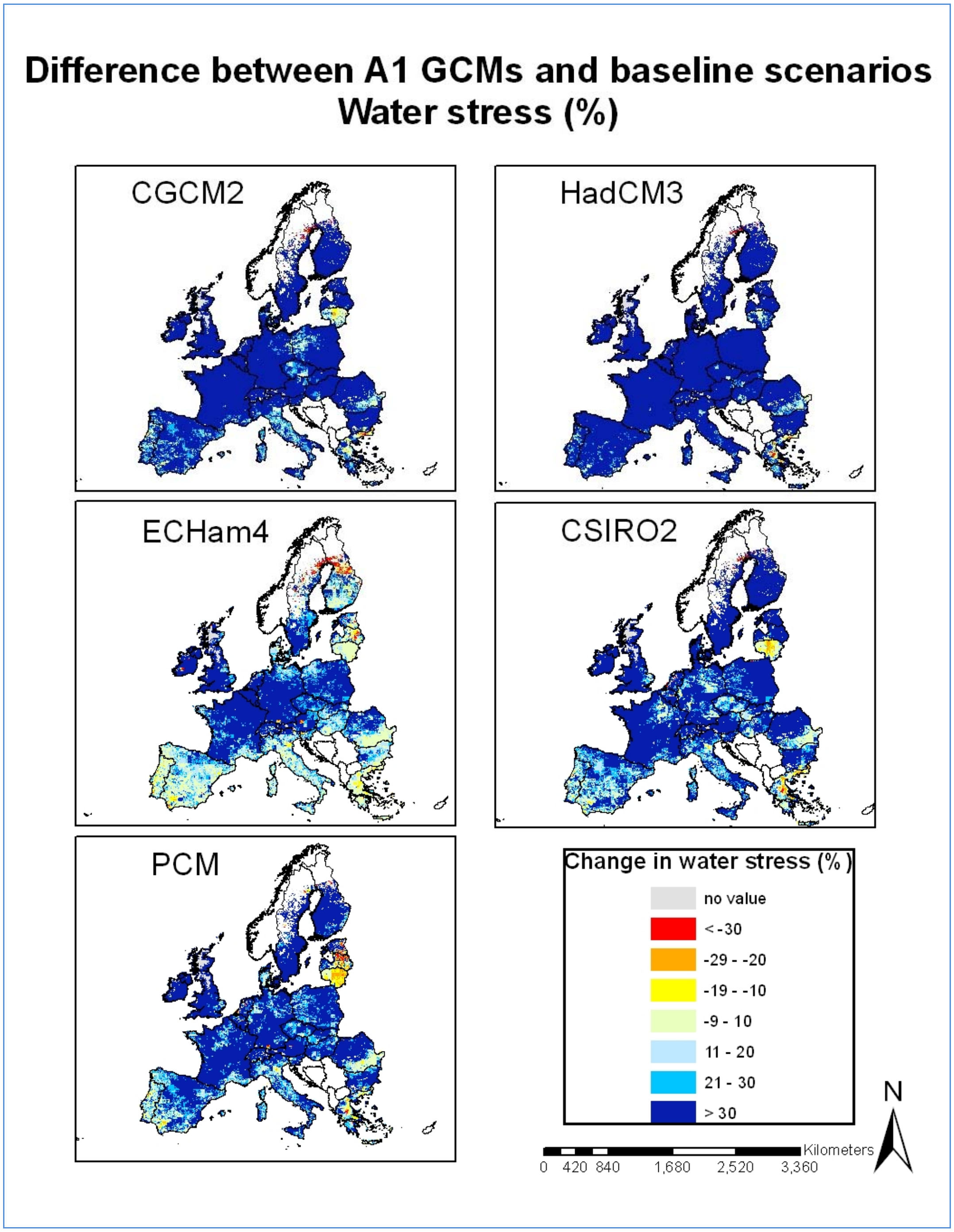

Figure 42. GCMs predicted relative change in annual water stress for the A1 scenarios

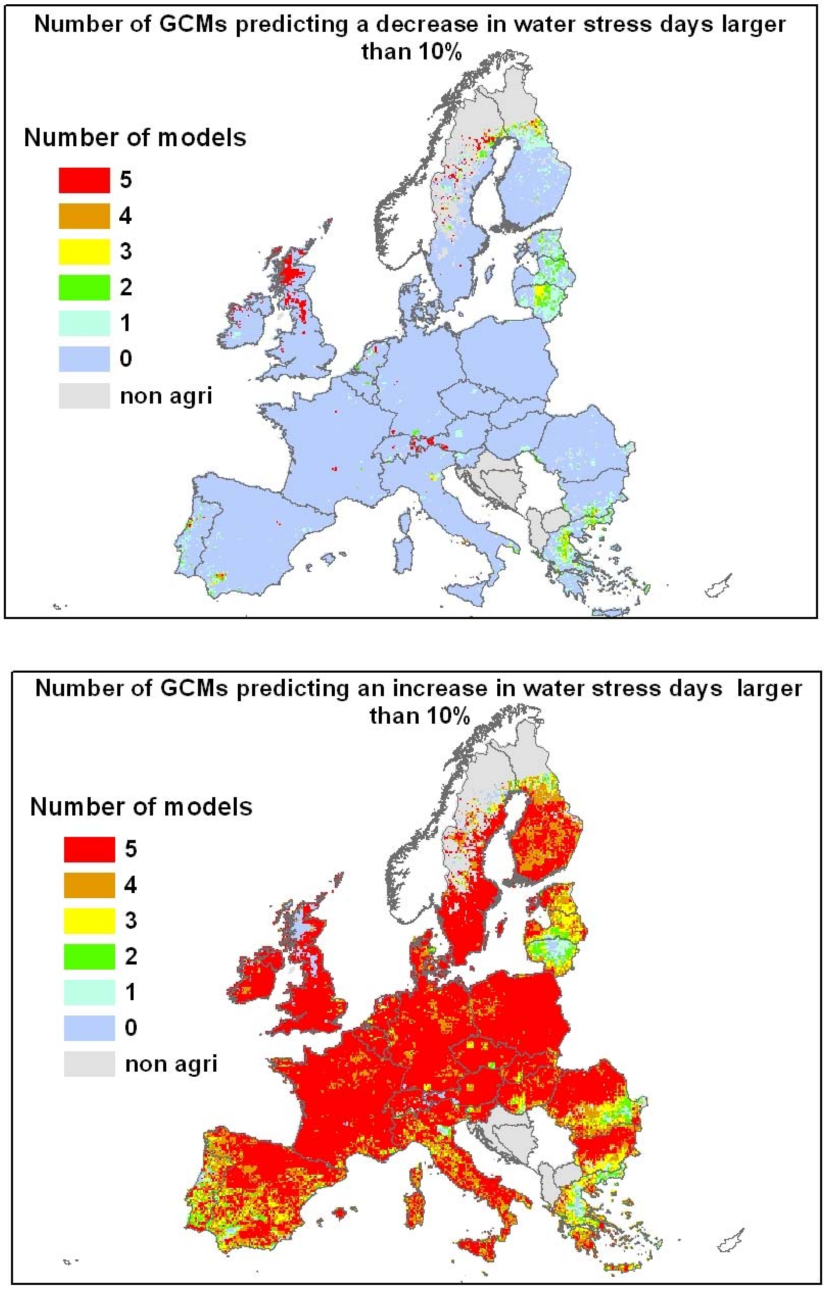

Figure 43. GCMs agreement for predicted changes in annual water stress for the A1 scenarios

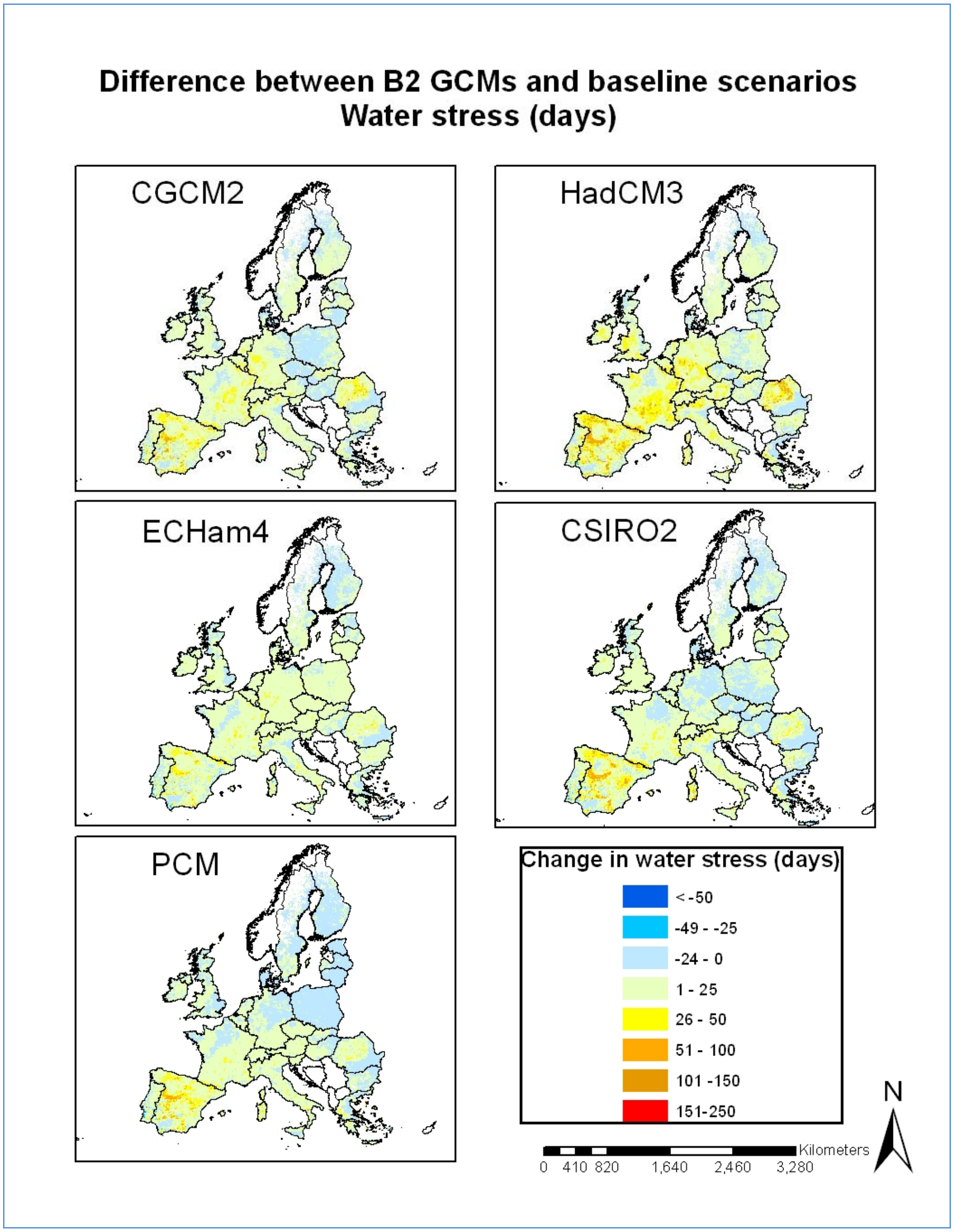

Figure 44. GCMs predicted absolute change in annual water stress for the B2 scenarios

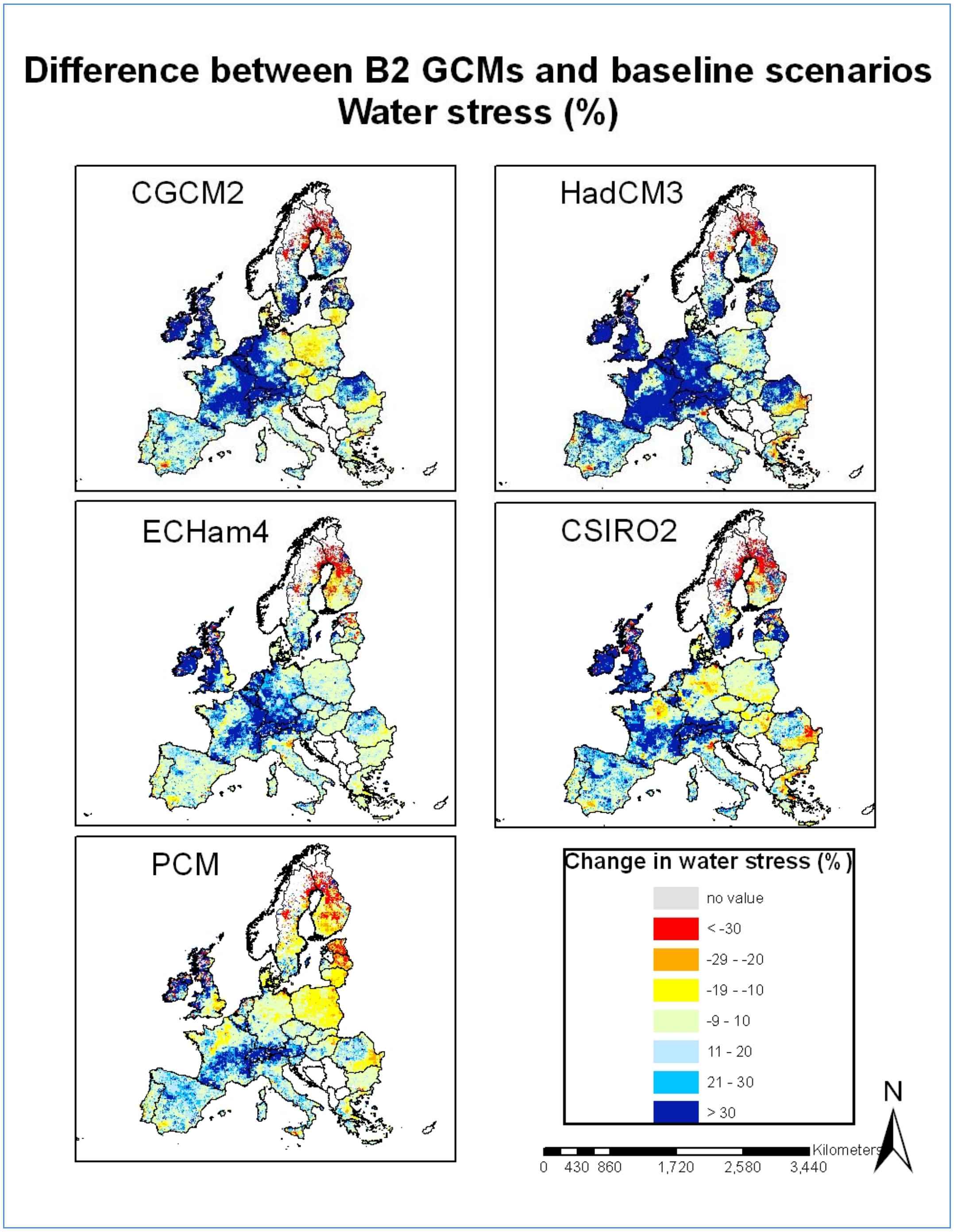

Figure 45. GCMs predicted relative change in annual water stress for the B2 scenarios

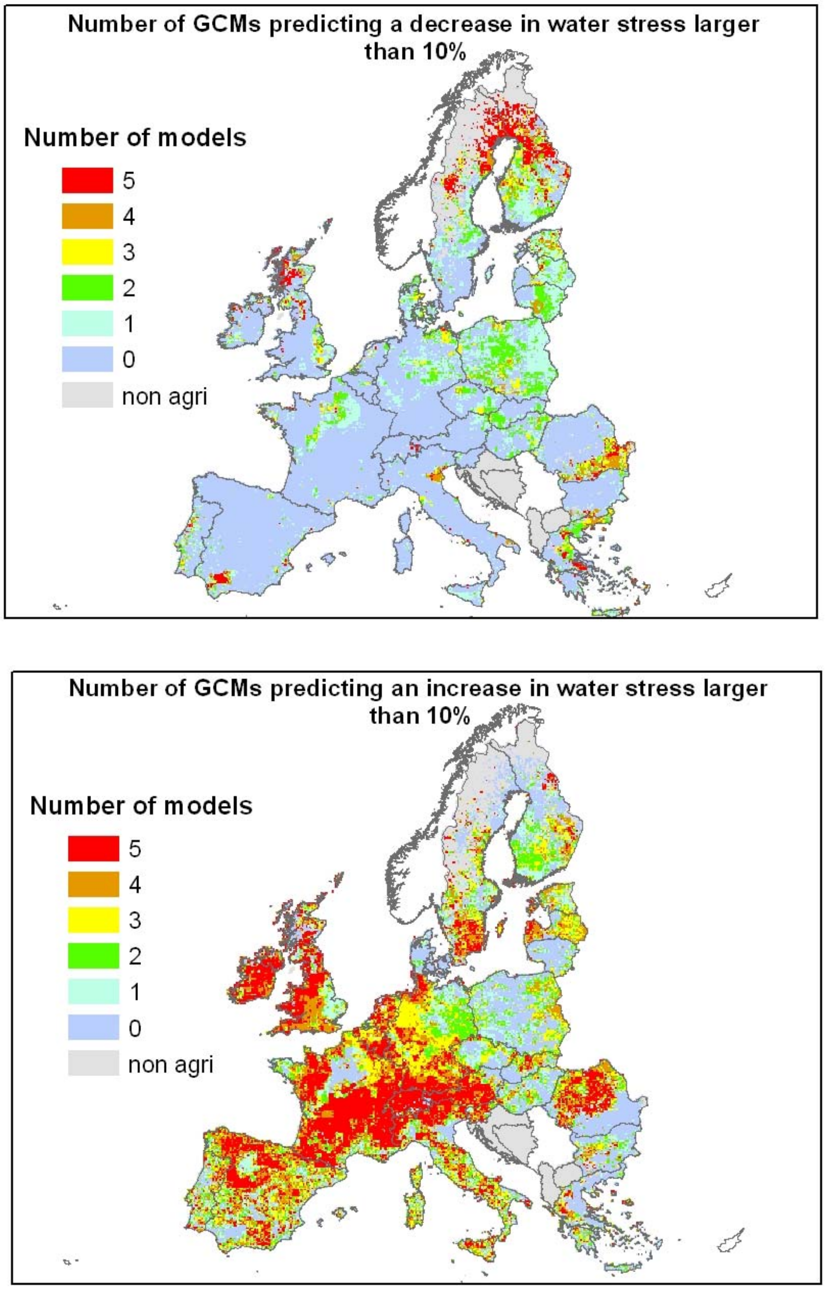

Figure 46. GCMs agreement for predicted changes in annual water stress for the B2 scenarios

4.5.5 NITROGEN APPLICATION

The last parameter analysed was the nitrogen application, and the results are shown in Figures 47 to 52. To evaluate the impact of the climate change scenarios, the EAGLE was set to auto-fertilisation. Clearly, the fertilisation is strongly linked to crop yield. Concerning the A1 scenarios, CGCM2 and HadCM3 predict a decrease in the application of nitrogen, corresponding also to the reduction of crop yield. However, this reduction is limited by the fertilisation effect of CO2 enrichment in the atmosphere. The other scenarios predict a general reduction in most of southern Europe while large portions of Germany, France and Lithuania see an increase in the fertilisation rate. A similar trend is observed for the B2 scenarios, however with a larger extent of the areas affected by a reduction in N application. In relative terms, the HadCM3 was the most extreme scenario with a decrease in N application by more than 30% for a large part of Europe explained by the reduction of crop yield. Concerning the A1 series, all models agreed in predicting a decrease in N application in south-eastern Spain, the Alps, Finland, Wales and Sweden. An increase was also predicted for all scenarios for Brittany, and the Netherlands. Concerning the B2 scenarios large portions of Europe are affected by a decrease of N application including Spain, Sweden, and Finland.

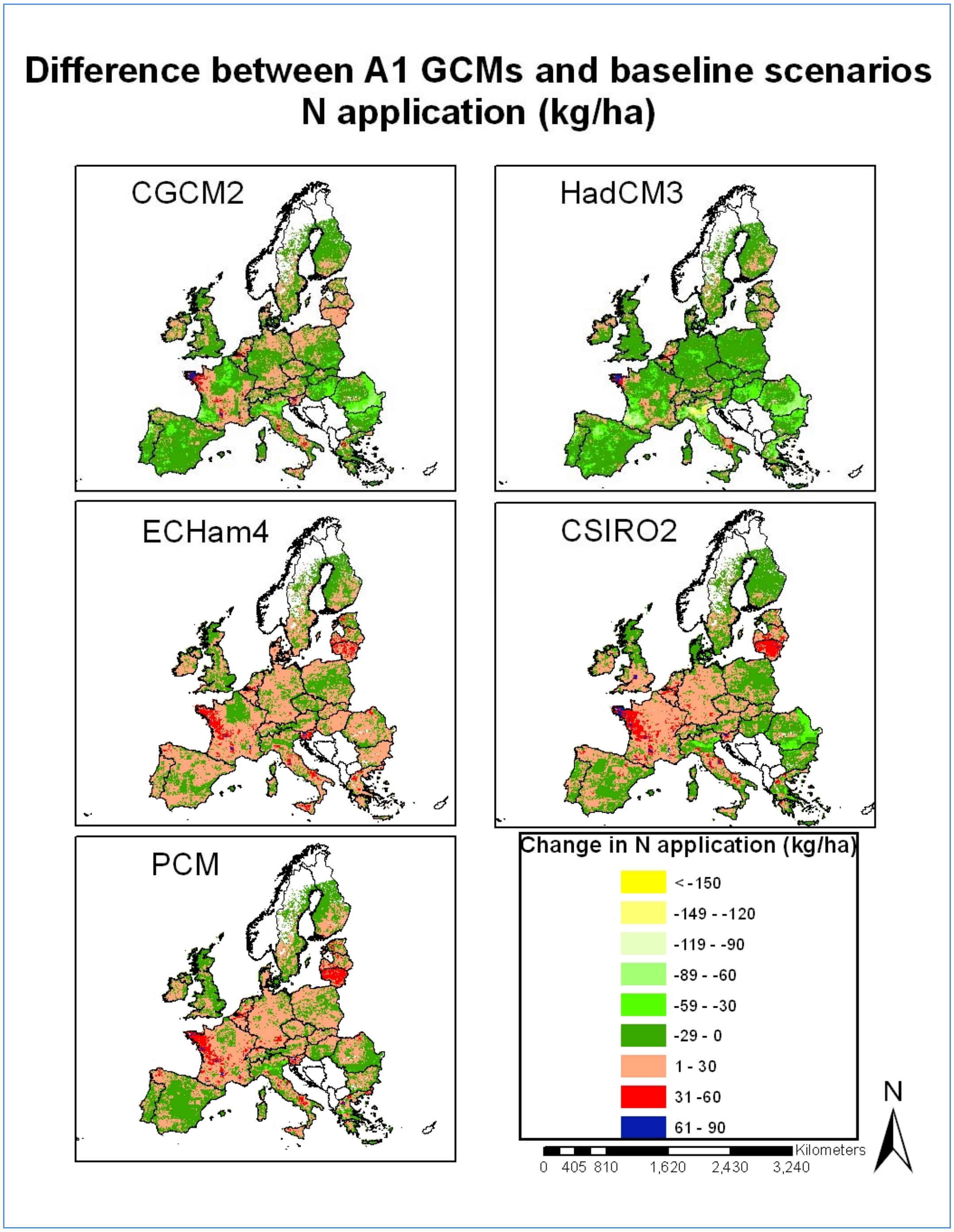

Figure 47. GCMs predicted absolute change in annual nitrogen application for the A1 scenarios

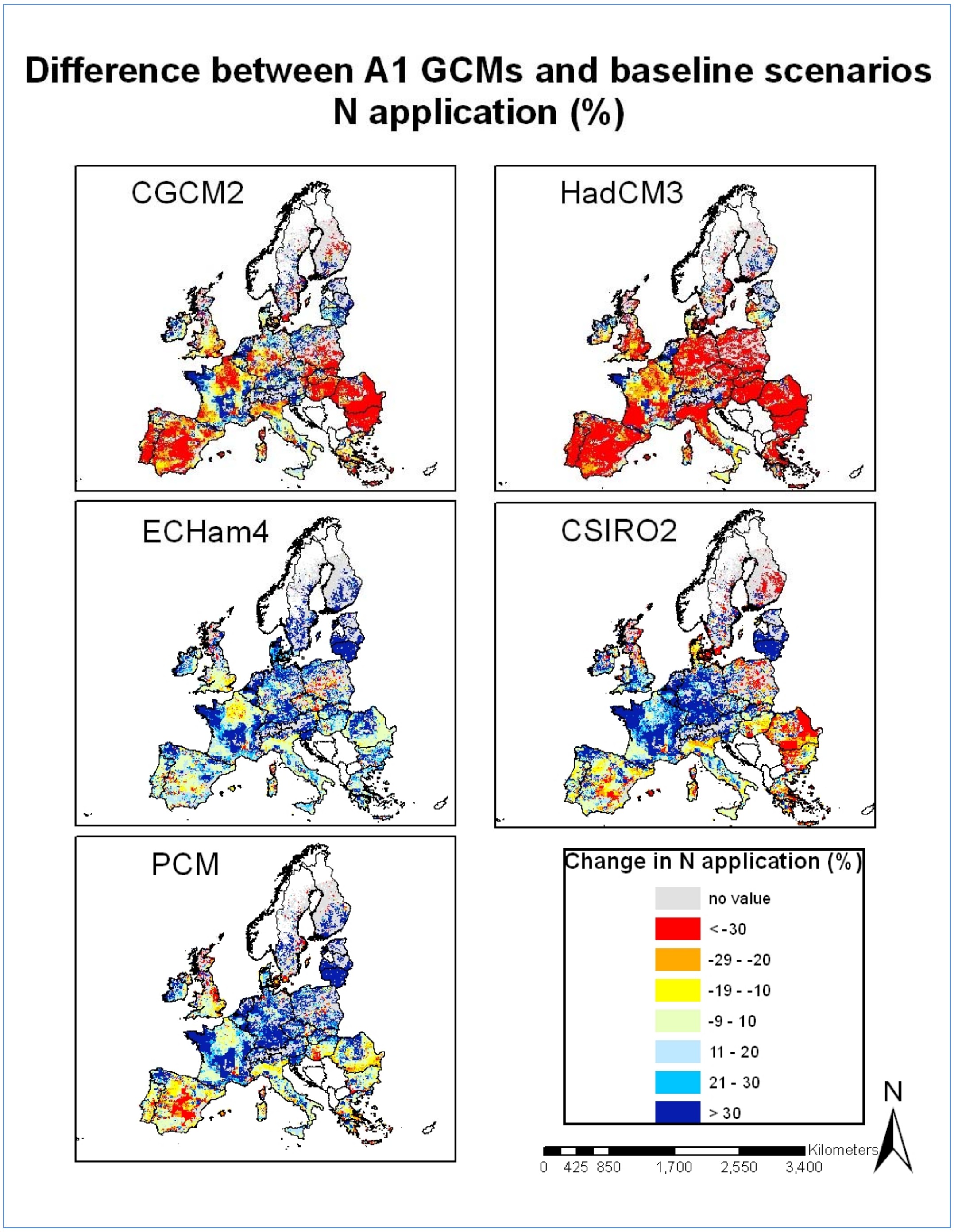

Figure 48. GCMs predicted relative change in annual nitrogen application for the A1 scenarios

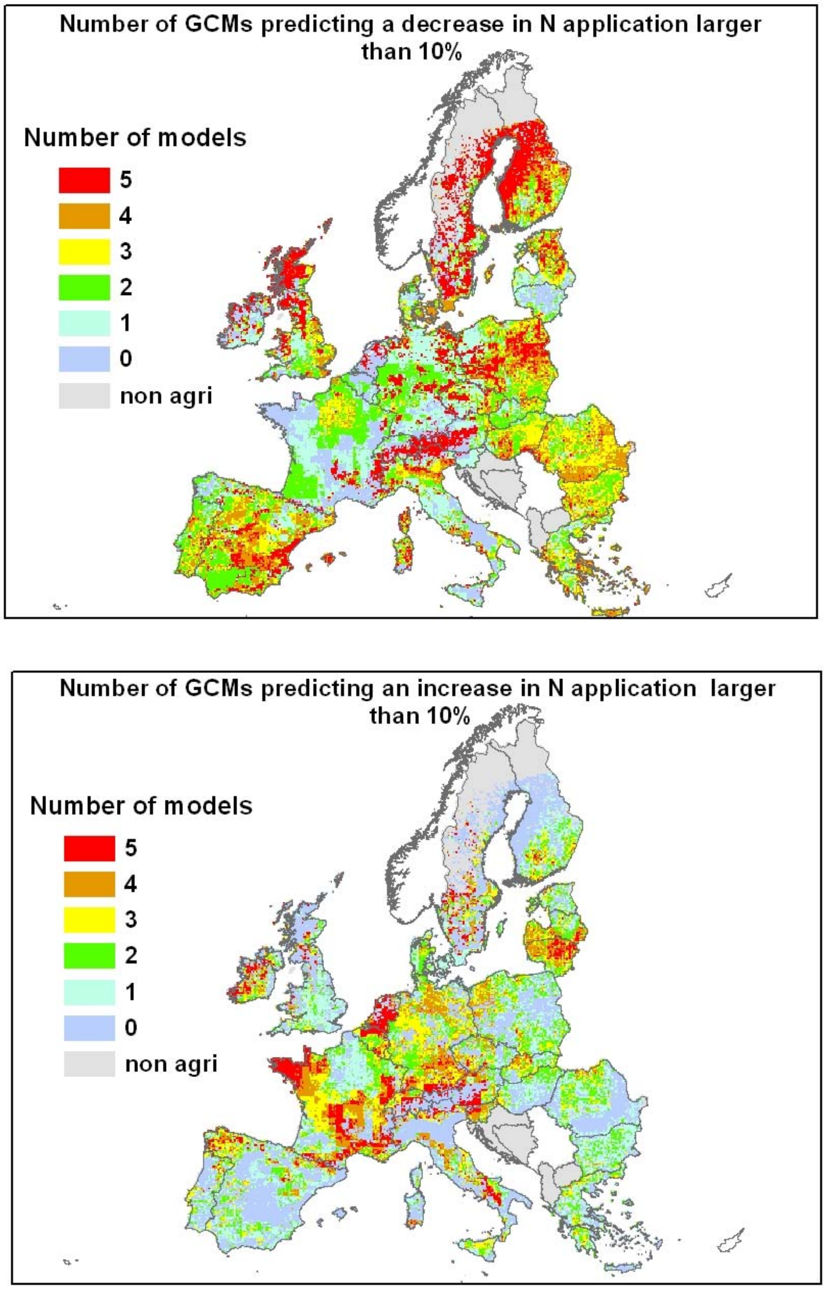

Figure 49. GCMs agreement for predicted changes in annual nitrogen application for the A1 scenarios

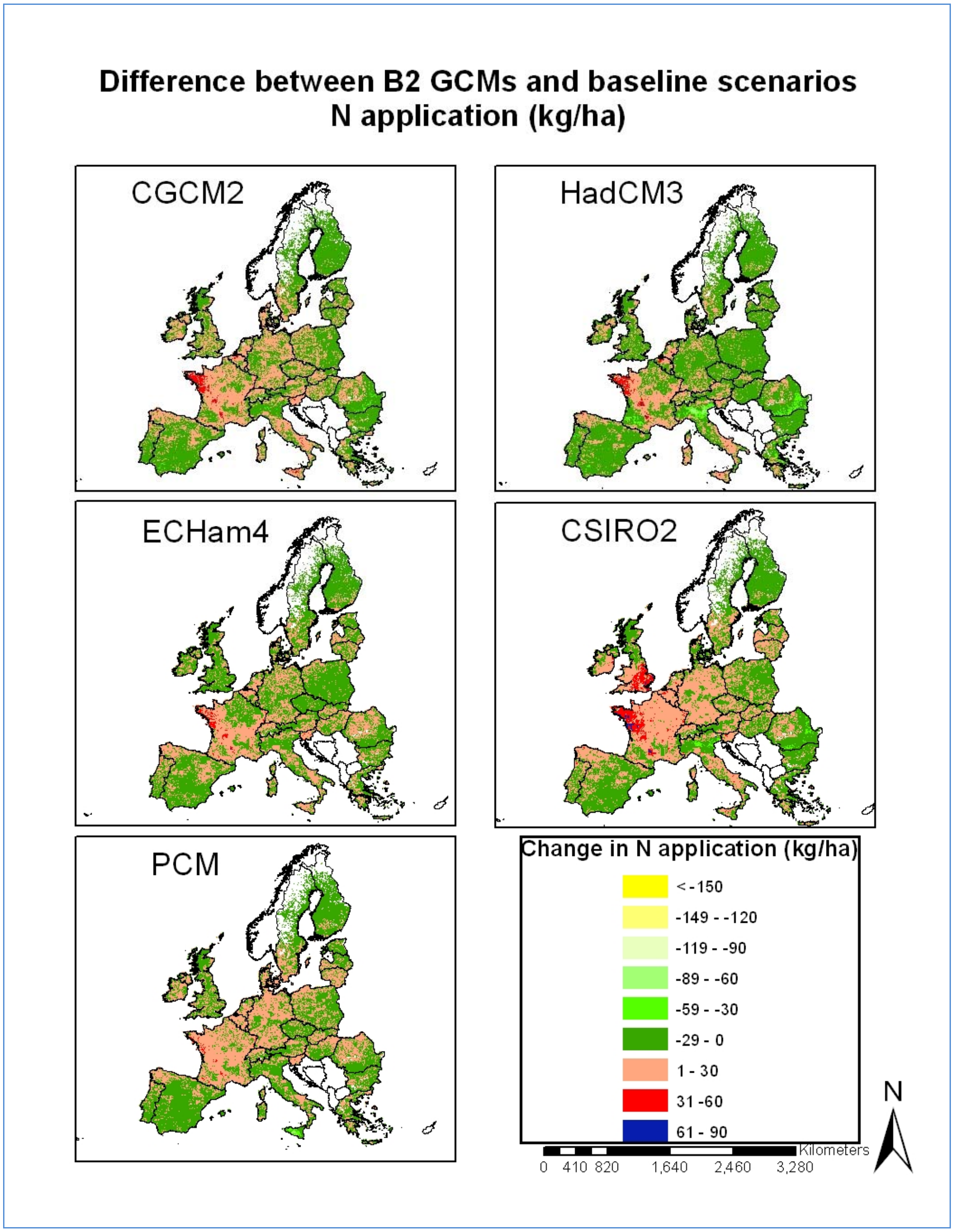

Figure 50. GCMs predicted absolute change in annual nitrogen application for the B2 scenarios

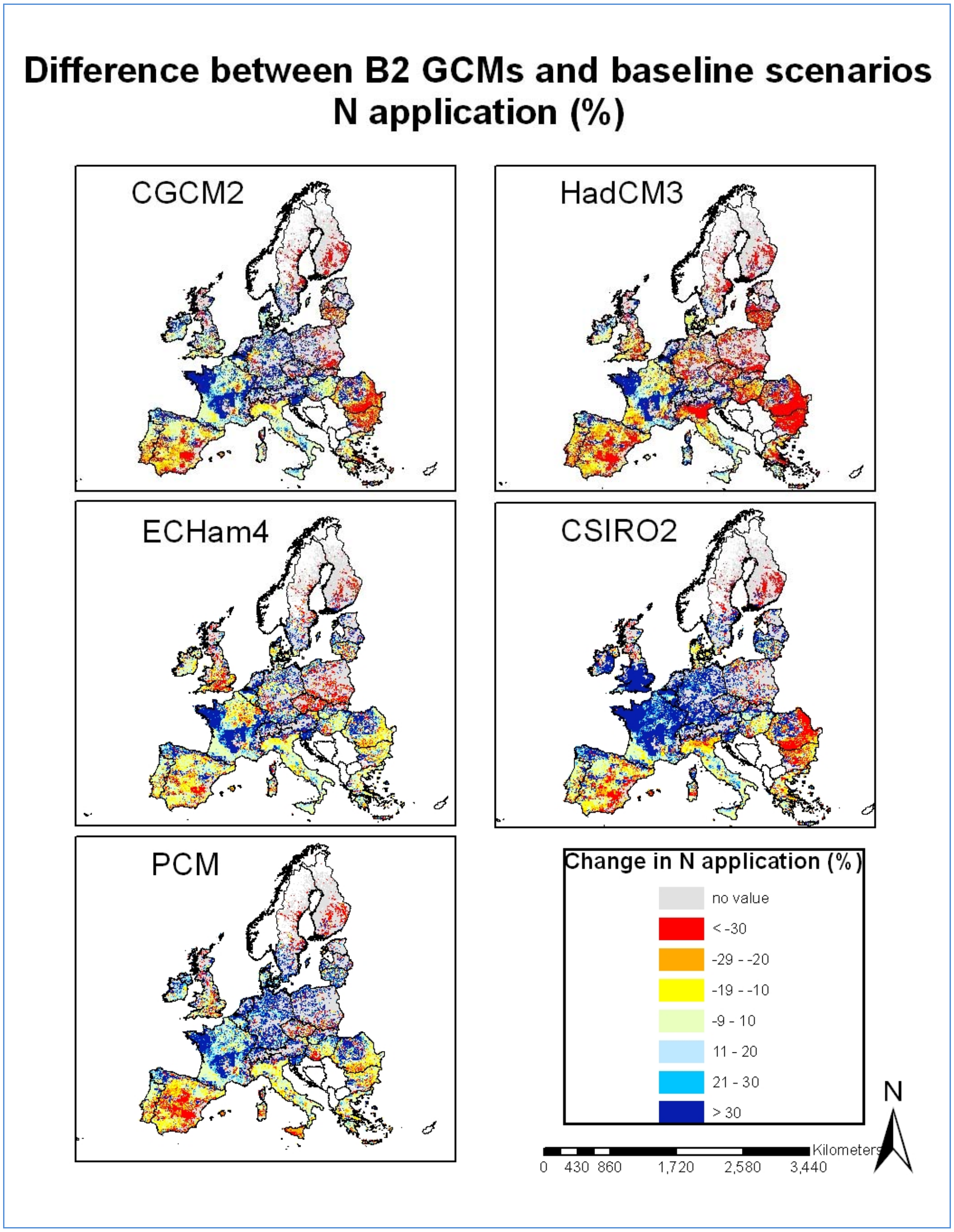

Figure 51. GCMs predicted relative change in annual nitrogen application for the B2 scenarios

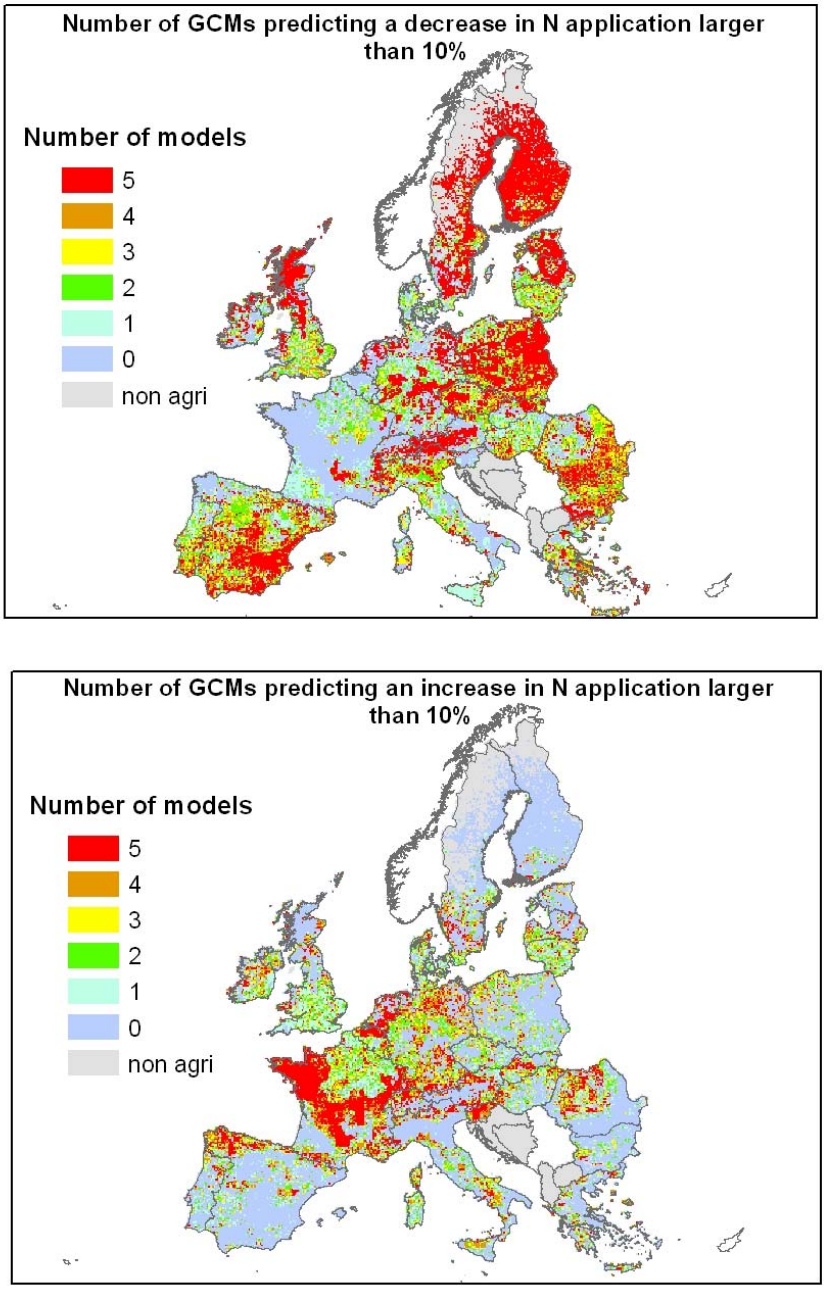

Figure 52. GCMs agreement for predicted changes in annual nitrogen application for the B2 scenarios

5 EAGLE APPLICATION TO ASSES PESTICIDE RISK

Many tools are available for calculating PEC (Predicted Environmental Concentration) of pesticides in various environmental compartment such as MACRO (Jarvis, 1994), GEOPEARL (Tiktak et al., 2002). However, it was decided to use EPIC to calculate the PEC of pesticides in surface water, groundwater and soil in order to include not only nutrients when developing best management practices but also integrate the fate of pesticides. The model results are used to derive exposure toxicity ratio (ETR) indicators. The ETR is calculated as the ratio of the PEC for a specific compartment divided by toxicity. The toxicological parameters are selected based on the non-target organism living in the considered environmental compartment: algae for surface water, earthworms for soil, drinking water limit for groundwater. Additional details about the methodology used can be found in Padovani et al. (2004).

An example of PEC results coming out of EPIC is shown in Figure 53 for Italy and France. The example results from the application of a herbicide, pre-emergence, on maize with the following properties: KOC: 80mg/l; water solubility: 33 mg/l; soil half-life 60 days, foliar half-life 5 days. The applied dose was set at 1kg/ha. The groundwater PEC was then converted to risk point (Figure 54) using the scale detailed in Table 6 (taken from Padovani et al., 2004), with one being the lowest risk point and five the maximum. Then the PECs for the various compartment can be combined together to derive an overall risk.

ETR	Risk Points
< 0.01	1
0.01 – 0.1	2
0.1 – 1.0	3
1.0 – 10.0	4
> 10.0	5

Table 6. Conversion from ETR to Risk points

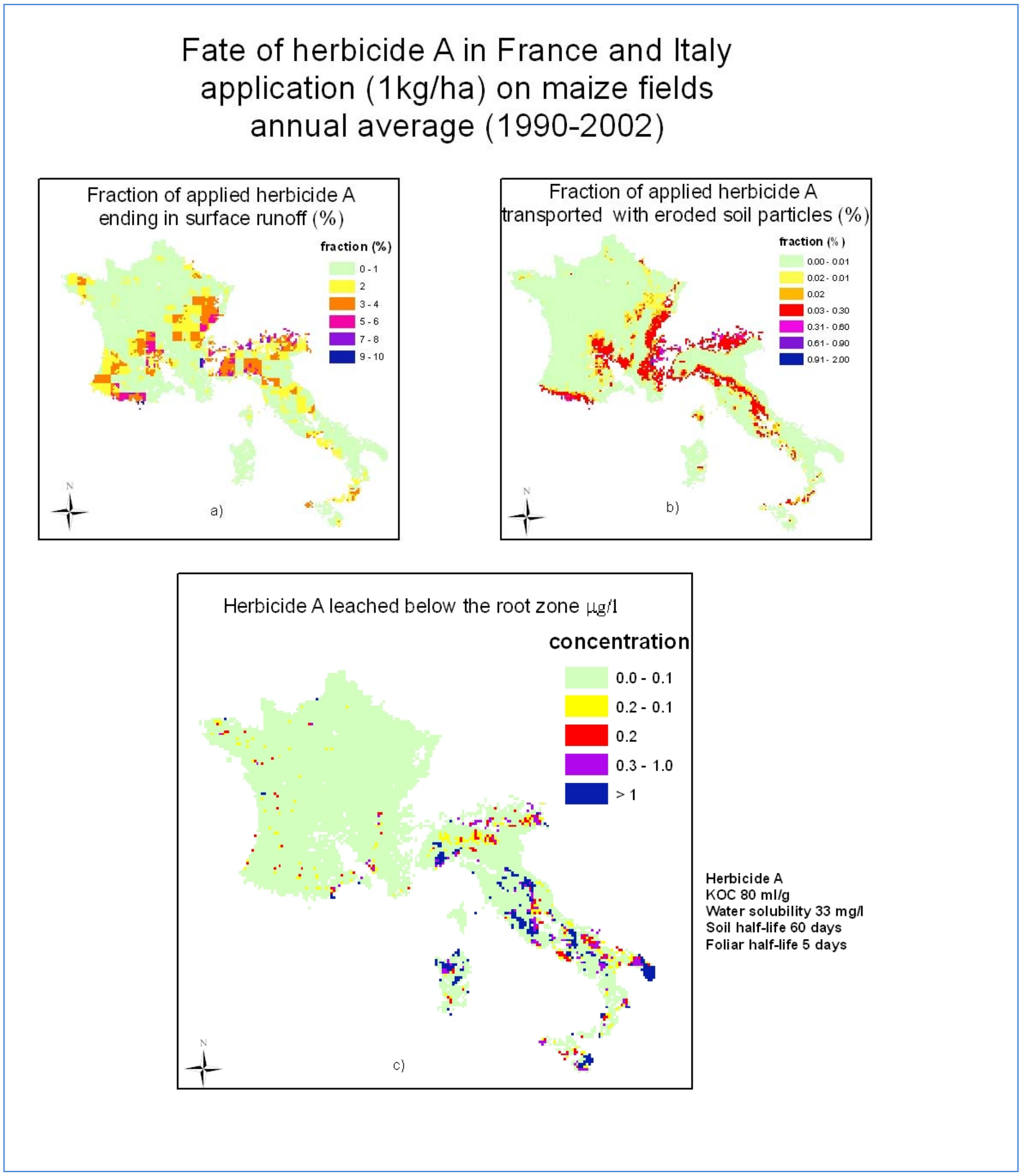

Figure 53. Calculated PEC for maize for a herbicide application pre emergence. The top left graph illustrates the fraction of pesticide lost in surface water; the top right graph illustrates the fraction of pesticide lost with eroded particle. The bottom graph is the calculated groundwater PEC.

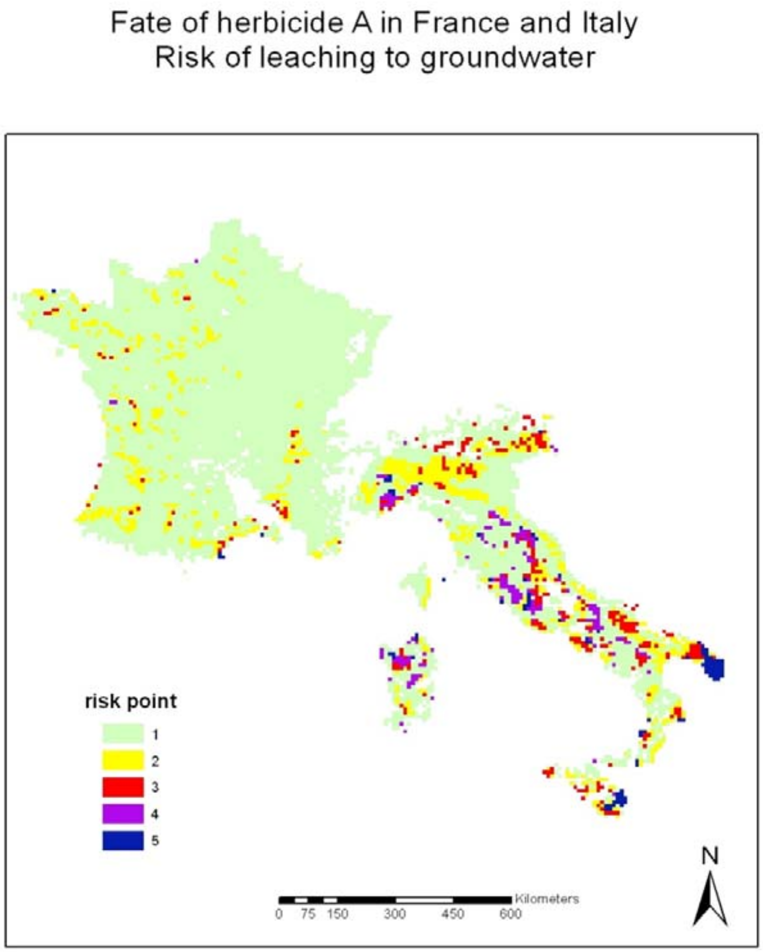

Figure 54. Risk points for herbicide leaching for France and Italy

6 SUMMARY

A multipurpose geospatial model, EAGLE, was developed to asses the fate of agrochemical at continental scale using readily available data. The model EPIC was linked to a European wide geodatabase and its use was illustrated by assessing the impacts of potential climate change on crop water and nutrient requirements. In order to consider the variability between the various GCMs, EAGLE was run for 18 different scenarios. It was predicted overall that northern Europe will be the big beneficiary of the potential climate change. A second application illustrated how the EAGLE could be used to calculate predicted environmental concentration in various compartment and how these can be then converted to risk points and then aggregated in order to predict an overall risk linked to pesticide application.

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Abstract

This report describes the development of a geospatial versatile tool for assessing the fate of nutrients and pesticides of agricultural origin at European scale. The bio-physical model EPIC has been linked to readily available data at European level in order to estimate the losses of nutrient as affected by farming practices and other human induced forcing such as climate change. The report details the theory behind the EPIC model, and then provides a description of the integration of the EPIC into a GIS. The tool called European Agrochemicals Geospatial Loss Estimator is used to estimate the impact of various Global Climate Models predictions on crop water and nutrient requirements. In addition the model is used to derive pesticide risk indicators.

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