SCIENCE OF THE TOTAL ENVIRONMENT 407 (2008) 574–588

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Development of agro-environmental scenarios to support pesticide risk assessment in Europe

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ARTICLE DATA

Article history:
Received 25 February 2008
Received in revised form 19 July 2008
Accepted 6 August 2008
Available online 24 September 2008

Keywords:
Pesticides
Risk assessment
Agro-environmental scenarios
FOOTPRINT
Agricultural pollutants

ABSTRACT

This paper describes work carried out within the EU-funded FOOTPRINT project to characterize the diversity of European agricultural and environmental conditions with respect to parameters which most influence the environmental fate of pesticides. Pan-European datasets for soils, climate, land cover and cropping were intersected, using GIS, to identify the full range of unique combinations of climate, soil and crop types which characterize European agriculture. The resulting FOOTPRINT European agro-environmental dataset constitutes a large number of polygons (approximately 1,700,000) with attribute data files for i) area fractions of annual crops related to each arable-type polygon (as an indicator of its probability of occurrence); and, ii) area fractions of each soil type in each polygon (as an indicator of its probability of occurrence). A total of 25,044 unique combinations of climate zones, agricultural land cover classes, administrative units and soil map units were identified. The same soil/crop combinations occur in many polygons which have the same climate while the fractions of the soils and arable crops are different. The number of unique combinations of climate, soil and agricultural land cover class is therefore only 7961. 26-year daily meteorological data, soil profile characteristics and crop management features were associated with each unique combination. The agro-environmental scenarios developed can be used to underpin the parameterization of environmental fate models for pesticides and should also have relevance for other agricultural pollutants. The implications for the improvement and further development of risk assessment procedures for pesticides are discussed.

1. Introduction

Residues of agriculturally applied pesticides can be transported to surface and ground water through infiltration, surface runoff, leaching, artificial drainage, and spray drift (Brown et al., 1995). Measuring such losses from every field is not a practical option and policy makers and land managers thus require effective, but less expensive, tools to assess the magnitude of pesticide exposure in water resources. Numerical models simulating the environmental fate of pesticides

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doi:10.1016/j.scitotenv.2008.08.017

can be employed as tools and their use has become increasingly common within the EU regulatory framework and environmental management communities. However, such models are usually only applied to local situations or to a limited number of 'representative' scenarios (FOCUS, 2000, 2001) because of the significant model input requirements. Possible refinements to such an approach including the development of a new range of location- or region-specific landscape and/or scenario parameters were outlined by FOCUS (2001) whereas the FOCUS working group on Landscape and Mitigation Factors in Aquatic Ecological Risk Assessment (FOCUS, 2007) have reviewed refinements based on probabilistic modelling approaches including expanding the modelling strategy to include a broader range of soils and climate conditions. Applying such expanded approaches at the European level would involve characterization of the diversity of the European agricultural environment, at least for those properties that are used to parameterize the selected models and most influence their results (Dubus et al., 2003). Such a characterization would contribute significantly towards the harmonization of risk assessment throughout Europe and would increase the consistency of the regulatory evaluation process (Azimonti, 2006).

The FOCUS Groundwater Scenarios Workgroup (2000) developed 9 realistic worst case scenarios and relevant data inputs which can be used to assess the potential transfer of pesticides at 1-m depth in the EU. However, simulations undertaken for a few standard scenarios may result in a large under- or over-estimation of risks associated with pesticide usage in a specific region (Van Alphen and Stoorvogel, 2002).

FOOTPRINT is a European-funded project which aims at developing software tools to assess and reduce the environmental transfer of pesticides, for use by end-user communities at the farm, catchment, and national/EU scales (FOOTPRINT, 2008). The overall objective of the project is to develop methodologies for: i) identifying the sources and contamination transport pathways in the agricultural landscapes; ii) estimating pesticides concentrations transiting towards surface water and groundwater resources; and iii) implementing effective mitigation strategies to reduce the potential contamination identified. In order to enable the FOOTPRINT tools to be implemented anywhere in Europe, it is necessary to derive pan-European data to underpin them. The work reported below describes how pan-European datasets on soil, climate, cropping and land cover were used to characterize the diversity in European agricultural and environmental conditions where pesticides are being used. Each dataset was intersected using a Geographic Information System (GIS, ESRI ArcGIS 9.1) to identify the full range of unique combinations of climate, soil and crop types that characterize European agriculture (agro-environmental scenarios).

2. Materials and methods

The following section gives an overview of the methods and databases used to create and characterize the agro-environmental scenarios. However the complexity of each methodological step means that it is not possible to provide full details of the methodology in this paper. The methodology for defining climatic scenarios is fully documented in Nolan et al. (2008) and Blenkinsop et al (2008) and a paper giving full details of the methodology used to identify, define and evaluate the utility of the FOOTPRINT soil types is in preparation. Further information can be obtained by contacting the authors.

2.1. *Definition of FOOTPRINT climatic scenarios*

A comprehensive sensitivity analysis using the preferential flow model MACRO (Larsbo et al., 2005) was undertaken. Univariate and multivariate statistics were used to relate predicted pesticide losses to climatic characteristics and identify those key climatic variables which most influence pesticide loss (Nolan et al., 2008). The eight key climatic variables were:

- Mean April to June temperature (°C);
- Mean September to November temperature (°C);
- Mean October to March precipitation (mm);
- Mean annual precipitation (mm);
- Number of days (April to June) where total precipitation >2 mm;
- Number of days (April to June) where total precipitation >20 mm;
- Number of days (April to June) where total precipitation >50 mm;
- Number of days (September to November) where total precipitation >20 mm.

A climatic classification for Europe was then constructed on the basis of these eight key variables (Blenkinsop et al., 2008). Within Europe, each variable was characterized spatially using two data sources: a) the CRU TS 2.0 dataset (Mitchell et al., 2004) and b) the European Climate Assessment & Dataset (ECA & D) (Klein Tank et al., 2002). The analysis was based on data over the period 1961–1990. In order to take into account the likely correlation between several of the input variables, a dimension reduction procedure was performed using principal component analysis which resulted in the retention of three factors. These factors were then used as variables in a cluster analysis (k-means) which objectively grouped grid cells with similar characteristics (Blenkinsop et al., 2008). The final solution produced 16 groups (the 'FOOTPRINT climatic zones') which represents a pragmatic compromise between producing a detailed classification and the need for a manageable number of representative climatic datasets for subsequent modelling work for the whole of Europe. A brief description of each climate zone and a listing of the EU Member States included in each zone are given in Table 1. The spatial distribution of the 16 FOOTPRINT climatic zones (FCZ) was digitized to provide a polygon dataset for GIS operations (Fig. 1).

To represent the spatial climatic variation in each climate zone, a methodological analysis that combined both objective and subjective components was used to select an ECA & D meteorological station displaying the most representative characteristics with regard to the particular zone of interest. This methodology is fully documented in Blenkinsop et al. (2008). Data from the selected station or from an equivalent MARS grid (MARS, 2007) were then used to create a 26-year

Table 1 – Summary description of the 16 FOOTPRINT climatic zones (FCZs) identified by cluster analysis and indication of the 24 European member states where each climatic zone can be found

FOOTPRINT climatic zone	Description	Member states
1. North Mediterranean	Warm and moderate precipitation	France, Germany, Italy, Slovenia, Spain
2. Temperate maritime	Temperate maritime climate	Belgium, Denmark, France, Germany, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Sweden, United Kingdom
3. Sub-alpine continental	Warm, moderate rainfall but less winter rainfall than FCZ 4, moderate frequency of extremes	Austria, Czech Republic, Germany, Hungary, Italy, Slovenia
4. North European and continental	Cool and dry	Estonia, Finland, Latvia, Lithuania, Poland, Sweden
5. Continental 3	Mostly warm and dry	Not in the European Union
6. Alpine	Cool and wet, relatively high extremes	Austria, France, Germany, Italy, Slovenia
7. Modified upland temperate maritime	More frequent extremes than FCZ 2	United Kingdom
8. Mediterranean 1	More extreme rainfall than FCZ 9	France, Greece, Italy, Malta, Spain
9. Mediterranean 2	Warmer, lower rainfall with more dry days but higher winter rainfall than FCZ 8	Greece, Italy, Portugal, Spain
10. North European	Cool and dry	Finland, Sweden
11. Modified temperate maritime 1	Warmer and wetter but fewer wet spring days than FCZ 16.	France, Portugal, Spain, United kingdom
12. Wet mountainous maritime	Very wet, frequent extremes	United Kingdom.
13. Wet maritime	On exposed western coasts frequent extremes	Ireland, United Kingdom
14. Continental 1	Warm and dry with moderate frequency of extremes	Austria, Czech Republic, Germany, Hungary, Poland, Slovakia
15. Continental 2	Warm and dry, but more frequent wet days than FCZ 14	Czech Republic, Germany, Greece, Hungary, Poland, Slovakia
16. Modified temperate maritime 2	Cool with moderate precipitation	Ireland, Sweden, United Kingdom

daily weather dataset for precipitation, mean, minimum and maximum temperatures, potential evapotranspiration, wind speed at 10 m above ground and solar radiation.

2.2. *Definition of FOOTPRINT agronomic characteristics*

Agronomic scenarios are defined in this work as areas in Europe where the dates of specific crop growth stages and data on specific crop cover area and management practices associated with them are similar. The identification of such areas was based on the intersection of two datasets. The precise location of broadly different categories of agricultural land was defined using the CORINE (2000) land cover database at a spatial resolution of 250 m × 250 m. Only CORINE land cover classes that represent agricultural land were selected to define agronomic scenarios and the following categories were used: Non-permanently irrigated (arable) land, permanently irrigated (arable) land, vineyards, fruit tree and berry plantations, olives, pasture, agro-forestry, annual crops associated with permanent crops, land principally occupied by agriculture with significant areas of natural vegetation and complex cultivation patterns. All other CORINE land cover classes were amalgamated as 'non-agricultural land' and deleted from the dataset.

Classes such as vineyards, olives, fruit trees and berry plantations and pasture in the resulting dataset represent land on which the agricultural crops are relatively permanent, whereas classes that are characterized as partly or wholly arable represent land on which crops may vary from year to year. In the latter case, the probability that a specific arable crop occurs at a certain location was determined using agricultural statistics for the EU administrative units called NUTS (Nomenclature of Territorial Units for Statistics) at level 2. This is the finest resolution at which pan-EU statistical data on crop cover area are available. Data on specific crop cover area and arable land area at the NUTS level 2 were obtained from the EUROSTAT dataset (EUROSTAT, 2006) and, where data were missing, these were obtained through national cropping statistics. The following arable crops were used in the probability analysis: barley; cotton; durum wheat; flax; fodder root and brassicas; fresh vegetables, melons and strawberry; maize fodder, maize grain; oats; other cereals; potato; pulse; rape seed; rye; soft wheat; soya; sugar beet; sunflower; tobacco. At the time of analysis, the most recent complete set of statistics for NUTS level 2 was for the year 2003 and data used to characterize the agro-environmental scenarios are thus for this year only. For each NUTS level 2 area, the probability that any specific arable crop occurs on a CORINE 'arable' polygon in that area was calculated using the EUROSTAT individual arable crop areas expressed as a percentage of the total arable land area. For those CORINE land cover classes that are only partly arable (agro-forestry, annual crops associated with permanent crops and land principally occupied by agriculture with significant areas of natural vegetation), it was assumed that arable crops cover 50% of the CORINE polygon.

Using GIS, the spatial distribution of each NUTS level 2 was intersected with the modified CORINE (2000) land cover dataset. This procedure resulted in a fine resolution (250 m × 250 m) dataset which characterizes the spatial distribution of agricultural land within Europe and, for arable land areas, gives an estimated probability of occurrence of specific arable crops. The total dataset incorporates four types of permanent crop and nineteen types of arable crop. The total

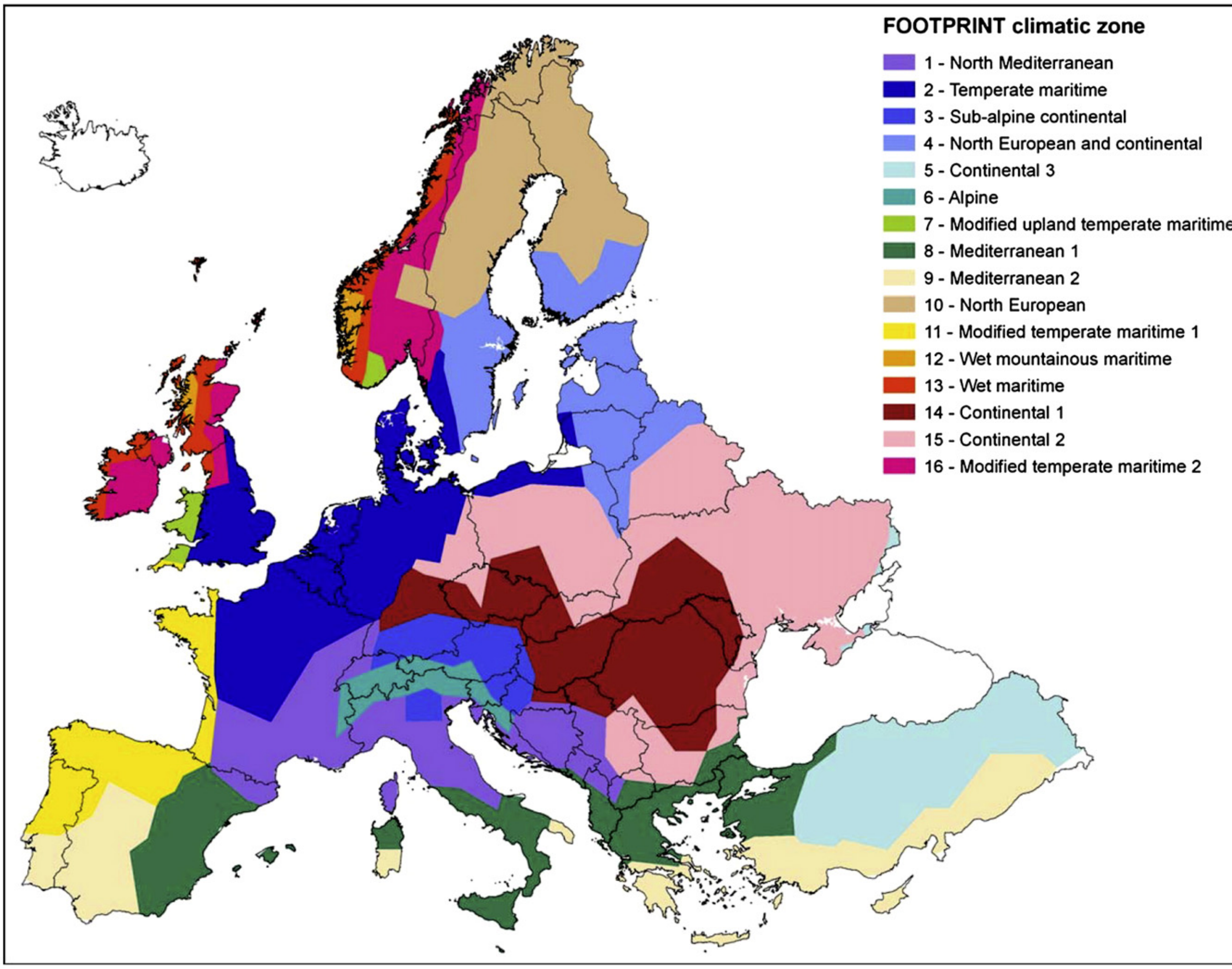

Fig. 1 – Distribution of the 16 FOOTPRINT climate zones (FCZ codes) within Europe; a description of the FCZ codes is in Table 1.

area (in hectares) of CORINE 'arable' land classes (including those that are only partly arable) within each NUTS level 2 was found to differ significantly on numerous occasions from the area of total arable land given in the EUROSTAT agricultural statistics. It is known that there are uncertainties in the allocation of CORINE satellite data to a specific land cover class and, to take this into account, for each NUTS level 2 region, the probability of a specific arable crop occurring within a CORINE (2000) 'arable' polygon was scaled such that the total area of arable land according to CORINE matched that given in the EUROSTAT data. The equation used to achieve this scaling is as follows.

$$AC\% = 100 \times \frac{AC_a - \text{NUTS}\,2}{A_a - \text{NUTS}\,2} \times \frac{A_a - \text{NUTS}\,2}{A_a - \text{CORINE}}$$

Where:

AC % Percentage probability of a specific arable crop occurring in a CORINE (2000) 'arable' polygon

AC_a-NUTS 2 Area (ha) of the specific arable crop in the NUTS 2 region according to EUROSTAT (2006)

A_a-NUTS 2 Total arable area (ha) in the NUTS 2 region according to EUROSTAT (2006)

A_a-CORINE Total arable area (ha) in the NUTS 2 region calculated using CORINE (2000).

An example of the cropping data which results from this scaling is shown in Table 2 for the NUTS 2 region of Andalucía.

Finally, agronomic information, in the form of seasonal 'window' dates for sowing, germination, shooting, flowering and harvest, along with likely periods for pesticide application, was assigned to each crop in each NUTS level 2. This information was provided by FOOTPRINT project partners from various European countries who have access to local and national data on crop management practices. An example of such information is presented in Fig. 2. Because these data incorporate different agronomic information for seasonal crop varieties such as autumn and spring sown barley or early and main crop potatoes, a total of 39 crop or crop varieties are included.

2.3. *Definition of FOOTPRINT soil types*

The main objectives in defining a set of FOOTPRINT Soil Types (FSTs) were to characterize a limited number of soil types suitable for modelling the environmental fate of pesticides in Europe such that they represent the complete range of relevant pollutant transfer pathways from the soil surface to surface water bodies as well as the complete range of soil sorption potential relevant to 'reactive' pollutants. This

Table 2 – Extract of the agronomic dataset for selected crops within NUTS level 2 region ES61 (Andalucía, Spain) used to calculate the probability of a specific arable crop occurring in a CORINE (2000) polygon designated as arable or partly arable

Arable crop	Area (1000 ha) of crop from EUROSTAT (2006)	Area (1000 ha) of arable land from EUROSTAT (2006)	Area of crop as a % of arable land (EUROSTAT, 2006)	Area (1000 ha) of arable land from CORINE (2000)	% probability of crop occurring in CORINE (2000) 'arable' land class
Barley	97.87	1914.4	5.11	1664.7	5.88
Cotton	92.8	1914.4	4.85	1664.7	5.57
Durum wheat	475.94	1914.4	24.86	1664.7	28.59
Fodder roots and brassica	1.07	1914.4	0.06	1664.7	0.06
Fresh veg, melon, strawberries	76.5	1914.4	4.00	1664.7	4.60
Green fodder	85.5	1914.4	4.47	1664.7	5.14
Maize foddder	3	1914.4	0.16	1664.7	0.18
Maize grain	47.06	1914.4	2.46	1664.7	2.83
Oats	71.73	1914.4	3.75	1664.7	4.31
Other cereals	18.31	1914.4	0.96	1664.7	1.10
Potato	9.74	1914.4	0.51	1664.7	0.59
Pulse	66.7	1914.4	3.48	1664.7	4.01
Rapeseed	0.4	1914.4	0.02	1664.7	0.02
Rye	9.65	1914.4	0.50	1664.7	0.58
Soft wheat	63.59	1914.4	3.32	1664.7	3.82
Soya	0.1	1914.4	0.01	1664.7	0.01
Sugar beet	43.01	1914.4	2.25	1664.7	2.58
Sunflower	295.8	1914.4	15.45	1664.7	17.77
Tobacco	1.3	1914.4	0.07	1664.7	0.08
Totals	1460.07	1914.4	76.27	1644.7	87.71

objective was achieved by differentiating European soils according to three groups of properties: those determining soil hydrological characteristics (permeability, density and soil water regime); those determining soil hydraulic characteristics (particle-size distribution, density and organic carbon content) and those determining soil sorption characteristics (organic carbon and clay content).

The distribution and variation of these soil properties within Europe were identified using the Soil Geographic Database of Europe (SGDBE, v.1) at 1:1,000,000 scale (Le bas et al., 1998). This database provides the only harmonized pan-European data defining soil spatial variability. It includes polygon data files which define the location of Soil Map Units (SMUs), each of which comprises a number of defined Soil Types (STUs). The percentage cover of each STU within each SMU and some general attributes of each STU are defined in separate data files. Using the attribute data files in the SGDBE, each STU was classified according to its hydrological, hydraulic and sorption potential characteristics as follows.

Differentiation of soil hydrology was based on the porosity and density characteristics of the soil and its substrate material, depth to a slowly permeable or impermeable soil layer and soil water regime as used in the Hydrology of Soil Types (HOST) classification system (Boorman et al., 1995; Schneider et al., 2007) which provides an empirical link between soil types and quantified stream responses to rainfall. These characteristics were identified using the following STU attributes from the SGDBE: SOIL (the FAO soil type code), soil parent material type (MAT1, MAT2), depth to obstacle to roots (ROO), depth to impermeable layer (IL) water regime (WR) and water management system (WM1, WM2 and WM3). Each STU was assigned to one of 15 FOOTPRINT soil hydrological classes, coded L to Z. This assignation was mainly achieved directly from the presence or absence of one or more specific STU attributes but in some cases, especially where STU attributes were contradictory and thus uncertain, expert judgement was used. Descriptions of the 15 soil hydrological classes are given in Table 3 along with their HOST class(es), as identified using the methodology described by Schneider et al (2007), and their significance for deriving hydrologic conditions for the MACRO and PRZM (FOCUS, 2001; Carsel et al., 2003) models which are used to support modelling activities for the FOOTPRINT agro-environmental scenarios.

Differentiation of the soil sorption characteristics was based on differences in the magnitude and distribution pattern of organic matter and clay within the soil profile. These differences were identified by combining the information given in the textural attributes of the STU data file (TEXT 1, TEXT 2, TD1, TD2, as described below) with pedological interpretation of the 'SOIL' attribute. The latter gives the FAO soil pedological class which can be used to identify soils with specific differences in the distribution of organic matter within the profile (see Table 4). Each STU in the SGDBE was assigned to a soil sorption potential class using an alphabetical code as defined in Table 4.

Soil hydraulic characteristics depend mainly on particle-size distribution, soil density and organic matter content. However, significant differences in soil density are already taken into account through the FOOTPRINT hydrological

	march				april				may				june				july				august				september				october				november		
es	1wk	2wk	3wk	4wk	1wk	2wk	3wk	4wk	1wk	2wk	3wk	4wk	1wk	2wk	3wk	4wk	1wk	2wk	3wk	4wk	1wk	2wk	3wk	4wk	1wk	2wk	3wk	4wk	1wk	2wk	3wk	4wk	1wk	2wk	3
ES11					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES12					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES13					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES21					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES22					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES23					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES24					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES30								1A	1A	12A	2	3B	3B	B			4	4								5	6	6	6						
ES41					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES42								1A	1A	12A	2	3B	3B	B			4	4								5	6	6	6						
ES43								1A	1A	12A	2	3B	3B	B			4	4								5	6	6	6						
ES51					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES52								1A	1A	12A	2	3B	3B	B			4	4								5	6	6	6						
ES53					1A	1A	1A	12A	12A	2	B	B	3B				4	4	4	4					56	56	6	6	6						
ES61			2	2	2		3	3	3			4	4			5	5	6	6	6															
ES62			2	2	2		3	3	3			4	4			5	5	6	6	6															
ES63																																			
ES70																																			

Legend

1	SOWING	B	POST-EMERGENCE APPLICATION (HERBICIDES)
2	GERMINATION	12	OVERLAY OF SOWING AND GERMINATION
3	SHOOTING	56	OVERLAY OF MATURITY AND HARVEST
4	FLOWERING	12A	OVERLAY OF SOWING, GERMINATION, AND PRE-EMERGENCE APPLICATION
5	MATURITY	12B	OVERLAY OF SOWING, GERMINATION AND POST-EMERGENCEAPPLICATION
6	HARVEST	12AB	OVERLAY OF SOWING, GERMINATION, PRE-EMERGENCE AND POST-EMERGENCE APPLICATION
A	PRE-EMERGENCE APPLICATION (HERBICIDES)	1AB	OVERLAY OF SOWING, PRE-EMERGENCE AND POST-EMERGENCE APPLICATION

Fig. 2 – Example of agronomic template of maize grain (spring sown) identifying seasonal 'window' dates for sowing, germination, shooting, flowering and harvest, along with likely periods for pesticide application for various NUTS level 2 in Spain.

classes whereas significant differences in organic matter content are included in the differentiation of soil sorption potential classes. Further differentiation of soil hydraulic characteristics was thus based solely on soil particle-size distribution. Each STU in the SGDBE was assigned to one of five topsoil and subsoil texture classes (1 to 5) as defined in the database and illustrated in Fig. 3(A). The topsoil textural class was assigned directly from the TEXT1 (Dominant topsoil texture of the soil type) and TEXT2 (Secondary topsoil texture of the soil type) attributes in the STU data file and the subsoil texture class from the TD1 (Dominant subsoil texture of the soil type) and TD2 (Secondary subsoil texture of the soil type) attributes. Where available, detailed particle-size data for an STU from the SPADE1 or SPADE2 databases (Hollis et al., 2006) were used to check and, if necessary, adjust the STU topsoil and subsoil texture classes.

Each STU in the SGDBE was then re-classified by combining their hydrological, textural and sorption potential classes to define a FOOTPRINT Soil Type (FST), identified using the combined codes for each class as shown in Fig. 3(B). This process resulted in 363 FSTs representing all of the STUs in the SGDBE and differentiated according to the hydrological, hydraulic and sorption characteristics that determine the environmental fate of pesticides. The spatial variation of the FOOTPRINT Soil Types within Europe is illustrated in Fig. 4, where the most extensive FST in the SGDBE Soil Map Unit is coloured according to its soil hydrological class.

Finally, the dominant and secondary land use attributes (USE 1 and USE 2) in the STU data file of the SGDBE were used to identify whether any of the FSTs were unlikely to have an agricultural use, either under arable cultivation or permanents crops such as pasture, olives, 28 fruit trees or vines. This showed that only 32 of the FSTs represent soils that are likely to occur solely under non-agricultural uses. Of the remaining 331 FSTs, 264 are likely to be found under arable or permanent crops whereas 67 are likely to occur only under managed permanent grassland or non-agricultural use.

For each 'agricultural' FST, a set of land use specific soil properties was created using data on soil horizon type, depths, particle-size distribution, organic carbon content, pH and bulk density derived from the SPADE 1 and SPADE 2 databases (Hollis et al., 2006). Although these data do not cover all of the STUs in the SGDBE, there are still over 1000 complete profiles with an agricultural land use available. All soil profile data for

Table 3 – Description of the FOOTPRINT hydrological classes and their relationship with hydrologic conditions for the MACRO and PRZM models

FOOTPRINT hydrological class	HOST class	Description	MACRO bottom boundary condition	PRZM soil hydrologic group
L	1, 2, 3, 5, 13	Permeable, free draining soils on permeable sandy, gravelly, chalk or limestone substrates with deep groundwater (below 2 m depth).	Unit hydraulic gradient	A
M	4	Permeable, free draining soils on hard but fissured substrates (including karst) with deep groundwater (below 2 m depth).	Unit hydraulic gradient	B
N	6	Permeable, free draining soils on permeable soft loamy or clayey substrates with deep groundwater (below 2 m depth).	Unit hydraulic gradient	B–C
O	7	Permeable soils on sandy or gravelly substrates with intermediate groundwater (between 1 and 2 m depth)	Zero flow	A
P	8	Permeable soils on soft loamy or clayey substrates with intermediate groundwater (between 1 and 2 m depth)	Zero flow	B–C
Q	9, 10, 11	All soils with shallow groundwater (within 1 m depth) and artificial drainage	Zero flow	A
R	17	Permeable, free draining soils with large storage, over hard impermeable substrates below 1 m depth	Zero flow	B
S	19	Permeable, free draining soils with moderate storage, over hard impermeable substrates at between 0.5 and 1 m depth	Zero flow	B–C
T	22	Shallow, permeable, free draining soils with small storage, over hard impermeable substrates within 0.5 m depth	Zero flow	C
U	20	Soils with slight seasonal water logging ('perched' water) over soft impermeable clay substrates	Zero flow	B–C
V	23, 25	Soils with prolonged seasonal water logging ('perched' water) over soft impermeable clay substrates	Zero flow	C
W	16	Free draining soils over slowly permeable substrates	Percolation rate regulated by water table height	B
X	18	Slowly permeable soils with slight seasonal water logging ('perched' water) over slowly permeable substrates	Percolation rate regulated by water table height	B
Y	14, 21, 24	Slowly permeable soil with prolonged seasonal water logging ('perched' water) over slowly permeable substrates	Percolation rate regulated by water table height	B–C
Z	12, 15, 26, 27, 28, 29	All undrained peat or soils with peaty tops	Not modeled	D

Table 4 – Description of the FOOTPRINT organic profile codes and their derivation from the pedological 'SOIL' code from the Soil Geographical Database of Europe (SGDBE)

FOOTPRINT organic profile code	Description	'SOIL' code from SGDBE
a	Alluvial soils with an uneven distribution of organic matter down the profile	Fluvisols, fluvic subgroups
g	With a thick (artificially deepened) topsoil relatively rich in organic matter	Plaggen soils
h	With an organic-rich topsoil	Chernozems, phaeozems humic and mollic subgroups
i	With a clay increase in the subsoil	Planosols, luvisols, podzoluvisols, luvic and planic subgroups
n	With a 'normal' organic profile	
f	Pemafrost soils (non-agricultural) with an uneven distribution of organic matter down the profile	Gelic subgroups
o	Soils in volcanic material with organic-rich upper layers	Andisols
p	Podzols with a relatively organic-rich topsoil and an relatively organic-rich subsoil layer	Podzols
r	Soils where the organic profile is limited by rock within 1 m depth	Rendzinas, rankers and lithosols
t	With a peaty topsoil	Histosols and histic subgroups
u	Undeveloped soils with relatively small organic matter content	Regosols

STUs with the same FST code were amalgamated and mean values for each parameter in each similar soil horizon calculated. This process provided land use specific soil horizon property data for 163 FSTs under arable, olives, fruit trees or vines and 136 FSTs under managed pasture. For the FSTs that did not have any representative in the SPADE 1 or

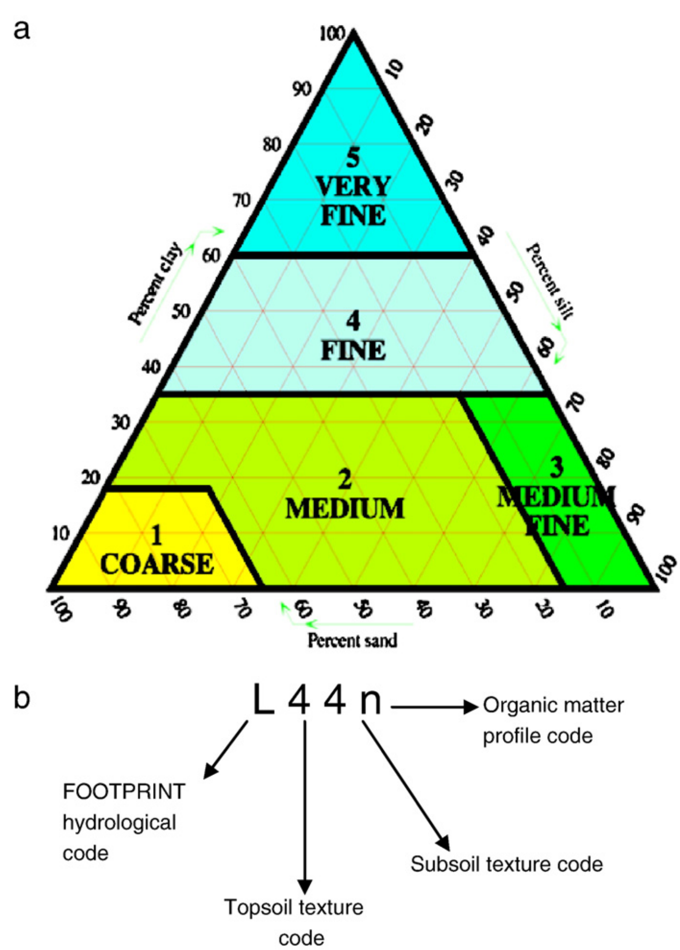

Fig. 3 – A) FOOTPRINT Soil Type code created by combining the codes for each of the hydrological, textural and organic profile components, and B) Textural triangle used for definition of topsoil and subsoil FST texture codes.

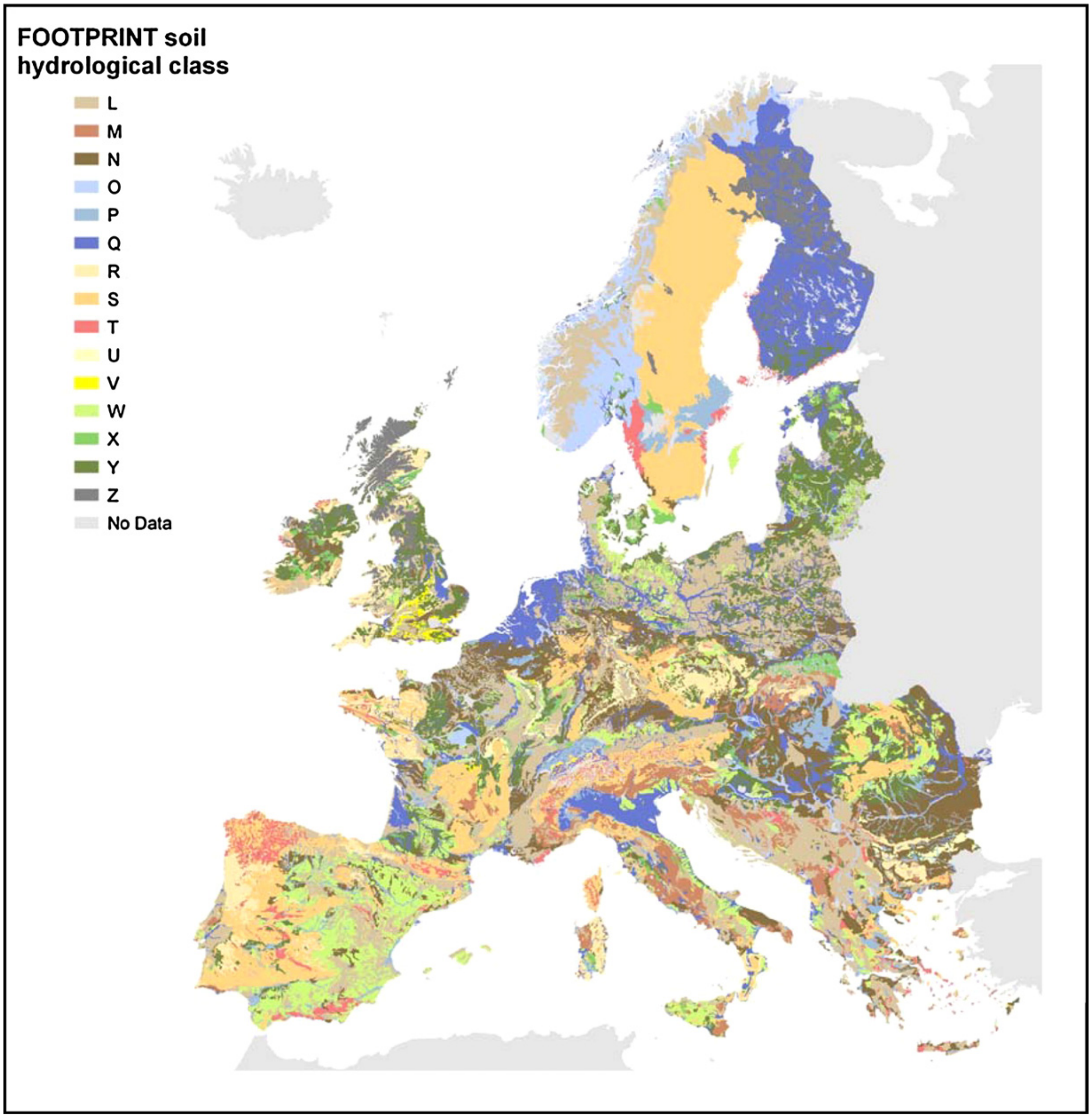

Fig. 4 – The spatial variation of the FOOTPRINT Soil Types within Europe where the most extensive FST in the SGDBE Soil Map Unit is coloured according to its soil Hydrological classes. A full description of the FOOTPRINT soil hydrological classes is provided in Table 3.

SPADE 2 databases, synthetic property data specific to either arable or managed pasture were derived using the three components of the FST code. Thus, soil horizon sequences were derived from those FSTs with data that had the same hydrological class as the uncharacterized soil type. Particle-size data were derived from those FSTs with data that had the same topsoil and subsoil textural codes. Stone content, pH and organic carbon content were derived from those FSTs with data that had the same 'SOIL' and sorption potential class codes as the uncharacterized soil type.

Finally, bulk density was derived using a set of pedotransfer functions incorporating particle-size distribution, organic carbon content and soil horizon type. These functions were empirically derived from multiple regression analysis of a large data set of measured values from England and Wales (Hallett et al., 1995).

3. Creation of the FOOTPRINT agro-environmental scenarios

Using GIS, the FOOTPRINT climate map and the combined CORINE land cover/NUTS level 2 spatial datasets were intersected with the SGDBE Soil Map Unit polygons to create the final FOOTPRINT European agro-environmental dataset. Because of the different resolution of the CORINE (250 m × 250 m) and SGDBE

(1:1,000,000 scale) datasets, spatial inconsistencies were observed between those areas which, in the SGDBE, are characterized as either 'undefined'; 'not surveyed'; 'soil disturbed by man'; 'water body'; 'glacier'; 'marsh'; or 'out of surveyed area' and equivalent areas in the CORINE data. Where such areas had an attributed CORINE land cover class they were assigned to the Soil Map Unit of the nearest soil polygon rather than their original 'non-soil' designation from the SGDBE. This ensured that all areas identified as 'land' by the fine resolution CORINE data had a designated soil type.

The final FOOTPRINT European agro-environmental data-set constitutes a large number of polygons (approximately 1,700,000) derived by the fragmentation of each NUTS level 2 polygon into homogeneous areas of FOOTPRINT climatic zone, SGDBE soil map unit and CORINE agricultural category. Each polygon has a defined NUTS level 2 code, climate zone code, Soil Map Unit code and CORINE agricultural land code. Attribute data files linked to the spatial data define the fraction of arable crops related to each CORINE arable category as an indicator of its probability of occurrence, as described in Section 2.2, and the fraction of each FST in each SMU, derived from STU data file held in the SGDBE. This fraction indicates the probability of occurrence of each FST in each agro-environmental polygon. Fig. 5 provides a diagrammatic representation of the derivation and content of the European agro-environmental scenarios and an example of the GIS-based geographic representation of the scenarios is shown in Fig. 6. A summary of the total number of unique scenarios in the NUTS level 2 region of Andalucia shown in Fig. 6 is given in Table 5, together with the areas covered by the most extensive soil types in each combination of climate zone and CORINE agricultural land cover class.

4. FOOTPRINT agro-environmental scenarios variability across Europe

A total of 25,044 unique combinations of FOOTPRINT climatic zone, NUTS level 2, CORINE agricultural land cover class and SMU were identified.

Each unique combination of CORINE agricultural land cover class, NUTS level 2, climate zone and SMU represents a single agro-environmental scenario in which the local soil is defined from a range of FSTs with a defined percentage probability of occurrence and, for those scenarios that have a partly or wholly 'arable' designation, a defined range of annual crops with an estimated percentage probability of occurrence. However, because of the uncertainty related to the spatial distribution of annual arable crops and FSTs within each polygon, the same FST/crop combinations occur in many polygons which have the same climate and CORINE agricultural land cover class although the fractions of the FSTs and arable crops are different. The number of unique combinations of climate, FST and CORINE agricultural land class is thus only 7961.

The number of unique combinations of climate, soil and CORINE agricultural land class varies strongly between countries (Table 6). These combinations were calculated using the agro-environmental scenarios database to identify the range of CORINE land cover types and Soil Map Units in each country, together with the attribute data files to identify the range of FSTs in each SMU in each country and the range of arable crop types in each CORINE arable land cover category in each country. Italy, France and Germany have the largest number of unique combinations (900 to 1050), whereas

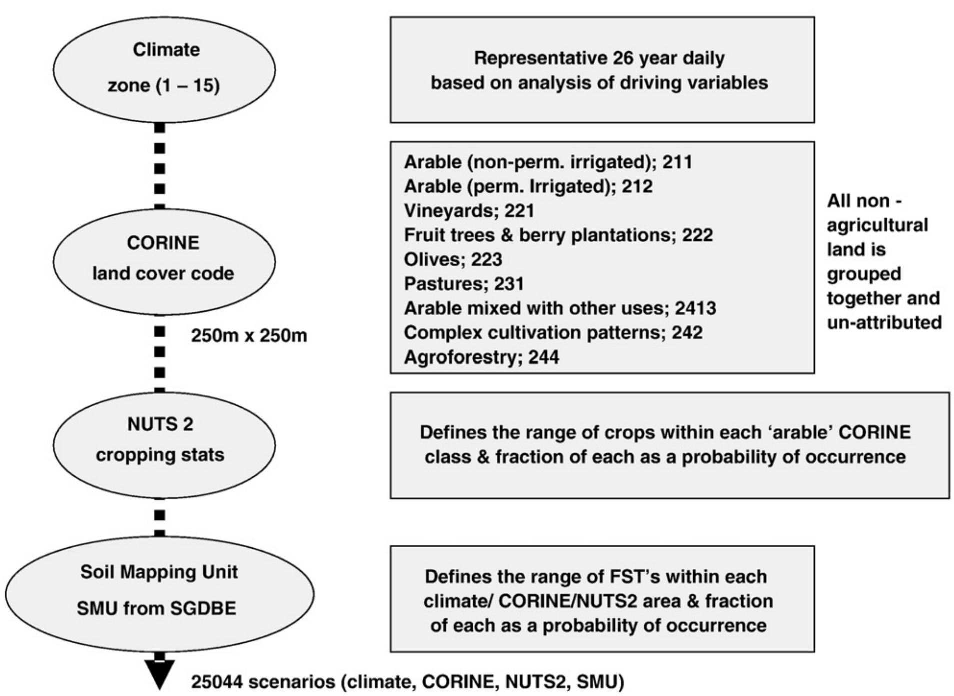

Fig. 5 – Diagrammatic representation of the derivation and content of the European agro-environmental scenarios. Land cover class 2413 has been obtained by combining CLC classes 241 and 243.

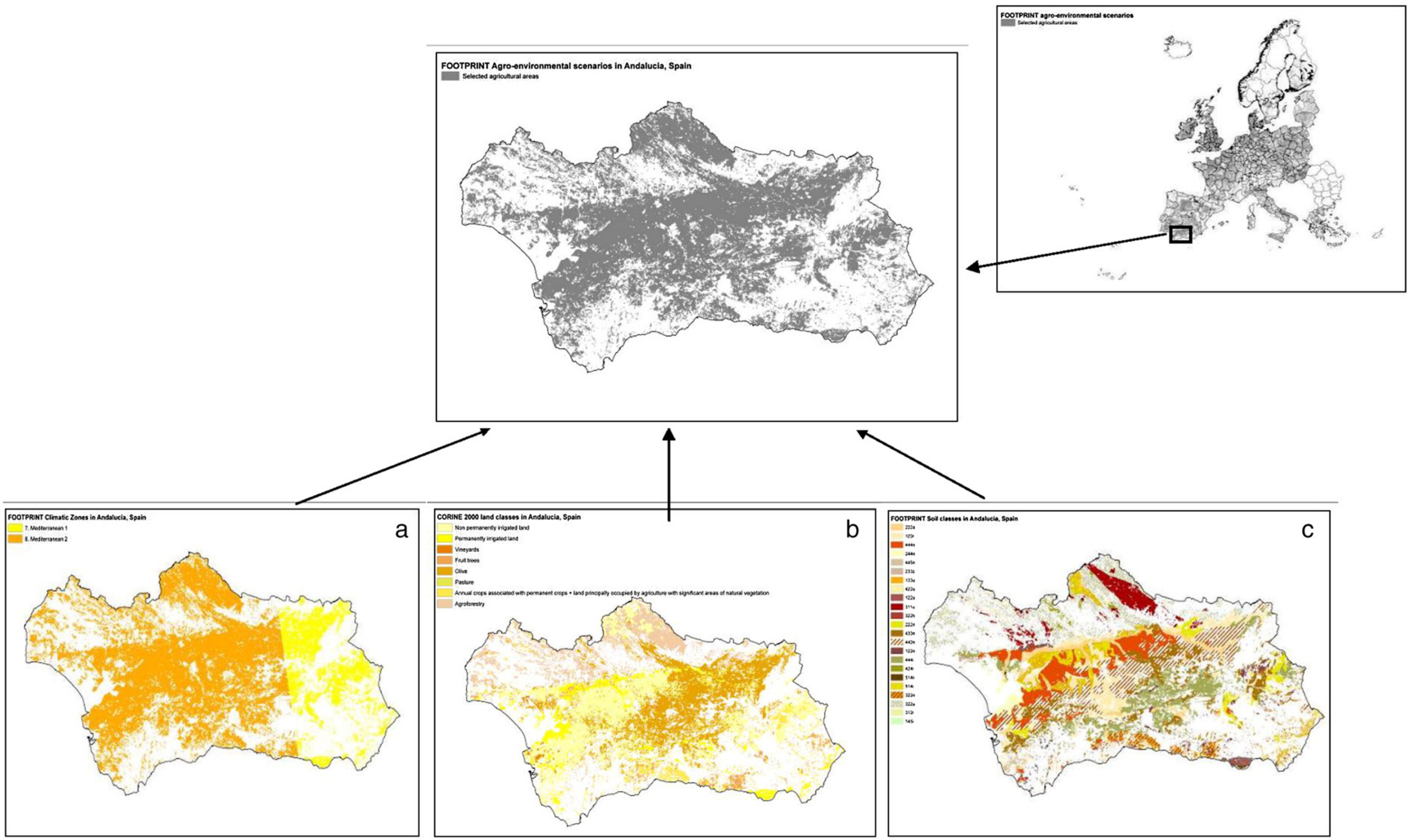

Fig. 6 – Map of the FOOTPRINT agro-environmental scenarios representative of European agriculture (1). The agro-environmental scenarios in Andalucía, Spain, are shown as example (2). The agro-environmental scenarios were obtained by the intersection of the FOOTPRINT climatic zones (a), the selected CORINE (2000) land use classes and European agricultural statistics (b) and the FOOTPRINT soil classes (c).

Table 5 – Summary of the total number of unique scenarios in Andalucia and scenario areas related to the three most extensive FOOTPRINT Soil Types (FSTs)

Climate zone	CORINE land use type	Number of FSTs	Areas (km^2) of the three most common FSTs					
			1st	Area	2nd	Area	3rd	Area
8	Arable, not permanently irrigated	32	W44n	540.3	N22n	380.4	W33n	206.0
8	Arable, permanently irrigated	30	N22u	181.4	W22u	105.2	P22a	67.5
8	Vines	8	W42n	1.0	W22u	0.6	T20r	0.5
8	Fruit trees	30	T20r	121.6	T10r	77.5	N22n	57.8
8	Olives	29	W42n	732.5	L20r	465.7	L22r	358.8
8	Mixed arable crops and non-agricultural areas	34	W33n	70.2	W22u	57.3	T20r	54.3
8	Agro-forestry	26	S22ru	92.9	S22r	37.2	L22r	36.6
8	Pasture	0	None	0.0	None	0.0	None	0.0
9	Arable, not permanently irrigated	39	W44n	3340.5	Y14i	1668.9	W44u	1098.4
9	Arable, permanently irrigated	38	P22a	682.6	W44n	382.2	Y14i	365.7
9	Vines	29	W42n	74.3	L20r	40.3	W44n	36.7
9	Fruit trees	37	T20r	243.9	P22a	132.6	W44n	112.5
9	Olives	41	W44n	2049.6	W42n	1311.4	L20r	864.8
9	Mixed arable crops and non-agricultural areas	43	T20r	317.4	W44n	119.0	S22ru	45.3
9	Agro-forestry	45	S22ru	1775.9	S11ru	748.1	S22r	697.7
9	Pasture	10	M45ir	0.02	N44n	0.01	W42n	0.002
	Total unique scenarios	471						

Denmark, Luxembourg and Finland have the smallest (20 to 40). The differences reflect the different sizes of the countries, as well as regional variations in environmental characteristics as they affect cropping possibilities and soil development. In addition, some differences relate to the different resolution of the soil data available at the national level.

Table 6 – Summary of the number of unique combinations of FOOTPRINT climate zones, soil classes and agricultural land groups (arable, managed grassland, fruit tress and berry plantations, olives and vines) in European member states (excluding Malta)

Country	Number of unique combinations	Total land area (1,000,000 ha)	Number of unique combinations per 1,000, 000 ha of land	Number of NUTS level 2	Number of FOOTPRINT climatic zones	Number of FOOTPRINT agricultural soil classes	Number of FOOTPRINT crops
Italy	1041	30.134	0.345	20	5	86	22
France	967	54.909	0.176	22	5	149	22
Germany	962	35.703	0.269	40	6	116	20
Spain	565	50.537	0.112	17	4	65	23
Hungary	535	9.303	0.575	7	3ss	100	20
Poland	524	31.268	0.168	16	4	95	16
Greece	451	13.196	0.342	13	3	79	20
Portugal	401	9.191	0.436	5	2	50	17
United Kingdom	381	24.382	0.156	36	6	87	13
Czech Republic	373	7.887	0.473	8	3	80	20
Slovakia	364	4.903	0.742	4	2	82	19
Austria	304	8.387	0.362	9	3	88	20
Slovenia	293	2.027	0.145	1	3	66	15
Lithuania	165	6.530	0.253	1	2	56	15
Ireland	136	7.027	0.194	2	2	37	13
Belgium	125	3.053	0.409	12	1	88	16
Latvia	105	6.459	0.163	1	2	34	15
Netherlands	59	3.736	0.158	12	1	52	12
Estonia	59	4.523	0.130	1	1	24	14
Sweden	52	4.1034	0.127	8	4	15	13
Denmark	40	4.310	0.928	1	2	30	14
Luxembourg	39	0.259	0.151	1	1	39	16
Finland	20	33.815	0.591	6	2	6	13
EU totals	7961	392.573	0.203	243	15[a]	322[b]	23

European member states are listed in decreasing order of number of unique combinations.

[a] FOOTPRINT climatic zone 5 named 'Continental 3' is only present outside the European Union as shown in Table 1.

[b] A number of FOOTPRINT Soil Types occur only under land that is not used for agriculture, other than for unenclosed grazing of stock.

The relatively large number of FOOTPRINT soil classes means that soil is the most heterogeneous of the three environmental categories used to define agro-environmental scenarios across Europe. However, the large number of scenarios and their national variability is the result of the interaction between the variability of each category within each European country. This can be seen by comparing national differences between the values in column 4 of Table 6, which eliminates area differences between countries.

The scenarios clearly encompass a wide variety of European agricultural environmental conditions but their representativeness is dependent on the accuracy of the pan-European data from which they have been derived. Although comprehensive, the MARS and ECA & D climate, SGDBE, CORINE (2000) and EUROSTAT datasets are only samplings of the continuous variability of European environmental conditions. There is thus uncertainty associated with each of the datasets, resulting from omissions and simplifications as well as errors. Such uncertainty is transferred to and to a certain extent, compound in, the agro-environmental scenarios which have been derived by intersecting each data layer. Attempts have been made to deal with some of this uncertainty, for example the distribution of arable land areas as defined in the CORINE (2000) and EUROSTAT datasets (see Section 2.2).

Inevitably however uncertainty as to the representativeness of the scenarios remains and needs to be borne in mind when using them. For example, the SGDBE, which has a scale of 1:1,000,000, does not specifically identify any artificial soils such as occurring in man-made terraces, restored quarries or some intensively cultivated horticultural areas, whereas the CORINE (2000) land cover classes do not differentiate intensive horticultural areas covered by glass or polythene which are thus included in other agricultural or non-agricultural classes. Thus the scenarios described here do not include any intensive horticultural scenario under glass or polythene, nor do they cover rice growing areas and their associated soils. Further work is required to clarify the full uncertainty associated with the scenarios.

5. Application of the scenarios

5.1. *Use of the scenarios for modelling the fate of pesticides within Europe*

The FOOTPRINT agro-environmental scenarios represent the spatial variability of climate, soils and crops across the EU with relevance to pesticide fate and could be used to support modelling activities for pesticides.

Each of the climate, soil and crop components of the scenarios has an associated set of data which can be used to parameterize environmental fate models. Each climate zone has a representative set of daily weather data for precipitation, mean, maximum and minimum temperature, potential evapotranspiration, wind speed, solar radiation over 26 years. Such a long period of daily data should be adequate to encompass most of the temporal variability in weather across the climate zone as well as including a sufficient number of extreme weather events to reproduce a representative spread of cases from 'realistic best' to 'realistic worst' for leaching, drainage or surface runoff and erosion. The crop calendar templates illustrated in 28 Fig. 2 should also provide much of the information to derive the crop growth input parameters necessary for modelling, whereas inherent crop growth parameters such as rooting depth, leaf cover and root water uptake can be derived from the FOCUS scenario documentation (FOCUS, 2000, 2001). Finally, the soil horizon type and depth, particle-size characteristics, organic carbon content, pH and bulk density data provided for each FOOTPRINT soil type can be used to derive any soil hydraulic characteristics required by models, using 'pedotransfer functions' such as those included in the HYPRES data files (Wösten et al., 1998) or derived from national datasets (Mayr and Jarvis, 1999). In addition, the hydrological component of the soil type code can be used to derive the hydrologic conditions to help parameterize leaching, drainage and runoff models such as MACRO and PRZM.

Taking into account the need for separate model simulation for autumn sown and spring sown varieties of the same crop, as well as early and late sown varieties of crops (i.e. potatoes and soya), a total of 35,158 model runs are required to represent the unique combinations of climate, soil and crop within Europe.

As with any modelling procedure, predictions are subject to error as well as the uncertainty associated with the representativeness of the scenarios (see Section 4). The scenarios described here can clearly be used to generate large amounts of model predictions that, potentially, represent the variation in environmental exposure resulting from use of specific pesticides across Europe. However, such data are misleading if they incorporate systematic errors resulting from, for example, any automated parameterization of the models used. It is thus necessary that, where the scenarios are used to parameterize models for use at the European scale, some sort of validation procedure should be applied to ensure that no systematic predictive error is present and that model results represent what is likely to occur. There is much published literature on the validation of model predictions but little of it addresses multiple model predictions generated from large datasets that represent the spatial and temporal variability of driving variables. The issue is highlighted in Section 2.1.4 of Volume 2 of the FOCUS report on Landscape and Mitigation Factors in Aquatic Ecological Risk Assessment (FOCUS, 2007) and possible approaches to validation have been proposed by EUFRAM (2008). These include: a) ensuring that the parameters used to derive model variables include those which most influence model results; b) ensuring that the spatial data includes at least some of the scenarios already created and tested by the FOCUS surface and groundwater groups and that model results are similar to the published FOCUS results; c) undertaking some preliminary model runs to ensure that results are in line with any relevant field monitoring or measured data available from higher-tier studies such as field dissipation studies, lysimetry, aquatic microcosm studies, and other field studies. Such validation procedures are being undertaken during the final phase of the FOOTPRINT project and the results will be presented in a future paper to demonstrate the viability of the agro-environmental scenarios in parameterizing the MACRO and PRZM models at the European scale.

5.2. *Implication for improvement of environmental risk assessment procedures*

Current European risk assessment procedures for pesticides use a limited number of scenarios to represent national and European spatial variability (Van Alphen and Stoorvogel, 2002). In Germany, Probst et al. (2005) and Herrchen et al. (1995) have identified eight different environmental scenarios in the central lowland region and five small scale national scenarios, respectively.

In contrast to these studies, the work presented here has derived a large number of agro-environmental scenarios representing land areas that are effectively homogeneous with respect to the critical factors that control the fate of agriculturally applied pesticides. The scenarios represent the spatial variation and heterogeneity of the European agricultural landscape and, because they incorporate data on the weather, soil physical, soil hydrological and crop growth characteristics that are required by most soil leaching, drainage and runoff models, they can be used to underpin model parameterization at the pan-European level. For example, the scenarios have been incorporated as default databases for the FOOTPRINT tools, where they are used to parameterize the MACRO and PRZM pesticide fate models.

These are the models used to predict the likely environmental exposure in surface waters resulting from pesticide use within the context of European pesticide registration (FOCUS, 2001). Within the FOOTPRINT national level tool therefore, these scenarios provide a suitably comprehensive basis for supporting higher-tier modelling applications within the current European registration process. They also provide a suitable basis for future development of probabilistic approach to estimating environmental exposure of agriculturally applied chemicals within Europe. Probabilistic approaches to risk assessment for pesticides are currently under consideration (Hart, 2001; FOCUS, 2007), but a recognized limitation to such approaches is the lack of harmonized data at the pan-European scale, both for estimating exposure and effects.

6. Limitations and potential future developments

The FOOTPRINT agro-environmental scenarios have the advantage of using harmonized pan-European datasets in their derivation. However, this process has highlighted some variability in scenario complexity between countries. The agro-environmental scenarios can obviously be improved by incorporating more comprehensive or higher spatially resolved data on weather, soil type and cropping, where it is available at the regional or local scale.

Whereas it is relatively easy to derive model input requirements from local weather and cropping information, parameterization of soil and hydrological input requirements using local soil information is usually far less straightforward, not least because of the many different systems used to describe and classify local soil types within different European countries. In order to facilitate improvement of the scenarios by the incorporation of local and more detailed soil information, a comprehensive 'decision-tree' has been developed and integrated into the FOOTPRINT software system to correlate local soil types with a FOOTPRINT soil type and its associated soil hydrological and 'organic profile' information. The decision tree consists of a series of questions relating to soil parent material, the presence of artificial drains, the presence of soil colours indicating intermittent waterlogging, organic-rich or organic-poor layers, topsoil and subsoil textures and the presence of coherent rock within 1-m depth. The use of the decision tree allows scientists and practitioners to readily correlate a local soil type with a FOOTPRINT Soil Type and its associated soil parameter dataset for the MACRO and PRZM models. It can also be used to identify the hydrological lower boundary condition, USDA Soil Conservation Service Soil Hydrological Group, and organic profile type.

Finally, the work described here has focussed on the use of environmental and crop characteristics to differentiate scenarios. Socio-economic factors also affect agricultural practices because managerial decisions of individual farmers are usually strongly influenced by local tradition, land inheritance, the national economy and global market forces. In many countries, the number of extensive 'agri-business'-type farms with large fields and a reliance on highly mechanized contract labour for field operations is increasing. In contrast, there are still many small-sized farm holdings comprising a mosaic of small fields and with a reliance on, often elderly, family labour. Such differences in farm structure can have an impact on the way crops are managed and, where they can be quantified using local or regional data on farm structure and economics (for example, EC, 2005), it should be possible to improve the scenarios by defining different crop management templates for the different types of farm structure that are present in areas with similar climate and soil.

7. Conclusions

A large number of agro-environmental scenarios representing land areas that are effectively homogeneous with respect to the critical factors that control the environmental fate of agriculturally applied pesticides have been identified. The 25,044 scenarios include 7691 unique combinations of climate, soil type and agricultural land use. They represent the spatial variation and heterogeneity of the European agricultural landscape and can be used to underpin the parameterization of environmental fate models.

Although the agro-environmental scenarios developed have a primary relevance to pesticide fate, they are also likely to be relevant to other agricultural contaminants such as nitrate or phosphorus since most of the driving climatic, soil and cropping characteristics underpinning their environmental fate are similar. As far as we are aware this work is the first attempt to quantify such variation at the pan-European scale. Further refinement of the approach could be based on incorporating more comprehensive and finer resolution data on crop and soil distributions as well as identifying locally representative weather datasets for individual soil and land combinations. In addition, integration of socio-economic aspects of farm structure could be used to refine the information on agronomic practices encompassed in the crop growth templates by indicating where differences in socio-economic factors may affect crop management techniques within areas with the same soil and climate.

Acknowledgements

This work was undertaken within the scope of the European project FOOTPRINT (Contract No. SSPI-CT-2005-022704) which develops tools for pesticide risk assessment and management in Europe (www.eu-footprint.org). The funding of the work by the European Commission through its 6th Framework Programme is gratefully acknowledged. The authors wish to thank all partners of the FOOTPRINT project for fruitful discussion and provision of national census data.

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