ASSESSMENT OF PESTICIDE LEACHING AT THE PAN-EUROPEAN LEVEL USING A SPATIALLY DISTRIBUTED MODEL

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ABSTRACT

This paper describes the implementation of a Pan-European spatially distributed pesticide leaching model, referred to as EuroPEARL. Simulations were performed for 1062 unique combinations of Soil Mapping Unit, Climate Zone and Country. Soil properties were obtained from the Soil Profile Analytical Database of Europe. Daily weather data were obtained from the MARS database. Irrigation data, crop data and product properties were compiled from various sources, such as inventories, field-studies and the literature. The 1062 unique combinations together represent 75% of the total agricultural area of the EU. Results confirm that the predicted leaching concentration generally increases with precipitation and irrigation and decreases with increasing organic matter content. Because of the strong sensitivity of the leaching concentration to soil properties, there is a strong variability of the calculated leaching concentration at relatively short distances. Due to large irrigation amounts combined with large temporal variation of rainfall in the Southern European countries, areas of high leaching risk ('hotspots') as assessed by means of the EuroPEARL model occur in all countries of the European Union, including the Southern European countries.

KEY WORDS: Pesticide leaching, PEARL, GIS, Spatially Distributed Models

INTRODUCTION

Contamination of groundwater is an important side-effect of the usage of plant protection products (PPPs) in agriculture. Today, the sale of PPPs that form a threat to the groundwater is banned by registration procedures (Council Directive 91/414/EEC). These procedures evaluate whether the concentration of a PPP or one of its transformation products meets the criterion for PPPs in the groundwater (0.1 μg L^{-1}). The registration procedures follow a tiered approach. Within the context of the first tier of the European registration procedure, nine standard scenarios have been created, which are combined with point scale leaching models (FOCUS, 2000). These scenarios are designed to represent realistic worst case conditions. FOCUS (2000) selected approximate 80% vulnerable soils to be included in the scenarios, which implies that pesticide leaching will be lower than the EU drinking water limit in 80% of the soils represented by that scenario. Given the limited availability of Pan-European environmental databases at the start of the FOCUS activity, a statistical approach to infer scenarios could not be adopted. The FOCUS PEC calculations may therefore be biased in representing worst case scenarios. It is of paramount importance to make progress in the validation of the groundwater scenarios and to quantify and reduce this possible bias.

A spatially distributed leaching model can be helpful in scenario validation as it allows consideration of the variability of environmental and land use properties in an explicit way. Such models provide the user with maps of the predicted leaching concentration. Frequency distributions and percentiles of the predicted leaching concentration can be directly inferred from the maps. In addition, bias due to undersampling, as is the case when using a limited number of standard scenarios, will be reduced. The maps contain a wealth of additional information, particularly high and low risk areas.

This paper describes the implementation of a Pan-European spatially distributed PPP leaching model, referred to as EuroPEARL. The implementation of this model has become possible after the release of a series of Pan-European environmental and land-use data bases, such as the European Soil Map, the European Soil Database (Madsen-Breuning and Jones, 1995), and the Pan-European Climate Database (Vossen and Meyer-Roux, 1995). The objective of this paper is to present and evaluate the methodology which was used to implement the spatially distributed leaching model and to illustrate the possibilities of the model to assess the PPP leaching risk at the Pan-European level. Results will be discussed on the basis of four theoretical plant protection products with different physico-chemical properties. The methodological approach to evaluate whether the FOCUS scenarios are representative of realistic worst case conditions is described in a separate paper (Piñeros Garcet et al., 2003, this issue). They combine results from the EuroPEARL model with a statistical approach.

MATERIAL AND METHODS

Simulations are carried out with the PEARL model (Tiktak et al., 2000) for unique combinations of spatially distributed model inputs (cf. Tiktak et al. 1996ab, 2002a). These unique combinations (here referred to as 'plots') were assumed representative for one or more grid cells within the area to be mapped. The plots were constructed by overlaying the following three maps:

1. The 1:1,000,000 soil map of the European Union (Jamagne et al., 1995). This map features a total number of 735 Soil Mapping Units (SMU's). Each map unit is an association of Soil Typological Units (STU's) occurring within the limits of a discrete physiographic entity. It is composed of a dominant soil type and of subdominant associated soils.
2. A map showing 8 major climate zones of the European Union. The climate zone map is based on maps of long-term averages of annual precipitation and temperature, which were constructed using data from approximately 1500 weather stations (Vossen and Meyer-Roux, 1995). The definition of the zones is shown in table 1.
3. The map showing the countries of the European Union. The country is not required in the EuroPEARL model itself, rather it is used to guarantee that the correct soil profile is linked to the Soil Mapping Units.

All original maps were digitally available and were converted to raster maps. A resolution of 10x10 km^2 was chosen, which is the highest justifiable resolution of the EU soil map 1:1,000,000. As discussed in the introduction, the PPP exposure assessment should apply to agricultural areas only. Therefore, the overlay was masked with a map showing agricultural land-use. The final result was a map with 1442 relevant unique combinations of soil type, climate zone and country. The size of the units was between 100 km^2 and 19,600 km^2; the average plot size was 1,037 km^2.

Table 1: Major climate zones of the Europe Union, based on mean annual rainfall and mean annual temperature. Classification according to FOCUS (2000).

Zone number	Mean annual rainfall (mm)	Mean annual temperature (°C)	Surface area† (km^2)
Cold	< 600	< 5	83,000
Temperate 1	< 600	5 – 12.5	36,300
Temperate 2	600 – 800	5 – 12.5	429,400
Temperate 3	800 – 1000	5 – 12.5	269,000
Temperate 4	> 1000	5 – 12.5	167,800
Warm 1	< 800	> 12.5	329,800
Warm 2	800 – 1000	> 12.5	148,400
Warm 3	> 1000	> 12.5	32,600

† Agricultural land only

Linking the soil profiles with the map of unique combinations

The Soil Profile Analytical Database of Europe (Madsen-Breuning and Jones, 1995) has been compiled through the collaboration of national experts of the EU countries (12 at that time) and has been extended to include data from Eastern European and Scandinavian countries. The profile database (SPADE) contains information at the soil profile level. The soil profiles are not georeferenced and are estimated profiles, meaning that the national experts have given a best possible description of *typical* soil profiles of their countries. Their estimate is not necessarily based on soil profile descriptions and measurements. Parameters include the full FAO soil name, country, dominant soil textural class and horizon designations. At the horizon level, the database contains information on bulk density, organic matter, pH in water, and textural distribution, which is the information required by the EuroPEARL model. The total number of profiles in the database is 621.

Due to the structure of the European soil map, it was not possible to establish a direct link with the profile database. As mentioned before, the Mapping Units of the soil map are associations of dominant and subdominant Soil Typological Units. The total coverage of all individual STU's within one SMU is 100%. The STU's and not the SMU's are the carriers of basic soil information such as the FAO soil name and textural class. The link between the profile database and the soil map was therefore made in a two step approach (Figure 1).

In a first step, the dominant STU within each SMU was determined. Then, a soil profile was assigned to the dominant STU. This second link was made at different confidence levels. The most reliable link could be obtained if the author of a profile has explicitly stated the corresponding STU. If the STU was not specified, a profile was assigned on the basis of the full FAO soil name, the textural class and the country code. By including the country code in the query, it was assured that soil profiles from the soil profile database of a given country could only be matched to Soil Mapping Units within that country. In those situations where it was still not possible to assign a soil profile, the query was repeated with the full FAO soil name and the country code only. Finally, a query was carried out using the major soil type only (e.g. Cambisol instead of Eutric Cambisol). Using this procedure, 1062 Unique Combinations could be assigned a soil profile, representing approximately 75% of the total agricultural area of the European Union. Unfortunately, Austria, Sweden and Finland had to be left-out, because there was insufficient soil profile information available for these countries.

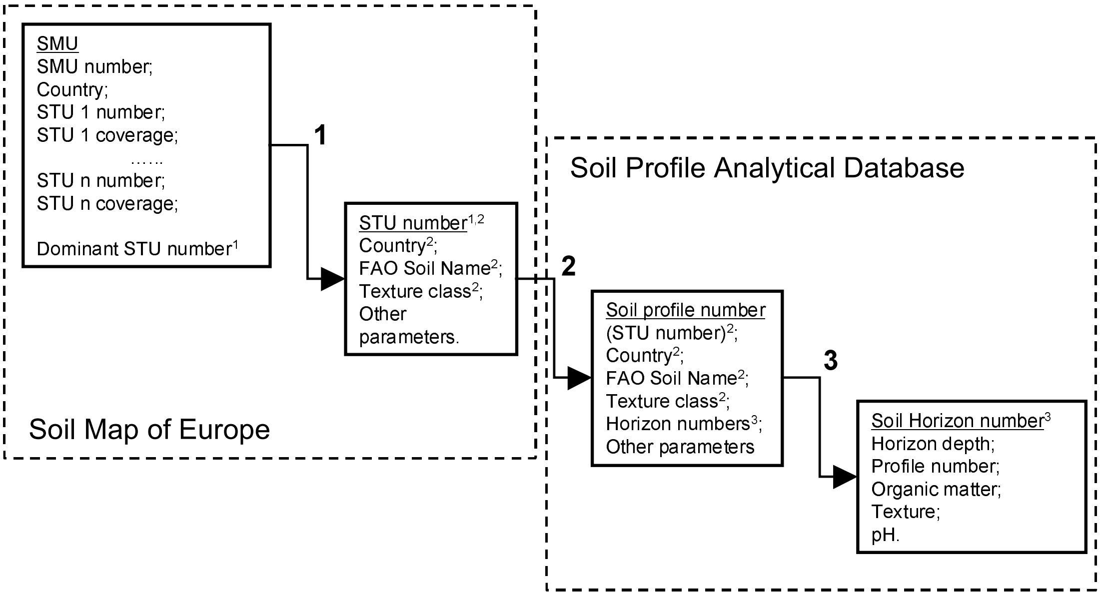

Figure 1: Link between the European Soil Map and the Soil Profile Analytical Database of Europe. Parameters with suffix 1 have been used for the link between the SMU and the STU; parameters with suffix 2 have been used for the link between the STU and the Soil Profile number, and parameters with suffix 3 have been used for the link with the soil horizon database.

Model parameterisation

Parameter values were assigned to the 1062 plots described above. To avoid data redundancy, all model parameters were stored in a relational database. The 'plot' is the central entry for all spatially distributed model inputs (see also the previous section). Long-term average rainfall and temperature are given at the plot level. All other spatially distributed parameters are related to climate zone or soil profile number.

Within each climate zone, a single weather station was selected from the MARS database (Vossen and Meyer-Roux, 1995). This weather station was assumed to correctly describe the seasonal dynamics of weather conditions within the entire zone. Daily precipitation and temperature for each plot were obtained by scaling the daily records from the nine weather stations to the maps of the long-term average annual precipitation and temperature.

Horizon distribution, textural distribution, *p*H and organic matter were taken directly from the soil profile database. A continuous pedotransfer approach was used to relate the bulk density to the organic matter content (Tiktak et al., 1996a). Parameter values for the Mualem-van Genuchten functions to describe the soil physical properties were taken from the HYPRES database (Wösten et al., 1999). Because there were insufficient data to quantify the mean groundwater depth, it was set constant at two meters below soil surface. This was justified, because the most important model outputs showed a very low sensitivity to the depth of the groundwater table as long as the groundwater table was below 1 m, which is usually the case in agricultural soils (Tiktak et al., 2002a).

The growth of a crop is described as a function of development stage, which ranges from zero at crop emergence to 2 at crop harvest. The dependence of crop development on actual weather conditions was described by making the crop development stage dependent on the temperature sum since emergence. Emergence date, harvest date, LAI and rooting depth were obtained from nine representative field sites, i.e. one for each climate zone (FOCUS, 2000). Crop factors in relation to the modified Penman-Monteith approach were taken from Allen et al. (1998). Critical pressure heads for drought stress and irrigation were taken from Van Dam (2000).

Simulations were carried out for two crops, i.e. winter wheat and maize. These crops were chosen, because they are grown in almost the entire EU. Following common agricultural practice (FOCUS, 2000), winter wheat is not irrigated and maize is irrigated whenever an irrigation system is present. The presence of an irrigation system was derived from inventories by Siebert and Döll (1995), who present maps of the fraction of land equipped for irrigation.
Simulations were carried out for four dummy pesticides with different properties, i.e. substance A, B and D as reported in FOCUS (2000) and an additional substance E, which shows *p*H dependent sorption behaviour (Van der Linden and Boesten, 2001). The model was run for a 26 years period. The first six years of the simulation were warm up years, which implies that the model results refer to the final 20 years period. The PPPs were surface applied at a rate of 1 kg ha^{-1} one day before crop emergence (pre-emergence PPPs). This implies that the pesticides are applied in autumn in the case of winter wheat and spring in the case of maize.

RESULTS

EuroPEARL was used to obtain maps of the predicted pesticide mass flux at 1 m below soil surface, which is the target depth considered in European legislation procedures (FOCUS, 2000). Substance balances were calculated for Europe as a whole, and for the climate zones described in table 1. The balances were included to show the large-scale variability of pesticide mass fluxes across Europe. The substance balances were calculated for the entire agricultural area of Europe, so no consideration was given to the actual crop area. As shown by Tiktak et al. (2002b), this may affect the average substance balances.

Water balances
Figure 2 shows the spatial patterns of the predicted 20 years average water fluxes in winter wheat and maize. The differences between the spatial patterns of water inputs in winter wheat and maize are remarkable. In the case of winter wheat the highest water inputs occur in north-western Europe (particularly Ireland), which is also the wettest area in terms of precipitation. In the case of maize, high water inputs also occur in Southern Europe, where irrigation is a common practice. Irrigation also has a large effect on the spatial patterns of predicted actual evapotranspiration rates. In the case of maize, the highest evapotranspiration rates occur in warm and sunny climates (Southern Europe). In winter wheat, which is usually not irrigated, low predicted evapotranspiration rates occur in dry regions (particularly Spain, Sicily and Greece).
Evapotranspiration is lower in Southern European countries because evaporation from the soil surface is lower. As soil evaporation rates are primarily affected by daily rainfall patterns, it can be concluded that the unpredictable rainfall patterns in Mediterranean regions and not the mean annual precipitation depths explain the large evapotranspiration deficits in winter wheat. There is a strong resemblance between the spatial patterns of the predicted groundwater recharge for winter wheat and maize. In both cases, the largest predicted groundwater recharge occurs in north-western Europe, Italy, and the mountainous regions of central Europe. Predicted groundwater recharge is lowest in East England, East Germany and Spain. There is also a strong resemblance to the precipitation map (which is the same map as the water input map for winter wheat). Apparently, the larger water inputs by irrigation in maize are compensated by larger predicted evapotranspiration rates, eventually leading to the same predicted groundwater recharge.

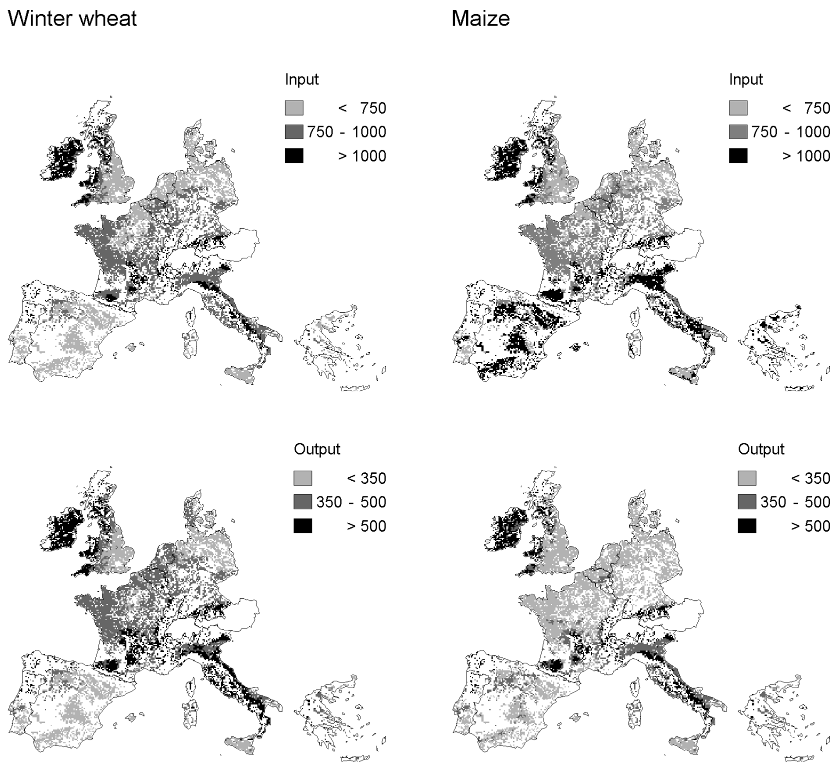

Figure 2: Average predicted water fluxes (mm a^{-1}) for winter wheat (left) and maize (right). Input is the sum of precipitation and irrigation, and output is the predicted groundwater recharge. Fluxes were calculated for a 20 years period (1971-2000).

Predicted pesticide leaching fluxes and concentration in leaching water

Table 2 shows the predicted 20 years average mass fraction of pesticides leached below 1 m depth for the major climate zones. Mass fractions are expressed as a percentage of the applied dosage. It is obvious that there are large differences between the four pesticides considered. The average leaching fraction generally decreases in the order E > B > A > D. The large sensitivity to the physico-chemical properties of the pesticide is entirely in line with investigations by Boesten and van der Linden (1991), who found that changing K_{om} or DT_{50} by roughly a factor of two changes the amount leached by roughly a factor of 10. The figure further shows that the predicted leaching fraction is larger for autumn applied pesticides (winter wheat) than for spring applied pesticides (maize). This confirms earlier findings (Boesten and van der Linden, 1991; Tiktak et al., 1996b) that the leaching fraction is extremely sensitive to the amount of rainfall in the period directly after product application. The differences between winter wheat and maize are usually larger for the warm (Mediterranean) climate zones, where there is a distinct wet season. The predicted average leaching fraction for the major climate zones shows two distinct series, i.e. one for the temperate climates (T4 > T3 T2 > T1) and one for the warm climates (W3 > W2 W1). This was expected on the basis of differences in the groundwater recharge. The differences between the warm and temperate climates are large in the case of maize and small in the case of winter wheat. Apparently, in the range of conditions studied, differences in seasonal rainfall patterns have a much stronger effect on the predicted leaching fraction than temperature differences.

Table 2: Twenty years average predicted mass flux of pesticide leached below 1 m depth. Mass fluxes are presented for the climate zones as described in table 1. The letter 'T' refers to temperate, the letter W to 'Warm'.

a) Winter wheat

	Percentage of dosage applied leached below 1 m depth						
	T1	T2	T3	T4	W1	W2	W3
Substance A	0.22	1.14	1.12	3.25	0.73	1.02	2.96
Substance B	0.60	3.58	2.83	9.07	2.88	1.95	8.02
Substance D	0.02	0.24	0.17	1.04	0.33	0.19	1.15
Substance E	0.76	2.96	2.39	5.40	2.40	2.91	6.67

b) Maize

	Percentage of dosage applied leached below 1 m depth						
	T1	T2	T3	T4	W1	W2	W3
Substance A	0.14	0.72	0.71	1.96	0.30	0.65	1.22
Substance B	0.08	0.55	0.75	1.62	0.25	0.20	0.39
Substance D	0.01	0.05	0.05	0.20	0.01	0.02	0.04
Substance E	0.38	1.42	1.36	2.75	0.73	1.28	1.99

Figure 3 shows maps of the leaching risk of substance A and D as calculated with the Euro-PEARL approach. According to harmonised European procedures (FOCUS, 2000), the leaching risk of a pesticide is approximated by the 80th percentile of the leaching concentration due to weather conditions. This percentile was calculated in a two step approach. First, for each year, the mass flux of pesticide leached was divided by the annual groundwater recharge, which is approximated by the predicted water flux at 1 m depth. Then, from a series of 20 years, the 80th percentile was chosen. The maps show that high and low risk areas occur at relatively short distances. This suggests that soil properties, which show a strong variability at short distances, have a large effect on the leaching risk. Additional analyses by Piñeros Garcet et al. (2003, this issue) indeed showed a large sensitivity of the leaching concentration to organic matter and (to a lesser extent) soil texture. The maps further show that high and low risk areas can occur everywhere in Europe. This could be expected on the basis of the maps of groundwater recharge (Figure 2), which show that a high groundwater recharge can occur in both Western and Southern Europe (particularly Italy).

DISCUSSION

The current version of EuroPEARL can be seen as an attempt to fully implement a Pan-European, mechanistic and spatially distributed leaching model for plant protection products. Based on common knowledge of the leaching process, the behaviour of the model can be judged 'plausible'. Nevertheless, the model predictions are subject to a high degree of uncertainty. Errors first result from how the system is conceived in the selected model (the conceptual level); second from how the model inputs and parameters have been generated. Limitations of the current PEC models are discussed in Vanclooster et al. (2003, this issue) and Jarvis et al. (2003, this issue). In this section some remarks are made on the soil and climate databases.

For characterising the spatial distribution of soil properties throughout Europe, the European Soil map at the scale of 1:1.000.000 was used in combination with the Soil Profile Analytical Database, release I (Jamagne et al., 1995). This version of the database has some serious limitations. The most serious limitation is that 25% of the total agricultural area of the European Union could not be assigned a soil profile. Moreover, only for a limited number of Soil Mapping Units a direct link could be established between the Soil Mapping Unit and the analytical data in the profile database, so a less certain link based on decision rules had to be established in many cases. Although each Soil Mapping Unit is an association of a number of Soil Typological Units, the soil profile database did not contain sufficient information to link more than one typological unit. This implies that information on the underlying spatial variability was lost. Tiktak et al. (1996b) showed that ignoring spatial variability in a leaching study may affect the final results. A further concern pertains to the way that the analytical data has been obtained. In many cases, available data were based on estimated profiles, potentially introducing a bias between the individual countries. These concerns have led to the development of a new version of the database (SPADE II), which will become available soon.

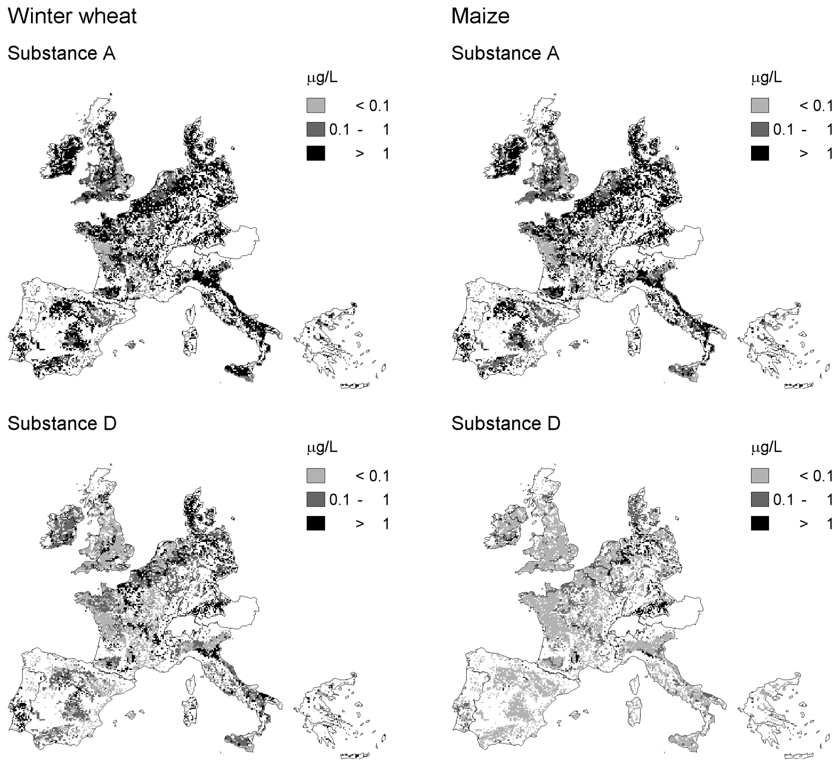

Figure 3: Leaching risk of substances A and D, approximated by the 80th percentile of the predicted leaching concentration. Concentrations were calculated according to FOCUS (2000). See further text.

To obtain the spatial distribution of daily weather data, a simple scaling procedure has been adopted. A central assumption in this approach is that data from one weather station could be used to correctly describe the seasonal dynamics of weather conditions within each climate zone. It is generally known that the annual variability due to weather conditions is larger in the warm climate zones than in the temperate climate zones. Moreover, maps of winter and summer precipitation (not shown) show a distinct dry season in the warm climate zones. These conclusions suggest that the adopted procedure is generally applicable. However, the maps also show some anomalies, for example in south-western France. It is therefore important that this procedure is validated against more detailed weather data as available in the MARS database.

Given these uncertainties, we believe that the maps generated by means of the EuroPEARL model should be treated with a lot of caution. The maps of PPP leachate concentrations generated by EuroPEARL should be considered as a measure of the potential of a PPP to contaminate the groundwater. These potential concentrations should be considered as proxies of the actual

concentrations that might be found in groundwater systems and should be compared to and/or combined with the results generated through more detailed higher tier modelling and through detailed monitoring of the groundwater system.
Notwithstanding this intrinsic high uncertainty associated with the PECs generated by means of large scale spatially distributed leaching models, the presented methodology is a major step forward in modelling potential groundwater contamination by the use of PPPs, in particular in view of Pan-European harmonised registration and risk assessment procedures. In contrast to the current procedure (FOCUS, 2000), the methodology presented in this paper allows to consider the variability of the environmental system in an explicit and statistical verifiable way. Considering variability in such a verifiable way will increase the quality of the exposure assessment, and should result in a more balanced and scientifically based process of registration (Piñeros Garcet et al., 2003, this issue).

CONCLUSIONS

The PPP leaching model PEARL in combination with European soil and climate databases could be used to describe the leaching risk of PPPs at the scale of the European Union. Using the approach described in this study, 75% of the total agricultural area could be parameterised. To test in a statistical way the validity of the FOCUS scenarios, it is necessary to consider also the combinations for which no data was available. For this purpose a statistical metamodel of EuroPEARL was derived, using an artificial neural network (Piñeros Garcet et al., 2003, this issue).
Simulations were carried out for four pesticides with different properties. Results showed that the leaching risk generally increased with precipitation and irrigation and decreased with increasing organic matter content. Because of the strong sensitivity of the leaching concentration to soil properties, there was a strong variability of the calculated leaching concentration at relatively short distances. Results further indicated that due to large irrigation amounts combined with large temporal variation of rainfall in the Southern European countries, areas of high leaching risk (‘hotspots’) as assessed by means of the EuroPEARL model occur in all countries of the European Union, including the Southern European countries.

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