How Spatial Analysis Can Help in Predicting the Level of Radioactive Contamination of Cereals

C. Mercat-Rommens, J.-M. Metivier, B. Briand and V. Durand

Abstract The study was devoted to the identification of the spatial parameters that contribute mainly to the assessment of the vulnerability of cereals in the context of accidental discharges of radioactivity into the environment. Linking an agronomical model and a radioecological model highlighted first that the flowering date was the main parameter, since it determines the beginning of an exponential transfer of contaminants from the leaves of cereal plants to the edible part, the grain. Secondly, yield also appeared to be an important parameter as it allows the quantification of the number of contaminated products. The spatial statistical analysis performed on the yield data allowed the creation of vulnerability maps with clear spatial trends, which can facilitate the management of risks associated with radioactive contamination of cereals during the post-accidental phase.

1 Introduction and context

The radiological consequences of radioactive releases, as shown, in particular, by feedback relating to the Chernobyl accident, highlight the fact that the consequences of industrial pollution on man and the environment depend not only on the extent and nature of this pollution but also on the territory that is polluted. Whether expressed in economic, toxic or health risk terms, these consequences can be more or less detrimental depending on the features of the environment affected (environmental parameters) and the usage of this environment by man (human parameters). Urban, farming, forest, river, lake, sea or mountain environments show different pollution sensitivity levels and, within these major environmental categories, the response or reaction to a pollution event is determined by different natural or human factors, specific to the ecosystem in question. For example, in a farming region,

---

C. Mercat-Rommens
Laboratory of radioecological studies for marine and terrestrial ecosystems, Institute for Radioprotection and Nuclear Safety (IRSN), DEI/SESURE/LERCM, Cadarache, Bld 153, 13105 St-Paul-lez-Durance cedex, France
e-mail: catherine.mercat-rommens@irsn.fr

A. Soares et al. (eds.), *geoENV VI – Geostatistics for Environmental Applications*, 71–82

the type of production is a significant sensitivity factor. For the same surface area affected by a given pollution event, wheat and milk products will show very different respective contamination levels and responses over time. The persistence of this contamination in successive crops will also strongly depend on the soil characteristics. Generally, a territory's specific sensitivity to the pollution will be determined by the features inherent in its ecosystem, which have an influence on pollutant transfer. The same effect is observed with human factors such as farming methods (use of fertilizers, irrigation, sowing periods) or zootechnical practices (animal feeding regimes, animals housed indoors or kept outdoors). A territory's radioecological sensitivity is therefore dictated by two components: environment and human factors.

Although we can establish that a territory may be susceptible to the pollution it receives, it remains difficult to compare overall sensitivity between different territories. Radioecological sensitivity is a concept for the evaluation of the intensiveness of a territory's response to a pollution event. Since 2003, the French Institute for Radioprotection and Nuclear Safety (IRSN) has been running an inter-organizational project entitled SENSIB (an acronym referring to radioecological sensitivity) (Mercat-Rommens and Renaud 2005). Its aim is to develop a standardized tool with a single scale of values to describe and compare the sensitivity of various environments to radioactive pollution, thereby providing a classification of the territory based on its intrinsic features (annual rainfall, soil type, agricultural practices, dietary habits etc.).

2 Objectives and Methods

This paper focuses solely on the agricultural aspects of the SENSIB project. The object is to develop a method for classifying agricultural areas by their sensitivity to atmospheric radioactive pollution. The factors likely to increase or reduce the consequences of the pollution event need to be identified, characterized and ranked, in order to develop a system of indices to be used for operational classification. The present study focused first on the sensitivity of winter wheat and then generalized the main results to other French cereals. The main objective was to establish whether a uniform, localized deposit would entail an identical contamination of cereals on a national scale. If not, we want to know the quantity of cereals that will be contaminated and where in France, according to the date of the accidental release. Three sources of spatial variability are taken into account (weather conditions, soil type and agricultural practices (fertilizer, irrigation and sowing dates according to variety)).

The study used the ASTRAL model ("Assistance Technique en Radioprotection post-Accidentelle"), a computing code developed by the IRSN, which enables the assessment of radionuclide transfers to the terrestrial food chain following an accidental atmospheric discharge (Mourlon and Calmon 2002). The aim is to determine the effect of a regionalization of the ASTRAL model parameters on a specific activity in farm produce. In this study, the agricultural produce analyzed was the winter wheat plants exposed to an accidental deposit of atmospheric cesium 137 (^{137}Cs), and the ^{137}Cs concentration in the grain at the time of harvest. The STICS software ("Simulateur mulTIdisciplinaire pour des Cultures Standard") from INRA (Brisson et al. 1998, Brisson and Mary 2002) was used in order to identify regional (environmental and agronomical) factors likely significantly to influence contaminant transfers in agricultural products. This model provides a day-by-day estimate of the leaf area index, a variable that could be correlated with radioecological parameters of the ASTRAL model. Coupling the radionuclide transfers in the food chain model (ASTRAL) and the STICS model will enable the spatial variability of the radioecological sensibility of agricultural products to be quantified.

3 Models Used for the Study

3.1 *The ASTRAL Radioecological Model*

ASTRAL comprises a calculation module involving geographical and radioecological databases (radionuclide transfer parameters in the environment), enabling the assessment of the impact of radioactive deposits on agricultural produce (specific activities), agronomic resources (areas and quantities affected) and populations (doses received) in areas affected by a possible nuclear accident.

In the case of cereals, only leaf transfer was studied, as this transfer pathway is predominant over root transfer for the first year following accidental release. Activity at time t after deposit, C, is thus determined by the initial contamination, the retention capacity of plants taking into account the weather conditions on the day of deposit, plant growth (activity dilution), radioactive decay during the period between deposit and harvest:

$$C = \frac{D \times TLF}{Yld} \times [Kr \times RC_{dry} + (1 - Kr) \times RC_{wet}] \times e^{-\lambda r \times t} \tag{1}$$

D: Total deposit on plant (Bq.m^{-2})
TLF: translocation factor, which defines the proportion of radionuclide migrating from the leaves to the grain (-)
Kr: Dry deposit as a proportion of total deposit
Yld: Crop yield (fresh kg.m^{-2}) at harvest
RC_{dry}, RC_{wet}: Retention ratio in dry and rainy weather, respectively
λr: Radioactive decay constants (d^{-1})
t: Time elapsed since deposit (d)

The parameter Kr indicates the proportion of dry deposit within a given total deposit. It is likely to be a regionalized value as it varies according to rainfall intensity at the time of the deposit. However, it is impossible to predict weather conditions in accidental situations. In fact, this is a risk factor exclusively linked to the event. For this study, a value of Kr equal to 1 (entirely dry deposit) or 0 (entirely wet deposit) was therefore used in the ASTRAL simulations.

The retention ratio (also referred to as "interception ratio") is the dimensionless ratio of activity taken up by vegetation and total activity deposited on 1 m^2 (Chamberlain, 1970). In the ASTRAL model, the retention value depends on the surface area occupied by plant cover at the time of the deposit. It corresponds to the total deposited activity fraction intercepted by the above-ground part of the plants. The retention ratio, RC_{dry}, can be estimated on the basis of the leaf area index, LAI, defined as the surface area likely to collect aerosols, i.e. the leaf area per soil surface unit. The German model, ECOSYS-87 (Müller and Pröhl 1993), proposes a calculation method for retention in dry weather conditions based on the LAI. It makes the assumption that a radioactive deposit, on any surface area, is calculated as the product of a deposition velocity by the radionuclide concentration value in air, and that deposition velocity on the plant depends on represented foliar development. The variable chosen in order to characterize the plant development stage is leaf area index, and the following equation defines the retention ratio in dry weather:

$$\mathrm{RC_{dry}} = \frac{\frac{\mathrm{LAI}}{\mathrm{LAI_{max}}}}{\frac{\mathrm{LAI}}{\mathrm{LAI_{max}}} + \frac{\mathrm{Vg_s}}{\mathrm{Vgi_{max}}}} \tag{2}$$

LAI: Leaf area index
$\mathrm{LAI_{max}}$: Maximum leaf area index
$\mathrm{Vg_{max}}$: Maximum deposit rate ($m.s^{-1}$)
$\mathrm{Vg_s}$: Deposit rate on soil ($m.s^{-1}$), a constant for all plant types

In the case of deposit in rainy weather (cumulated rainfall over the deposit period in excess of 1mm, according to the ASTRAL model assumptions), the studies by Angeletti and Levi (1977), followed by those by Hoffman (1989) demonstrated that interception (represented by retention ratio in damp conditions, RC_{wet}), essentially correlates to the biomass, represented by the LAI, and to the contaminated rainfall (P):

$$\mathrm{RC_{wet}} = \left(\mathrm{LAI} \times \frac{\mathrm{S_2}}{\mathrm{P}}\right) \times \left(1 - 2^{-\frac{\mathrm{P}}{3 \times \mathrm{S_2}}}\right) \tag{3}$$

S_2: Saturation coefficient (mm), dependent on the radionuclide and the plant
P: Rainfall (mm)

3.2 The STICS Agronomical Model

STICS is a daily crop growth model developed by INRA (Brisson and Mary 2002). Its input variables relate to climate, soil and technical management. Its output variables relate to production (quantity and quality), environment and soil property changes under the influence of cultivation. STICS was designed as an operational simulation tool for agricultural conditions. Its main objective is to simulate the consequences of variations in environment and farming methods on production from an agricultural plot, over the course of the year. Crop growth is generally appraised through its above-ground biomass and nitrogen content, its leaf area index, as well as the number and biomass (and nitrogen content) of harvested organs.

The soil is considered as a series of horizontal layers, each characterized by its water, mineral nitrogen and organic nitrogen reserves. Interactions between soil and crops occur via the roots, which are defined by a distribution of root density in the soil profile. The model simulates the system's carbon, water and nitrogen balances and allows the calculation both of agricultural variables (yield, fertilizer consumption) and environmental variables (water and nitrate loss) in various agricultural situations.

3.3 Coupling Both Models

This study assumes that plant cover is not at the same stage at any given time t, across the entire French territory. The ASTRAL model's radioecological parameters of retention (RC_{dry} and RC_{wet}) change in accordance with the STICS model's agronomic parameter LAI. This enables the ASTRAL model's outputs (radioactive contamination of the crops), to take regional diversity in cultivation conditions into account.

4 The Winter Wheat Study

In order to study the influence of regional variability, we tried to define the simulation scenarios able to illustrate the full variability of agricultural conditions in France. 12 kinds of weather conditions (Fig. 1) and two varieties of winter wheat (one early variety, Talent and one late variety, Allure) were chosen. The values for the interception ratios during dry and wet weather were then calculated by STICS for each of the 24 scenarios.

The results showed that the process of interception during dry weather conditions can be correctly represented by a single curve because the effect of regional climatic variability is low (Fig. 2). However, if regional variability leads to a low effect on the magnitude of the interception, it can influence the contamination of the crop because of a shift during the year. With respect to wet interception, regional variability influences the magnitude of transfer and also causes a shift between the curves according to region.

The flowering date is another parameter which varies in space and which highly influences the contamination process of grain by the translocation process (Fig. 3).

When we combined the various regional sources of variability in a simulation of an accidental fallout of radionuclides on various French regions, it appeared

Fig. 1 Localization of the 12 stations of the study

that the date fallout occurs is the main point of contamination of the crop. If the fallout occurs before the flowering date, grain contamination is negligible because translocation is very low, even if the interception process is very high. If the fallout occurs after the flowering date, the grain is highly contaminated. That is why during

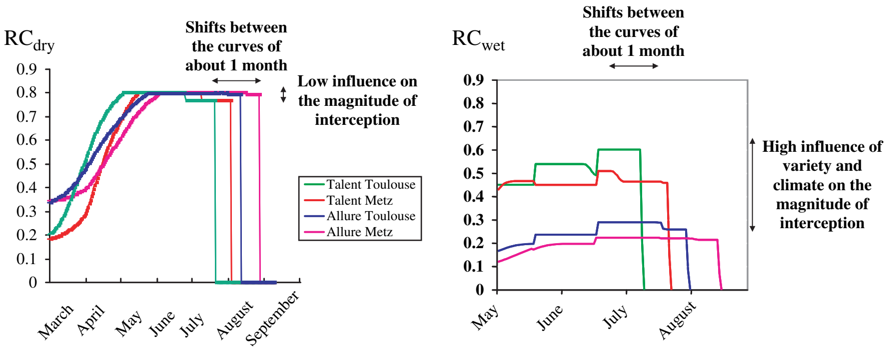

Fig. 2 Examples of evolution of the interception ratio during dry and rainy weather for both varieties and for two very different climatic conditions (stations of Metz and Toulouse)

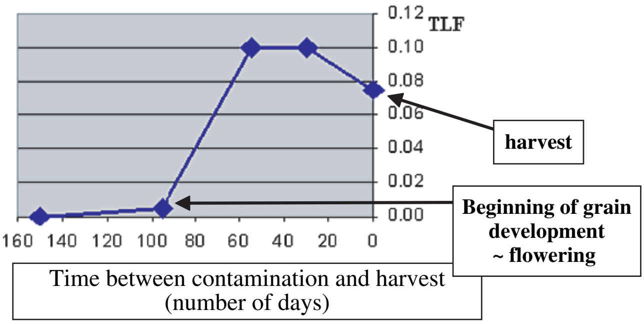

Fig. 3 Evolution of the translocation process in ECOSYS (Müller and Pröhl 1993)

spring and early summer, some French regions could totally avoid the contamination because flowering has not happened whereas other regions would be seriously affected. It depends mainly on the day of flowering, which determinates the exponential increase of transfer of radionuclides from leaves to crop (Fig. 3). As an example, the Fig. 4 shows the results for both varieties, Talent and Allure, and for two stations (Perpignan and Rouen which are located respectively in Southern and Northern France – cf. Fig. 1).

From the Fig. 4, we can see that an accidental fallout before May would not contaminate the grain, either in the South of France or in the North. Any fallout in May and at the beginning of June would cause contamination of the winter wheat produced in the Perpignan region, whereas that produced in the Rouen region would avoid the contamination because the flowering stage would not have started. From late June, and until the harvest in Perpignan (beginning of July) both produce types

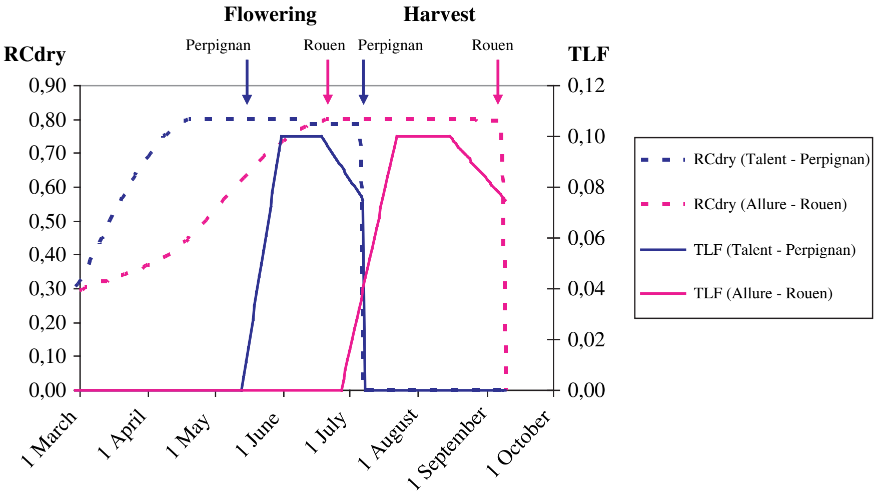

Fig. 4 Results for interception and translocation for 2 stations

and consequently the entire territory of France would be contaminated. Then in August and September, only the wheat of the Rouen region would be vulnerable because the harvest would not have taken place.

These modeling results were confirmed by the contamination values measured in wheat crops in France after the Chernobyl accident. In the first days of May, very few varieties of wheat had flowered and so the level of cesium 137 measured remained low in grain, very often below the detection threshold of 50 Bq per fresh kg, in most French regions. The ten samples of wheat, in which cesium 137 was significantly detected after the Chernobyl accident, came from regions located in the south of France (French administrative regions labeled “Drôme”, “Ardèche”, “Bouches-du-Rhône” and “Vaucluse”).

5 Generalization to Other French Cereals

The previous study of winter wheat shows that the radioecological sensitivity of grains relies primarily on the flowering date. This flowering date indicator may also account for the level of contamination of other French cereals because the translocation process acts in the same way for all cereals. That is why we proposed - as a tool for managing potential contaminated cereal fields - an early calculation of the flowering date of all cereals, combined with an estimation of regional cereal production. The first indicator, “the flowering date”, will answer the question “where in France would cereals be contaminated?”, while the second indicator, “the yield”, will answer the question “what quantity of cereals would be contaminated?”.

The determination of the main factor for the contamination can be made from spatial parameters such as rainfall and temperature, which mainly influence the date flowering takes place. This work is being done by the French Institute “Arvalis-Institut du vegetal” which is conducting a reconstruction of the spatial variability of the flowering dates of the main French cereals (winter wheat, barley, corn and triticale) from meteorological data available from 309 stations in France. This reconstruction will be made for each location in the country and respectively, for early and late varieties and will also consider the variability in time of flowering dates by taking annual changes of climatic parameters into account.

In parallels, we studied the effect of the spatial distribution of the 309 stations cross-referenced with the variability of potential cereal production, represented by yield. The objective was to determine the area where cereal production is more (or less) intensive and subsequently the degree of vulnerability of cereal production in the event of an accidental fallout occurring after the flowering date. The 309 meteorological stations are distributed fairly homogeneously throughout French territory (except in Corsica). We calculated the Voronoï polygons corresponding to the stations with GeoStatisticalAnalyst of ArcGis9.1 (Fig. 5).

The Voronoï polygons represent the area of influence of each meteorological station. The Voronoï polygons were then cross-referenced with the agricultural statistical data available for the total cereal producing area (Agreste 2000) and for

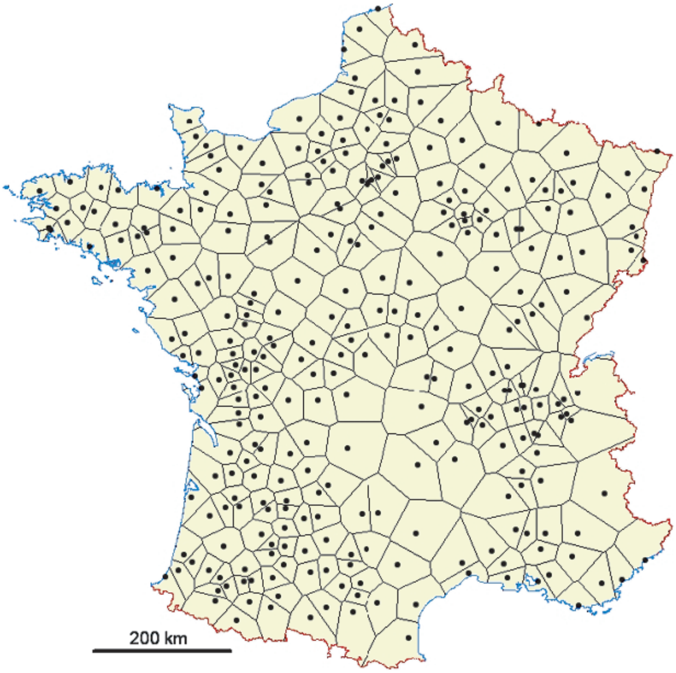

Fig. 5 Voronoï polygons

the total yield of cereals (Agreste 1988), in order to reconstruct the occupation of agricultural lands by cereals and the yield expected in each polygon (Fig. 6).

Then we performed a local cluster analysis on yield to detect any potential geographical clusters (if Voronoï polygons are significantly correlated with surrounding polygons) in order to propose a judicious classification of the territory by aggregating the polygons. We performed a spatial statistical analysis with the LISA statistics of the software TerraSeer-STIS (Jacquez *et al.* 2005):

$$LISA(u) = \underbrace{\left[\frac{z(u)-m}{s}\right]}_{term\,1} \times \underbrace{\left(\sum_{j=1}^{J(u)} \frac{1}{J(u)} \times \left[\frac{z(uj)-m}{s}\right]\right)}_{term\,2} \tag{4}$$

u: one of the 309 Voronoï polygons constructed from the 309 meteorological stations,
z(u): yield reconstituted in the u polygon,
m: mean of the 309 yield values,
s: standard deviation for the 309 yield values,
J(u): number of neighbors.

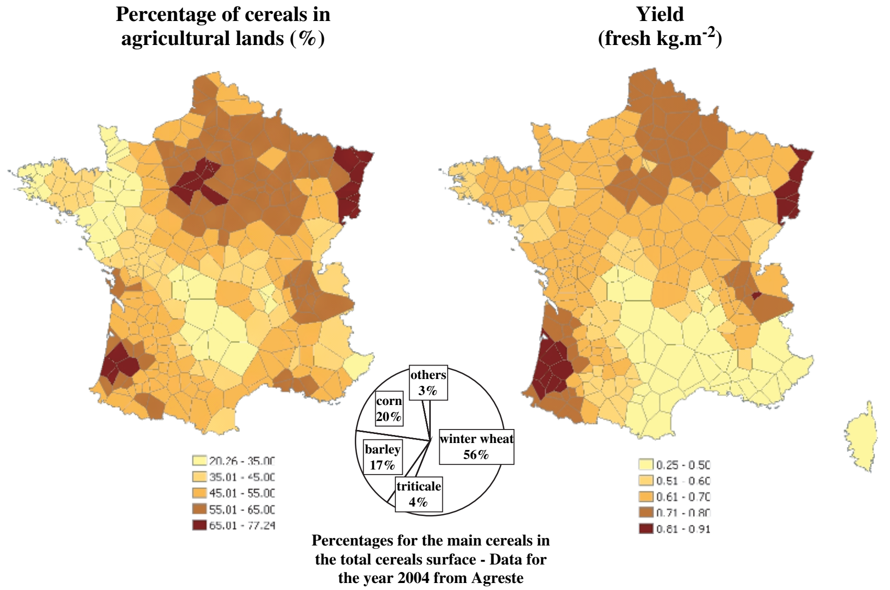

Fig. 6 Spatial patterns for French production of cereals as a percentage of the cereal share of arable land (%) and yield (kg.m^{-2})

This statistic is based on the local Moran test (Moran 1950) (Anselin 1995) for the detection of local spatial autocorrelation.

LISA $<$ 0: when term 1 is negative and term 2 is positive (or the opposite). It happens when the value z(u) is higher than the mean, whereas the values for the neighboring polygons are globally lower than the mean. In this case, we have an outlier named High-Low, which identifies an anomaly. The opposite (when a value is lower than the local mean whereas neighboring values are globally higher than the local mean) is named a Low-High outlier and is also considered as an anomaly.

LISA $>$ 0: when the value z(u) and most of the surrounding values go in the same direction (higher or lower) compared to the local mean. In these cases, we have clusters respectively High-High or Low-Low. The spatial correlation of a polygon with its neighbors can then justify propositions of spatial aggregation, a first step towards a classification of the territory.

In addition to the sign of the LISA statistic, its magnitude informs on the extent to which the value of a polygon differs from or corresponds to its neighbors' values.

The LISA statistic was applied for the 1st order queen neighbors, which are defined as polygons sharing a common border or vertex with the u polygon. We tested the LISA significance by applying a Monte Carlo randomization (10 000 calculation) and a significance level of 5% (Moran test). The results are presented in Fig. 7.

No outlier was detected. Good agreement was observed between the results of LISA statistics and the French agricultural patterns. As shown by Fig. 6, the main

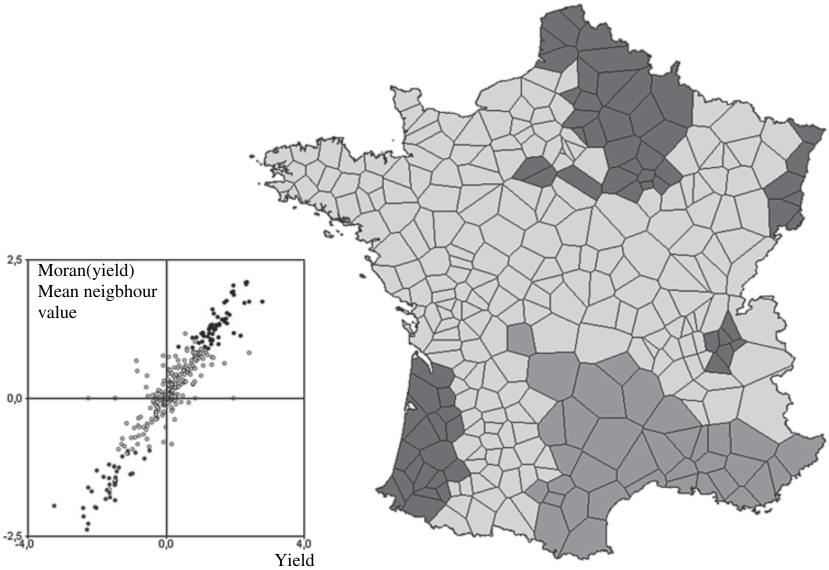

Fig. 7 Results of local cluster analyses for global yield of cereals. High-High clusters are shown in red and Low-Low clusters are shown in blue

regions for cereal production in terms of surface devoted to cereal growing are the Center and the North of France (wheat and barley), the Southwest (corn) and the East (corn). We observed in Fig. 7 that the yield is high (High-High cluster) for almost all of these regions, except the Center, whereas the Southeast region is less productive (Low-Low cluster). A small area with a High-High cluster also appeared in the North of the Alps, which corresponds to a more secondary region for cereal production.

If we cross-reference knowledge about the yield and flowering dates for winter wheat reconstructed by the STICS model, we observe that the yield is higher for the Northern part of France while flowering dates are later. This result can provide information for improving the dimensioning of countermeasures from a spatial point of view (where are the vulnerable areas?), but also from a temporal point of view (at which period of the year?) and a magnitude point of view (what quantities of contaminated cereals are expected?).

6 Conclusion

The study was devoted to the identification of the spatial parameters that contribute mainly to the radioecological sensibility of cereals. The flowering date appeared to be the main parameter because it determines the beginning of an exponential transfer of contaminants from the leaves of the cereal plants to the edible part, the grain. This parameter, the flowering, is especially useful in decision-making for at least two reasons: 1. It is a stage in the development of cereals, easily visualized on fields; 2. An early calculation of flowering dates based on the spatial variability induced by weather conditions, soil types and farming practices is achievable for all cereals. The spatial statistical analysis allows the creation of vulnerability maps with clear spatial trends, which can facilitate the management of risks associated with radioactive contamination during the post-accident phase for cereals, and guide the decision for possible countermeasures.

Acknowledgments Part of this work was made by Aude Delboe in the framework of the agricultural engineer training course ("Ecole Nationale Supérieure d'Agronomie de Montpellier", France). This study has received financial support from ADEME (French Agency for Environment and Energy Management). The authors wish to thank Pierre Goovaerts for his prompt and accurate answers to several e-mails of questions.

References

Agreste (1988) Recensement général de l'agriculture. Agreste(ed), France

Agreste (2000) CD ROM Recensement agricole 2000 - La fiche comparative., Eds Agreste France

Angeletti L, Levi E (1997) Etudes comparatives des facteurs de transfert de l'eau, de l'iode et du strontium sur le ray-grass et le trèfle. Rapport CEA-R-4960, Commissariat à l'Energie Atomique, Saclay, France

Anselin L (1995) Local Indicators of Spatial Association — LISA, Geographical Analysis Vol 27. pp 93–115

Brisson N, Mary B, Ripoche D, Jeuffroy MH, Ruget F, Nicoullaud B, Gate P, Devienne F, Antonioletti R, Dürr C, Richard G, Beaudoin N, Recous S, Tayot X, Plénet D, Cellier P, Machet JM, Meynard JM, Delécolle R (1998) STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. Agronomie, 18: 311–346

Brisson N, Mary B (2002) STICS : Notice concepts et formalismes. Version 5.0. (eds) INRA, France

Chamberlain AC (1970) Interception and retention of radioactive aerosols by vegetation. Atmos Environ 4: 57–78

Hoffman FO (1989) Pasture grass interception and retention of 131I, 7Be and insoluble microspheres deposited in rain. OAK-RIDGE Laboratory, Environmental Sciences Division.

Jacquez GM, Goovaerts P, Rogerson P (2005) Space-Time intelligence Systems: Technology, applications and methods. J Geo Syst 7: 1–5

Mercat-Rommens C, Renaud P (2005) From radioecological sensitivity to risk management: the SENSIB project, second international conference radioactivity in the environment, nice.

Moran PAP (1950) Notes on continuous stochastic phenomena, Biometrika 37: 17–23

Mourlon C, Calmon P (2002) ASTRAL: a code for assessing situations after a nuclear accident. 12th annual meeting of SETAC Europe, Vienna 37: pp 12–16

Müller H, Pröhl G (1993) ECOSYS-87: a dynamic Model for assessing radiological consequences of nuclear accidents. Health Phy 64(3): 232–252