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Identifying the Relationships Between Agronomic and Radioecological Variables Using a Crop Model Applied to Lettuce

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Abstract: This research examines two common variables of radioecological computer codes for the land environment: crop yield (agronomic variable) and interception capacity (radioecological variable). The aim is to characterise their variability and bring to light any relationships between these variables and other input data for the transfer equation. The crop considered in this pilot study is field-grown lettuce, the most widely consumed variety of salad in France. The study is based on the crop model STICS developed by INRA, the French National Institute for Agricultural Research. STICS makes it possible to propose a daily follow up of the production of fresh biomass (yield) and the rate of vegetative cover, which has been linked with the interception capacity via the leaf area index. In our assessment of these variables, we were also able to account for the technical practices used to cultivate lettuce as well as the regional variations in agricultural conditions. The results obtained enable quantifying the relationships between growth time and yield at maturity and between the interception capacity and the development of lettuce.

Key words: Yield, interception capacity, growth time, lettuce, STICS

INTRODUCTION

Various computer codes have been developed in the radioecology community in order to evaluate the transfer of radionuclides to the different compartments of the ecosystem. These mathematical models are used to predict the outcomes of severe accidents and chronic pollution but also to perform simulations, as experiments are often costly or even impossible to conduct. A precise understanding of the input variables is therefore necessary to accurately characterise the consequences of the contamination scenario of interest and to assess the uncertainties associated with the results. To this end, it is important to determine the variability of each of the model's input variables and to quantify any potential relationships between them.

This study is based on ASTRAL (Assistance Technique en Radioprotection Post-Accidentelle) (Mourlon and Calmon, 2002), a radioecological model developed by the French Institute for Radiological Protection and Nuclear Safety (IRSN). The objective of this study is to characterise two variables from an equation used in the radioecological model, variables which mainly influence the sensitivity of the agricultural environment to radioactive pollution: crop yield (agronomic variable) and interception capacity (radioecological variable that quantifies the interception of the radioactive contaminant by the vegetative cover). More precisely, the main goal is to propose a range of values for these variables and to bring to light any relationships between these variables and other transfer equation input variables. The vegetable used for the methodological part of this study is field-grown lettuce, the most widely consumed variety of salad in France. In order to characterize both variables we use STICS, a crop model developed by the INRA Avignon Centre (Brisson *et al*., 1998, 2003). The simulations are carried out for two French regions with very different climates: Brittany and Provence (Fig. 1). This approach has already been used in radioecology to characterise the retention ratio and yield variables of other crop types: winter wheat (Mercat-Rommens *et al*., 2006) and permanent meadow (Durand *et al*., 2007). Applied to lettuce, STICS makes it possible to propose a daily follow up of the production of fresh biomass (yield) and the rate of vegetative cover, which has been linked with the interception capacity via the leaf area index.

MATERIALS AND METHODS

ASTRAL, radioecological model developed by the IRSN: Includes a computer module which uses geographical and radioecological databases (radionuclides transfer parameters into the environment). This model makes it possible to evaluate the impact of radioactivity deposition on agricultural produce (specific activities), on agronomic

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resources (surface area and other quantities affected such as crop tonnage) and on the populations (dose received) in areas affected by a possible nuclear accident.

The activity of the lettuce at harvest is based on the initial contamination and accounts for weather conditions on the day of deposition, radioactive decay between deposit and consumption and plant growth (activity dilution). In this case, for a radionuclide r, the activity due to foliar transfer is calculated as follows (Mourlon and Calmon, 2002):

$$C_{v,fol,r} = D_r\left(K_r.FTds_{v,r}.Dils_{Dat_D,H_p} + (1-K_r).FTdh_{v,r,H_p}.Dilh_{Dat_D,H_p}\right).e^{-(\lambda_{bw}+\lambda_r).t} \quad (1)$$

Where:
$C_{v,fol,r}$ (Bq kg^{-1}) = Specific activity (at harvest) resulting from foliar transfer
D_r (Bq m^{-2}) = Radionuclide deposition
K_r (sd) = Dry deposition as a proportion of total deposition
$FTds_{v,r}$, $FTdh_{v,r,Hp}$ (m^2 fresh kg^{-1}) = Transfer factors (for dry and rainy weather, respectively)
$Dils_{DatD,Hp}$, $Dilh_{DatD,Hp}$ (sd) = Protection factors if a greenhouse is used (for dry and rainy weather, respectively). Theses parameters are used to account for the protection afforded by the greenhouses used for vegetable production. In our study (field-grown lettuce), these parameters are not taken into consideration (assigned a value of 1 by default).
Dat_D (d) = Date of deposition
Hp (mm) = Precipitation rate
λ_{bw} (d^{-1}) = Biomechanical decay constant of the radionuclide for the plant. Changes in activity during the days following deposition are modelled by an exponential decay characterised by λ_{bw}. This decay takes into account foliar leaching and the plant's biological growth.
λ_r (d^{-1}) = Physical decay constant of the radionuclide
t (d) = Period between deposition and harvest

Contamination (specific activity) is essentially determined by the direct transfer factor. This parameter includes interception and translocation process when the plant organ eaten is not directly exposed to contamination (e.g., potatoes), as well as resuspension. In the case of lettuce, for which there are no translocation process, the factors for direct transfer via dry or wet deposition can be broken down as follows, where the two main variables of the model are interception capacity and yield:

$$FTds_{v,r} = RCs_{v,r}/Yld_v \qquad FTdh_{v,r,H_p} = RCh_{v,r,H_p}/Yld_v$$

Where:
$Rcs_{v,r}$, $RCh_{v,r,Hp}$ (sd) = Interception capacity, for dry weather and rainy weather, respectively
Yld_v (fresh kg m^{-2}) = Crop yield at harvest time

Only the dry weather transfer factor figured in our study. The corresponding variables were thus evaluated by means of the STICS crop growth model. This approach has already been used in radioecological studies, enabling characterisation of the interception capacity and yield variables for other crops: winter wheat (Mercat-Rommens *et al*., 2006) and permanent grassland (Durand *et al*., 2007).

STICS, agronomic model developed by INRA (Avignon centre): STICS is a daily crop growth model (Brisson *et al*., 2003). Its input variables relate to climate, soil and technical management. Its output variables relate to production (quantity and quality), environment and changes in soil characteristics under the influence of cultivation. STICS was designed as an operational simulation tool in agricultural conditions. Its main objective is to simulate the consequences of variations in environment and farming methods on the production from an agricultural plot over the course of a year. Crops growths are evaluated globally by their above-ground biomass and nitrogen content, their leaf area index and the number and biomass of organs harvested (and their nitrogen content).

The soil is considered as a succession of horizontal layers, each characterised by its water reserve and its inorganic and organic reserves. Interactions between the soil and the crops are facilitated by the roots, which are defined by the root density distribution in the soil profile. The model simulates the system's carbon, water and nitrogen balances and allows the calculation of the agricultural variables (yield, input consumption) and the environmental variables (loss of water and nitrates) in various agricultural situations.

The interception capacity in dry weather conditions (RCs): Also known as the interception factor, corresponds to the fraction of the total activity deposited (in dry conditions) that is intercepted by the above-ground part of the plants. It can also be estimated using the leaf area index, defined as the surface area likely to collect aerosols, i.e., leaf area per soil surface unit. Therefore, leaf surface area is considered at all levels of vegetation; the total is expressed per soil surface unit (m^2 leaf area/m^2 soil), independently of the photosynthetic activity of the leaves. Hence this definition differs from the agronomical definition, which only considers the surface areas of green leaves.

The variable selected to characterise the plant development stage is the leaf area index and the relation used to express the dry interception capacity is as follows:

$$\mathrm{RCs} = \frac{\mathrm{LAI_i}/\mathrm{LAI_{imax}}}{(\mathrm{LAI_i}/\mathrm{LAI_{imax}}) + (\mathrm{Vg_s}/\mathrm{Vg_{imax}})} \qquad (2)$$

Where;

LAI_i	= Leaf area index of the plant i
LAI_{imax}	= Maximum leaf area index of the plant i
Vg_i (m sec^{-1})	= Deposition rate of the plant i
Vg_s (m sec^{-1})	= Deposition rate on soil, a constant for all plant type
Vg_{imax} (m sec^{-1})	= Maximum deposition rate on the plant i

This equation is taken from ECOSYS-87, a German radioecological model (Müller and Pröhl, 1993). It makes it possible to calculate, for dry weather conditions, the deposition on the plant and the total deposition (ratio gives the interception capacity) by postulating that a radioactive deposit on any surface is the product of the deposition rates for a concentration of radionuclides in the air and that the deposition rate on the plant depends on its foliar development. The rate of deposition on the plant depends on the foliar development at the time of deposition and at maximum foliar development. However, as there was no correlation between Vg_{imax} and LAI_{max}, the parameter Vg_i was considered a constant. For leaf vegetables and radionuclide deposition in the form of aerosols, Müller and Pröhl (1993) recommend using the value 2 mm sec^{-1} for Vg_{imax}. The rate of deposition on the soil, Vg_s, is considered a constant for all types of plants and takes the value 0.5 mm sec^{-1}.

In the case of lettuce, given its rounded shape, the leaf area index ordinarily used for radiation interception is replaced, in the STICS model, by the rate of vegetative cover. For the cultivation of lettuce, the STICS crop model provides values for the rate of vegetative cover rather than LAI directly. The relationship between these two quantities can nonetheless be deduced from the work of De Tourdonnet (1998) related to the control of the quality and nitrate pollution for lettuce production in plastic greenhouses. De Tourdonnet developed a complete agrosystem model which integrates environmental heterogeneity and proposed the following relation to link absorption efficiency of a lettuce and LAI:

$$\varepsilon a = \varepsilon a_{max} \times (1 - e^{-k \times LAI}) \qquad (3)$$

Where:

εa	= Radiation absorption efficiency
εa_{max}	= Maximum radiation absorption efficiency
k	= Radiation extinction coefficient for vegetative cover (characteristic parameter for the species)

This relation is based on Beer's radiation extinction law and its validity reposes on the hypothesis that foliar surfaces are randomly distributed in space. According to De Tourdonnet (1998), the value of parameter k is around 0.68±0.02. For present study, this parameter was set at 0.6 (default value in the STICS crop model).

De Tourdonnet (1998) also expressed absorption efficiency as a function of the rate of vegetative cover (TAUXCOUV), according to the following relations:

$$\varepsilon a = \begin{cases} f \times \mathrm{TAUXCOUV}^2 & \text{if TAUXCOUV} < 77\% \\ \mathrm{TAUXCOUV} \times (1 - R) & \text{if TAUXCOUV} \geq 77\% \end{cases} \qquad (4)$$

where, R corresponds to the reflectance of the vegetative cover (set at 0.08) and f is a parameter whose value is estimated at 1.196 (De Tourdonnet, 1998).

These two relations enable linking the rate of cover, TAUXCOUV, with the foliar index, LAI and to express LAI as a function of the rate of cover, as in the following equations:

$$\mathrm{LAI} = \begin{cases} -\frac{1}{k} \times \log\left(1 - \frac{f \times \mathrm{TAUXCOUV}^2}{\varepsilon a_{max}}\right) & \text{if TAUXCOUV} < 77\% \\ -\frac{1}{k} \times \log\left(1 - \frac{\mathrm{TAUXCOUV} \times (1 - R)}{\varepsilon a_{max}}\right) & \text{if TAUXCOUV} \geq 77\% \end{cases} \qquad (5)$$

where, is the maximum radiation absorption efficiency, set at 0.92 (De Tourdonnet, 1998).

Both equations give rise to two relations which express dry interception capacity as a function of the rate of vegetative cover:

If TAUXCOUV < 77%:

$$\mathrm{RCs} = \frac{\left.\dfrac{-\log\left(1 - \frac{f \times \mathrm{TAUXCOUV}^2}{\varepsilon a_{max}}\right)}{k}\middle/ \mathrm{LAI_{max}}\right.}{\left(\left.\dfrac{-\log\left(1 - \frac{f \times \mathrm{TAUXCOUV}^2}{\varepsilon a_{max}}\right)}{k}\middle/ \mathrm{LAI_{max}}\right.\right) + \left(\mathrm{Vg_s}/\mathrm{Vg_{imax}}\right)} \qquad (6)$$

If TAUXCOUV ≥ 77%:

$$\mathrm{RCs} = \frac{\left.\dfrac{-\log\left(1 - \frac{\mathrm{TAUXCOUV} \times (1 - R)}{\varepsilon a_{max}}\right)}{k}\middle/ \mathrm{LAI_{max}}\right.}{\left(\left.\dfrac{-\log\left(1 - \frac{\mathrm{TAUXCOUV} \times (1 - R)}{\varepsilon a_{max}}\right)}{k}\middle/ \mathrm{LAI_{max}}\right.\right) + \left(\mathrm{Vg_s}/\mathrm{Vg_{imax}}\right)} \qquad (7)$$

Equation 6 and 7 thus enable reconstructing dry interception capacity via the rate of vegetative cover (TAUXCOUV), an output parameter of the crop software STICS, by integrating weather, soil and farming conditions variabilities.

The yield variable (Yld): Or yield of above-ground biomass, corresponds to the mass of the plant (in fresh kilograms per square metre of soil) at harvest. Yld is a direct output variable of the STICS model.

Simulations performed with STICS and data used: The STICS model has been downloaded from INRA's Internet site (Avignon centre), http://www.avignon.inra.fr/stics/. It provides access to several input files which contain a parameter database required for use of the model. It is important to modify certain default values therein, in order to test several scenarios of lettuce growth and to account for different sources of variability (climate, lettuce variety, farming conditions, etc.). The values for these parameters were provided by various French agricultural institutes, associations.

Climate data: To identify any potentially significant variations in lettuce cultivation, two stations with very different climates were selected: Orange, with a Mediterranean climate and Rennes, with an oceanic climate (Fig. 1). The oceanic climate is characterised by mild winters (10°C on average) which are very humid and marked by intermittent rain, especially drizzle; summer weather is much drier but very cool (not more than 23°C on average). In contrast, the Mediterranean climate is uneven in terms of precipitation; very heavy rains in the spring and fall may cause flooding, while there is practically no precipitation the rest of the year. As for temperatures, they are very high in the summer (40°C occasionally) and mild in the winter (16-17°C). We used daily climate data for a calendar year (2005), which were specific to the sites selected for the simulation (Météo France, 2005). These included minimum and maximum daily temperatures, daily global radiation, evapotranspiration and daily precipitation.

Soil data: Information on the soil characteristics relevant to the simulations (clay content of the surface layer, pH, albedo of bare soil in dry conditions, evaporation limit of the potential evaporation phase of the soil, etc.) are provided by default in the STICS model. These values are actually associated with a specific lettuce crop cultivated as part of INRA experiments. However, other simulations have been conducted for validation purposes using regional values from a database maintained by the

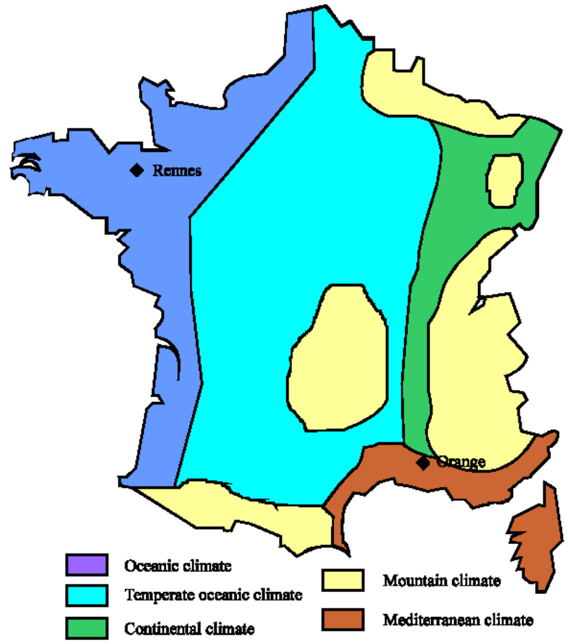

Fig. 1: Schematic representation of the different French climate. We can distinguish different types of climate in France: Oceanic climate, Temperate oceanic climate, Continental climate, Mountain climate and Mediterranean climate

Association Française pour l'Etude des Sols (AFES). The rates of vegetative cover thus obtained are very low and deviate from agronomic values (INRA, personal communication). These results appear to be linked to the water stress parameters in the STICS crop model. It has been therefore considered preferable to use the default values of the STICS model.

Physiological and agronomical data: Setting parameters for the technical itinerary is very important because crop development depends in large degree on the technical practices used.

For both climates, soil preparation takes place immediately prior to planting, generally the day before (successful planting is noticeably dependent on freshly prepared soil). For the Orange region, supplementary organic matter is required (APREL, personal communication). Because records of prior cultivation were scarce, default values from the STICS crop model were used for residue of preceding cultivation in the Orange region. Supplementary organic matter is not required in the Rennes region (AGRIAL, personal communication).

The sowing date of the lettuce in the STICS model corresponds to the planting of a young lettuce seedling at the two-leaf stage. The STICS crop model encompasses several specific practices along the technical itinerary, for example plastic mulching (which is used only for thermal protection). This option is therefore used in the itineraries of lettuce planted under plastic sheets between February and March and also between August and November. The planting dates used in our study were based on correspondence with CTIFL engineers and on (Thicoïpé, 1997). Twenty three planting dates were selected for the Orange region, between weeks 9 and 36. For the Rennes region, lettuce plantings were spaced between week 6 (early February) and week 35 (late August) (AGRIAL, personal communication) that is to say 27 planting dates. The Rennes period includes different cycles: from week 6 to week 18, lettuce plants are covered with plastic; weeks 20 to 31 constitute the period of spring lettuce and weeks 32 to 35, the period of summer lettuce. The STICS model then provides dates for the development phases of lettuce, especially for the phase of maximum vegetative cover. Harvest takes place at the phase when the lettuce is with a good heart. This phase is not mentioned in the STICS model but corresponds to the phase of maximum vegetative cover. Therefore, in order to obtain the date of peak vegetative cover, it is enough to specify that harvest takes place at physiological maturity.

For the two regions, we chose the irrigation forcing option. For Orange, the dates of irrigation were calculated based on rainfall data from Météo France: irrigation (supplying 5 mm) will take place the day of planting and on days where an additional water supply is necessary for good plant development. For the Rennes region, irrigation practices are slightly different. Vegetable producers irrigate based on climate conditions, but also every day of the week during which planting takes place, supplying 10 mm per watering (AGRIAL, personal communication).

For the Orange region, the data concerning fertilisation were provided to us by the CTIFL. We used this data for the Julian days of application and for the quantities of inorganic nitrogen used on the plants (unit: kg N ha^{-1}), which makes it possible to adjust this technical parameter to real cultivation practices. In the case of lettuce, nearly all applications took place in the beginning, e.g., when the young lettuce plants were sown. In the Orange region, 30 nitrogen units were supplied the day of planting. According to AGRIAL, Rennes vegetable producers always fertilise their lettuce at planting, but the quantities differ based on the corresponding cycle (thermal protection, spring lettuce or summer lettuce…). Winter lettuce (covered in plastic) generally receives 650 kg ha^{-1} of nitrogen fertiliser, which corresponds to a nitrogen solution and contains 15% nitrogen, equivalent to 97 units of inorganic nitrogen. For summer lettuce, 75 units of nitrogen are applied (500 kg ha^{-1} of 15/5/20 fertiliser, N/P/K fertiliser composed of nitrogen, phosphorus and potassium) and spring lettuce receives 60 units (400 kg ha^{-1} of 15/5/20 fertiliser). However these quantities may vary based on the location of production.

RESULTS AND DISCUSSION

Fifty datasets were simulated using the STICS crop model (23 from the Orange region and 27 from the Rennes region). The results for each of these samples are presented below, in particular the various relationships between the interception and yield variables.

Relationship between yield and growth time: The results obtained from the various simulations conducted using the STICS crop model (one for each planting date) provide information on daily changes in the biomass produced (in tonne per hectare of dry matter), from the seedling phase until harvest. For the purposes of our study, we are only concerned with yield values at commercial maturity because the contamination of the plants is evaluated when they are ready for consumption. Most radioecological models for the transfer of radioactivity to plants express radioactive contamination in becquerels per fresh kilogram. We therefore changed units, converting the STICS yield values (at plant maturity) from t ha^{-1} of dry matter to kg m^{-2} of fresh matter. A mean value of the fresh weight dry weight ratio for leaf vegetables (18) was used for this unit conversion calculated using data from the SYLVESTRE database (Duffa *et al*., 2007) (database of environmental radioactivity measurements collected as part of field studies conducted by the IRSN). This value corresponds to around 94% water in the fresh weight, which is consistent with the value of 92% (Quinault *et al*., 1989). We obtained different yield values from the Rennes and Orange regions and various statistics were calculated: minimum (2.250), maximum (9.234), first, second and third quartiles (3.461, 4.329 and 5.909) as well as the mean (4.898). According to Thicoïpé (1997), the mean yield for lettuce is 4.2 kg m^{-2} of fresh matter; the mean value obtained (4.9 kg m^{-2} of fresh matter) is therefore consistent with the bibliographic data.

The graphic representation of the yield data according to the time of growth of lettuce revealed a linear relationship between these two variables. The linear regression parameters (slope and y-intercept) were estimated using the least-squares method (with the function lm( ) from the statistical software R (Ihaka and Gentleman, 1996)) and their significance was tested using a Student's t-test. The y-intercept can be considered as nil and the results relative to the estimate of the slope are: slope estimation (0.117), estimation of the standard deviation for the estimated value (2.867E-03), value of Student's t-statistic (40.8) and p-value (<2E-16). The equation for the estimated regression line is:

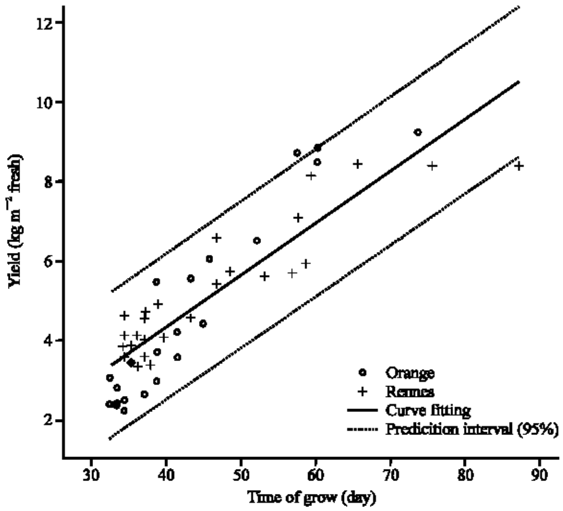

Fig. 2: Linear regression with the yield variable and the growth time variable. The dotted straight lines represent the 95% prediction interval for the regression line

$$\hat{Y}ld = 0.117 \times T_C \quad (8)$$

where, $\hat{Y}ld$ represents the estimated yield and T_c, the growth time for lettuce.

After verifying the normality of residuals, we determined the 95% prediction interval for the regression line. All these results are shown in Fig. 2.

Relationship between dry interception capacity and lettuce development: According to Eq. 6 and 7, dry interception capacity is a function of the rate of vegetative cover. Since this variable can be expressed as a function of time, interception capacity also becomes a function of time. Throughout the plant's growth phase, the interception capacity has different values, continuing to change from the moment the plant emerges from the soil (0) until it reaches commercial maturity (maximum plateau close to 1).

For the 50 datasets studied, we calculated the statistics for all interception values obtained: minimum (0), maximum (0.8), first, second and third quartiles (0.024, 0.695 and 0.8) as well as the mean (0.478). The dry interception capacity varies between 0, obtained just after planting (the first two leaves produce a rate of vegetative cover which is practically nil) and 0.8, once maximum cover is reached. The mean value (0.478) is consistent with that of 0.5 for leaf vegetables in the FOCON computer code (Rommens *et al.*, 1999) and slightly superior to the value of 0.3 in the FARMLAND code (Brown and Simmonds, 1995). The representation of dry interception capacity as a function of lettuce development, for all datasets studied, reveals a sigmoid relationship between these two variables (Fig. 3).

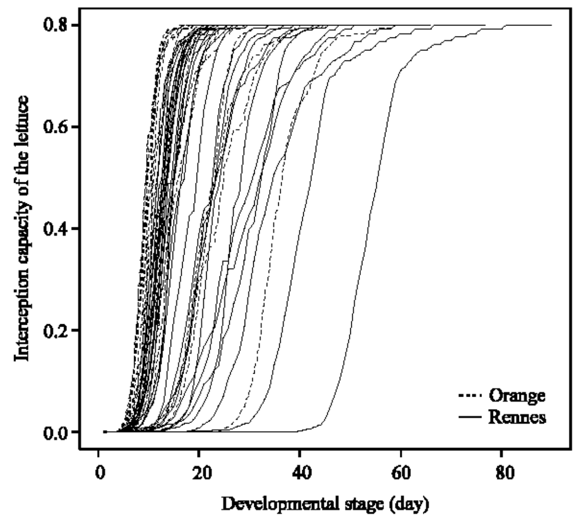

Fig. 3: Representation of dry interception capacity as a function of lettuce development, for all datasets studied. This representation reveals a sigmoid relationship between these two variables

For each simulation set, we performed a non-linear regression between interception capacity and plant development. The data observed were approximated by a sigmoid function with the following equation:

$$R\hat{C}s = \frac{0.8}{1 + e^{-b(Dv+a)}} \quad (9)$$

where, $R\hat{C}s$ represents the estimated interception capacity and Dv, the development of the plants (in days). In order to propose variation ranges for interception capacity based on the different values for lettuce growth times, parameters a and b were estimated by a method of numerical minimisation (using the function nls( ) from R software). The statistical analysis of the various estimation results reveals the following:

- A linear relationship between parameter a and growth time: the greater the growth time, the greater the distance between the origin and the curve's centre of symmetry,
- A linear relationship between parameter b and growth time (via logarithmic transformation of the two variables): the estimated values of parameter b tend to decrease as growth time increases.

The results of the parameter estimations for these two regression lines are (intercept, slope):

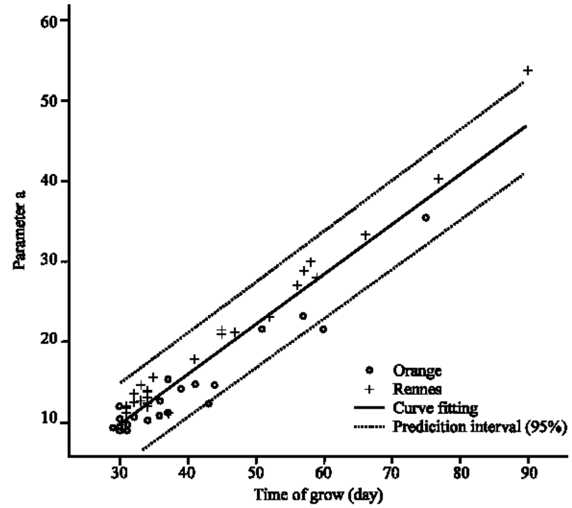

Fig. 4: Linear regression with the parameter a and the growth time of lettuce. The dotted straight lines represent the 95% prediction interval for the regression line

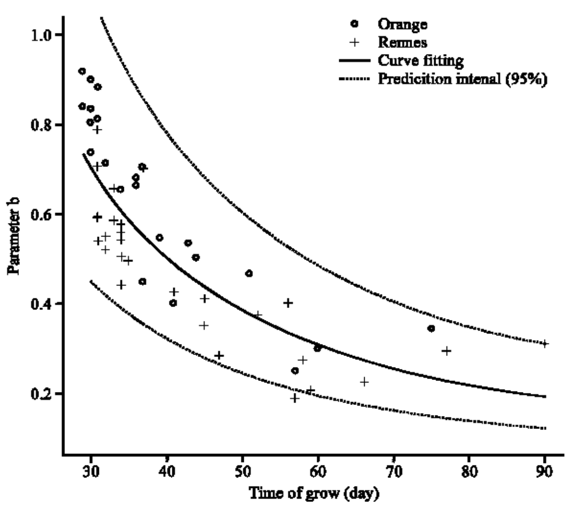

Fig. 5: Nonlinear regression with the parameter b and the growth time of lettuce. The dotted straight curves represent the 95% prediction interval for the regression curve

- Estimated value (-8.939, 0.621), estimation of the standard deviation for the estimated value (1.144, 0.026), value of Student's t statistic (-7.814, 24.181) and p-value (4.21E-10, <2E-16),
- Estimated value (3.6737, -1.1833), estimation of the standard deviation for the estimated value (0.3904, 0.1053), value of Student's t statistic (9.411, -11.240) and p-value (1.78E-12, 4.81E-15).

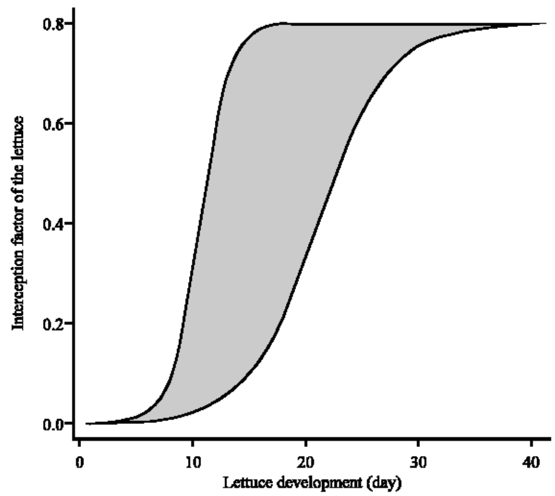

Fig. 6: Variability of the interception capacity of a lettuce plant with a growth time of 40 days

The normality of residuals was verified for both cases. Confidence intervals of 95% were determined. All these results are shown in Fig. 4 and 5.

These two relationships can be used to propose variation ranges for parameters a and b in Eq. 9 based on the different values for lettuce growth time. By combining these values, a range of likely values for the RCs variable can be proposed for a given growth time. For example, if lettuce growth time is 40 days, the variability of the change in dry interception capacity according to plant development can be reconstructed (Fig. 6).

CONCLUSION

The object of this study was to propose a methodology for characterising input variables from radioecological computer codes and to determine the relationships between these variables. By using the STICS crop model, we were able to characterise the variability of the agronomic yield variable directly and that of the radioecological interception variable by using the STICS output parameter for vegetative cover. We were also able to identify and quantify two relationships between the variables studied and other variables implicitly involved in the transfer model equation: a linear relationship between growth time and yield at commercial maturity and a non-linear sigmoid relationship between the lettuce's dry interception capacity and its development (which varies according to growth time).

These two types of variables (agronomic and radioecological) are used in radioecological models of radioactivity transfer to plants and play a decisive role in the degree of plant contamination. For the case of lettuce, the results of this study can be used directly in radioecological models, in order to:

- Estimate as accurately as possible the radioactive contamination of plants for simulation studies,
- Perform statistical analyses (sensitivity or uncertainties analysis) for which an accurate understanding of the key agronomical and radioecological variables controlling the radioactive contamination in plants is essential.

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