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RESEARCH ARTICLE

First cropping system model based on expert-knowledge parameterization

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Abstract

Models are promising tools to support the design of cropping systems toward sustainable agriculture. Process-based deterministic models are predominantly used, whereas most of them involve a limited range of crop techniques, and are unsuited to organic agriculture. Moreover, their parameterization and local adaptation require a large amount of experimental data. We thus designed a model simulating the yields of successive crops, taking into account the effects of most crop techniques embedded in a cropping system, and suited for both conventional and organic farming. This model was designed assuming that its parameterization, mostly based on expert-knowledge elicitation, could enlarge the range of environmental conditions and crop techniques considered. The PerSyst model involves three types of parameters based on expert knowledge: (i) reference yields reached in the most common cropping system conditions, (ii) yield change due to crop sequence variation, and (iii) yield change due to variation in crop management. These parameters are stochastic to report yield variability across climatic years. The model was parameterized through an original expert elicitation method—combining individual interviews and collective validation—on three case studies, including one in organic farming. Model accuracy was assessed for two long-term experiments. Parameters such as yield change due to crop sequence and to crop management were close among case studies, highlighting possibilities to compensate for a local lack of knowledge. Moreover, simulated yields in both experiments showed great consistency with observed yields, with average relative root-mean-square error of prediction of 15% for winter wheat and faba bean for example. For the first time, thanks to expert-knowledge parametrization, we built a cropping system model, considering all techniques, which could be easily tailored to a diversity of conditions, both in conventional and organic farming. Lastly, advantages and limits of the PerSyst model to assess innovative cropping systems were discussed.

Keywords Arable crops · Yield · Crop management plan · Crop sequence · Organic farming · RMSEP

1 Introduction

Major changes in the current cropping systems are required to face numerous challenges, such as environmental preservation (Millenium Ecosystem Assesment 2005), food security, and economic value-creation. Models are often used to simulate a large number of alternatives and quickly assess their performances (Rossing et al. 1997; Sadok et al. 2008), as the number of alternatives tested in system-experiments cannot be high (Colnenne-David and Doré 2015).

Two types of models have been developed for the design or *ex ante* assessment of cropping systems. The first type relates to mechanistic and dynamic soil-crop models, such as DSSAT (Jones et al. 2003) or CROPSYST (Stockle et al. 2003) for arable cropping systems. They generally concern a low range of crop techniques, compared to those existing in farmers' fields, and apply mainly to those dealing with water and nitrogen stresses. A few models deal with soil tillage, preceding crop effect, or pest management (e.g., Florsys for weed management in Gardarin et al. 2012), but to our knowledge, none

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addresses incidence on crop yields. As these models are highly sensitive to environmental conditions, they require large amounts of input data and extensive preliminary experiments, although experimental data are not always available in the environmental conditions in which cropping systems are to be designed or assessed. This reliance on input data could limit their use, as Plaza-Bonilla et al. (2015) and Jones et al. (2003) have pointed out.

The second type of models is based on input-output relationships derived from production ecology theory (Van Ittersum and Rabbinge 1997). These models include TCG_CROP (Rossing et al. 1997), ROTOR (Bachinger and Zander 2007), and ROTAT (Dogliotti et al. 2003). Only three sets of parameters are usually required to estimate crop yield: parameters related to potential yield, to yield losses due to limiting factors (i.e., water and nutrient availability), and to yield losses due to reducing factors (i.e., weeds, pests, and diseases). Most of these models also rely on experimental data, but in some of them, parameterization relies on expert knowledge, thus enlarging the range of crop techniques and environments considered (De Wispelare et al. 1995; Girard and Hubert 1999). This makes it possible to assess cropping systems using innovative combinations of crop techniques for which experimental data are scarce, and aiming at achieving a set of goals, such as cropping systems aiming at decreasing the use of pesticides while maintaining profitability (Jacquet et al. 2011). To our knowledge, only a few applications have been developed for specific targets in agronomy. They deal with the encoding of expert knowledge on grazing management in a model (Girard and Hubert 1999) and with the elicitation of expert knowledge to evaluate agricultural production systems (Cornelissen et al. 2003). In Adam et al. (2013), expert knowledge is even used for crop model reassembly. However, none of these examples simulates crop yield considering both crop sequence and crop management effects.

The aim of this study is to design the PerSyst model for arable cropping systems, both for conventional farming (CF) and organic farming (OF) conditions. This model aims at simulating crop yields taking into account most of the components of cropping systems. To reach this target, the PerSyst model combines both process-based and input-output sub-models, and both stochastic and deterministic parameters. To parameterize such a model, we first built and implemented an expert elicitation-based method at a local scale (region or *département*) and assessed its reproducibility through three case studies. We then assessed the predictive capacity of PerSyst for two long-term experiments in organic farming (Fig. 1).

Fig. 1 Field of winter wheat under organic farming in the Île-de-France region

2 Materials and methods

2.1 General organization of the PerSyst model

PerSyst simulates the effects of the whole cropping system (i.e., a crop sequence and the crop management of each crop) on the yield of each individual crop (Fig. 2). The time step of simulation is the year. For each simulation, input variables include location, soil type, climate, and a description of the cropping system to be simulated. The outputs are yields achieved for each crop. PerSyst is composed of five sub-models: (i) reference yield sub-model, (ii) crop sequence sub-model, (iii) N requirement sub-model, (iv) crop N management sub-model, and (v) crop management sub-model (Fig. 2). For three sub-models among five, parameters are represented by distributions, taking into account the major part of yield variability across years. As the model is stochastic, a simulation is composed of several iterations; the number of which is to be defined by the user. Thus, each iteration results in a single output value for predicted yield, randomly sampled from these distributions, and a given simulation results in a distribution of actual yield gathered from iterations.

2.2 Sub-models of the PerSyst model

2.2.1 Reference yield sub-model

This sub-model estimates the reference yield for each crop, which is the yield supposed to be achieved within a crop sequence widely practiced by farmers, and with a crop management that aims at minimizing yield losses due to limiting and reducing factors, as much as

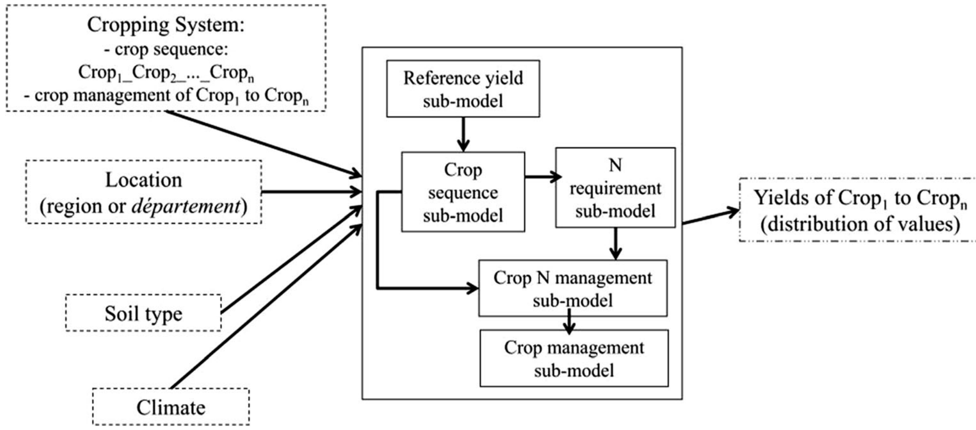


Fig. 2 Inputs, outputs, and sub-models of the PerSyst model

possible on farm conditions. The input variables for this sub-model are soil type (i), nature of the crop (j), and location (a given case study). The output variable of this sub-model is the reference yield (Y_REF_{ij}). Parameters of this sub-model represent minimum and maximum values, and the probability distribution reflecting variability across years. At each iteration, Y_REF_{ij} is calculated from Eq. (1).

$$Y\_REF_{ij} \text{ is sampled from } y\_ref\_dist_{ij} \text{ in } [y\_ref\_min_{ij} : y\_ref\_max_{ij}] \tag{1}$$

with

Y_REF_{ij}	Reference yield (t ha^{-1}) for a crop j grown in a soil type i
$y\_ref\_dist_{ij}$	Reference yield distribution between $y\_ref\_min_{ij}$ and $y\_ref\_max_{ij}$ for a crop j grown in a soil type i
$y\_ref\_min_{ij}$ and $y\_ref\_max_{ij}$	Reference yield (t ha^{-1}) for a crop j grown in a soil type i in years with unfavorable or favorable climatic conditions, respectively

2.2.2 Crop sequence sub-model

This sub-model calculates yield change due to the crop sequence from the reference yield Y_REF_{ij}. It takes into account the preceding crop (k) effect (Sebillotte 1990), and the effect of the duration (l) of the period between the crops susceptible to the same diseases or pathogens in the crop sequence. Changes could be losses, as well as gains, for crop sequences respectively less or more favorable than those widely practiced by farmers and used as a reference in the previous step. The input variables of this sub-model are the nature and order of crops in the crop sequence. For each iteration, yield changes are randomly sampled from a uniform distribution. The output data is the yield within the crop sequence (Y_CS_{ijkl}), calculated from Eq. (2):

$$Y\_CS_{ijkl} = Y\_REF_{ij} + YC\_CSP_{ijk} + YC\_CSR_{ijl} \tag{2}$$

with

Y_CS_{ijkl}	Yield of the crop j in the soil type i after the crop k for a return time l, within the crop sequence (t ha^{-1})
YC_CSP_{ijk}	Yield change (t ha^{-1}) due to the preceding crop effect, for a crop j grown in a soil i after a preceding crop k, randomly sampled between $yc\_csp\_min_{ijk}$ and $yc\_csp\_max_{ijk}$
$yc\_csp\_min_{ijk}$ and $yc\_csp\_max_{ijk}$	minimum and maximum yield losses due to the preceding crop effect,
YC_CSR_{ijl}	Yield change (t ha^{-1}) due to the return time of a crop i in a soil j for a return time l randomly selected between $yc\_csr\_min_{ijl}$ and $yc\_csr\_max_{ijl}$ (respectively, minimum and maximum yield losses due to the return time).
$yc\_csr\_min_{ijl}$ and $yc\_csr\_max_{ijl}$	respectively minimum and maximum yield losses due to the return time.

2.2.3 Nitrogen requirement sub-model

This process-based sub-model estimates the amount of nitrogen (X_MAX_{ijklm}) required to achieve the crop sequence yield Y_CS_{ijkl} according to the balance-sheet method. It takes into account nitrogen supply from mineralization of soil organic matter and of the residues of the preceding cash crop and preceding cover crop (Meynard et al. 1997). The input variables are the nitrogen requirement per ton of yield of the crop

(j), the characteristics of the soil (i) (i.e., organic matter, clay, limestone, and stone contents), the nature of the preceding crop (k), and cover crop (m), the residue management techniques and average temperature, as a driver of mineralization process (see Eq. 3). This sub-model is not fully described here, as it is based on equations and parameters already described by Bockstaller and Girardin (2008).

$$X\_MAX_{ijklm} = Y\_CS_{ijkl}.\mathrm{b}_j + N\_SSmin_i - N\_SSEW_{jk} - N\_SM_{ij} - N\_ICM_{jm} - N\_PCM_k - N\_ABS_j \tag{3}$$

with

- X_MAX_{ijkm} Amount of nitrogen required by crop j in soil i after preceding crop k and preceding cover crop m to achieve yield within the crop sequence (kg $_N$ ha^{-1})
- b_{ji} Amount of nitrogen required to achieve one unit of yield of crop j (kg $_N$ t^{-1})
- N_SSmin_i Minimum nitrogen soil status for soil i (kg $_N$ ha^{-1})
- N_SM_{ij} Amount of nitrogen from the mineralization of soil organic matter for soil i (as a function of organic matter, clay, limestone and stone contents, and average annual temperature) available for crop j (kg $_N$ ha^{-1})
- N_SSEW_{jk} Nitrogen soil status at the end of winter between preceding crop k and crop j (kg $_N$.ha^{-1})
- N_ICM_{jm} Amount of nitrogen from the mineralization of residues from cover-crop m preceding crop j (kg $_N$ ha^{-1})
- N_PCM_k Amount of nitrogen from the mineralization of residues from preceding crop k (kg $_N$ ha^{-1})
- N_ABS_j Amount of nitrogen absorbed in autumn by crop j (kg $_N$ ha^{-1})

2.2.4 Crop nitrogen management sub-model

This sub-model simulates yield change of each crop according to the nitrogen rate applied, based on the crop yield response according to a "linear_plus_plateau" model (Makowski et al. 1999; Makowski et al. 2001). The input variable is the total nitrogen rate applied. The output variable is the yield including nitrogen management (Y_N_{ijklm}), calculated from Eq. (4).

$$\begin{aligned} &\text{If } X \geq X_{MAX},\ Y\_N_{ijklm} = Y\_CS_{ijkl} \\ &\text{else } Y\_N_{ijklm} = Y\_CS_{ijkl} - a_j\left(X\_MAX_{ijkm} - X_i\right) \end{aligned} \tag{4}$$

with

- Y_N_{ijklm} Yield including nitrogen management (t ha^{-1}) for a crop j in soil i after preceding crop k and preceding cover crop m
- a_j Yield loss (t ha^{-1}) per missing kilogram of nitrogen for a crop j (estimated by Makowski et al. 2001 for winter wheat and corn and from expert knowledge for the other crops).
- X_i Total amount of nitrogen applied in the form of inorganic nitrogen fertilizer or manure (kg $_N$ ha^{-1})

2.2.5 Crop management sub-model

This sub-model simulates yield change of each crop as a function of the combination of crop management techniques applied to it. Crop management techniques such as sowing period, cultivar choice, and pest management techniques are characterized through options, as proposed in Loyce et al. (2002). For example, the "sowing date" options could be "standard," "advanced," or "delayed," depending on the reference sowing period defined for the considered location. Cultivar choice options could be, for the case of winter wheat (*Triticum aestivum* L.), "high productivity and high sensitivity to lodging," and "low productivity and low sensitivity to lodging," etc. Insecticide, fungicide, or growth regulator application options could be: "no" or "yes" or "no", "light", "standard," or "enhanced".

Each simulated crop management plan is converted into qualitative scores characterizing yield change, through a decisional tree based on the DEXi software (Bohanec and Rajkovic 1990). Leaves of the tree are crop techniques, and trunk is yield change (Fig. 3a, b). Crop techniques are gathered into intermediate variables (e.g., lodging risk), which are described by utility functions, allocating an intermediate qualitative score of yield change (e.g., yield change due to lodging). For a given crop, the structure of the tree is to be adapted from one region to another. The final score (yield change due to sowing, pests, and lodging (Fig. 3a)) is then converted into a quantitative yield change value, randomly selected from a uniform distribution. The output variable of this sub-model is the yield, including the crop management effect (Y_CM_{ijklmn}), calculated from Eq. (5).

The direct effect of N fertilizer applications on yield is not considered in this sub-model as it is already taken into account in the previous one. Here, N fertilization only influences lodging, or increases pest incidence for N rates exceeding X_MAX_{ijklm}. Conversely, even if a crop sequence sub-model was described previously, several characteristics of the crop sequence are considered in this sub-model, in order to take into account the mitigation of a crop sequence effect by an appropriate crop management. For example, we included the effect of an enhanced fungicide protection of winter wheat to partly compensate for the unfavorable effect of a preceding cereal. Another example concerns how weeding can

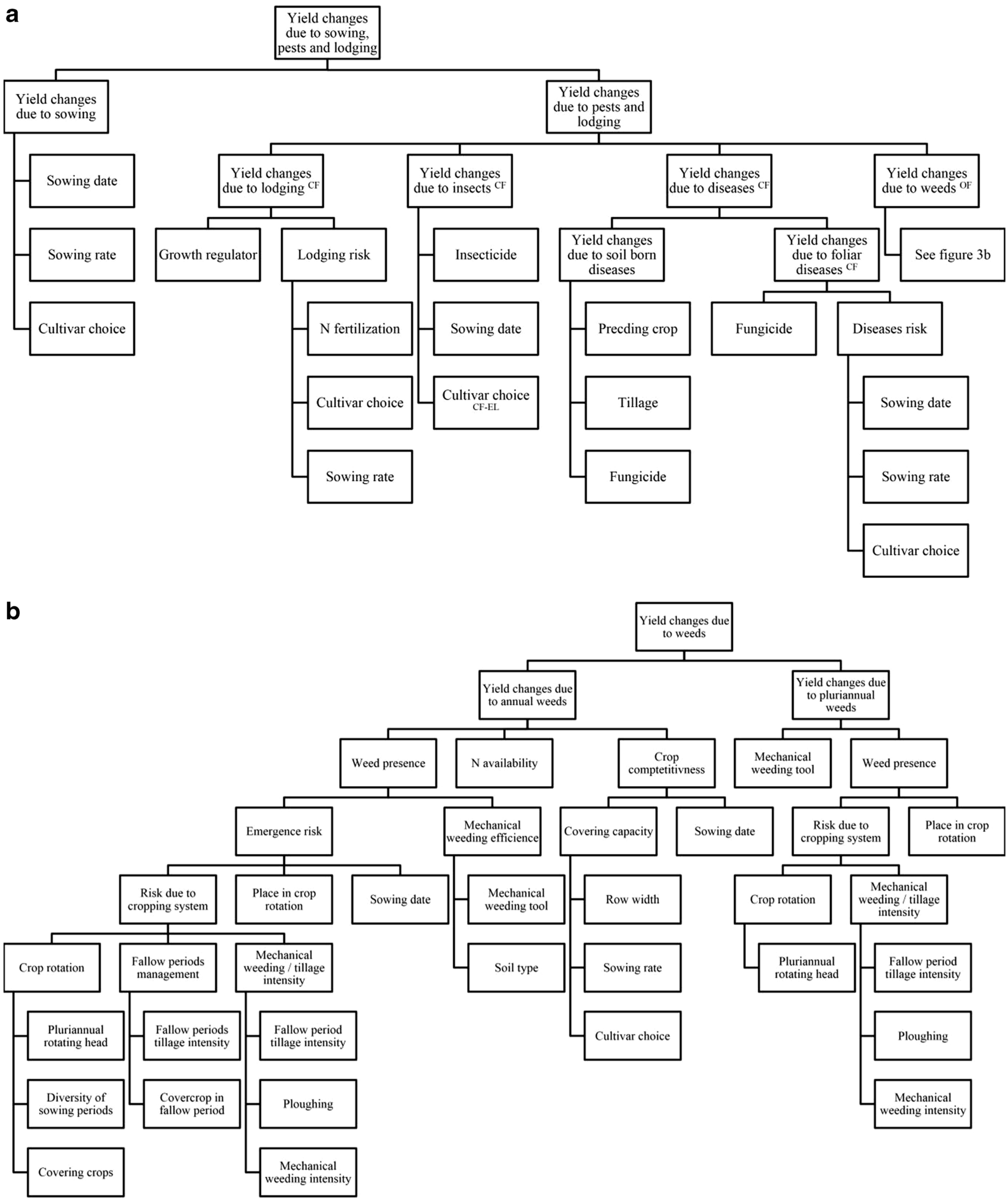


Fig. 3 Organization of the crop management and weed management sub-models: qualitative score of yield change due to the combination of crop techniques. **a** Crop management sub-model: some effects differ according to the type of system (CF conventional farming, OF organic farming) or the region (EL only in Eure-et-Loir *département*). **b**. Weed management sub-model for organic farming

compensate for the presence of weeds due to the crop sequence.

$$Y\_A_{ijklmn} = Y\_N_{ijklm} + YC\_CM_{ijn} \quad (5)$$

with

Y_A_{ijklmn}	Actual yield (t ha^{-1}) for a crop j in a soil i after a preceding crop k, a return time l, a preceding cover crop m, and a score of losses due to crop management n (i.e., sowing date, sowing rate, cultivar choice, tillage, and pest management).
YL_CM_{ijm}	Yield losses due to crop management (t ha^{-1}) for a crop j in a soil i and a score n of losses due to crop management randomly selected between $yl\_cm\_min_{ijn}$ and $yl\_cm\_max_{ijn}$
$yl\_cm\_min_{ijn}$ and $yl\_cm\_max_{ijn}$	Minimum and maximum yield losses due to crop management).

2.3 The expert elicitation method used for parameter estimation

PerSyst was parameterized independently in three study areas: (i) in the Bourgogne region (eastern France) for CF, for eight soil types and 11 crops; (ii) in the Eure-et-Loir *département* (central France) for CF, for five soil types and 12 crops; and (iii) in the Île-de-France region (central France) for OF, for eight soil types and 18 crops.

As explained above, PerSyst parameterization partly relied on expert knowledge. We designed and implemented a two-step elicitation method, combining individual interviews and collective meeting in each region.

The first step aimed at gathering expert knowledge without the influence of a group. We considered as an expert any person with knowledge about one or several crops involved in the PerSyst model and farmers practices in the study areas. We paid attention to select people from various organizations: 23 experts were interviewed in Bourgogne (10 from chambers of agriculture, eight from cooperatives, and five from technical institutes), 18 in Eure-et-Loir (six from chambers of agriculture, four from cooperatives, six from technical institutes, one from a farm accounting firm, and one from a research lab in agronomy), and two in Île-de-France from a chamber of agriculture. We tried to interview at least five experts by case study, as recommended by O'Hagan et al. (2006), but it was not possible in Île-de-France, as there were few experts on OF in this region. We began each interview by an introductory talk, explaining the aim of the study and what the expert could get from it, to minimize motivational biases. Then, we asked the expert to define a value for each parameter. To cover all crops and soil types for which experts had knowledge, each interview lasted maximum half a day. The following questions were addressed to set the parameters in brackets:

What is the achievable yield for a crop j grown in a soil type i, in years with unfavorable and favorable climatic conditions, respectively, within a crop sequence widely practiced by farmers, and with management minimizing yield losses as much as possible on-farm conditions? ($y\_ref\_min_{ij}$ and $y\_ref\_max_{ij}$).

What is the preceding crop in such a widely practiced crop sequence, and what is the return time of the crop j?

What are the characteristics of such a management minimizing yield losses? (i.e., fallow period management, soil tillage, sowing date, rate and cultivar choice, nitrogen fertilization practices, and pest management strategy).

What is the yield distribution within this range considering the 10 last years: are low yields as frequent as high yields, or more frequent, or less frequent? ($y\_ref\_dist_{ij}$).

What are the consequences on yield for a crop j grown in a soil type i of a preceding crop k in comparison to the preceding crop defined as a reference, without any changes in crop management? ($yc\_csp\_min_{ijk}$ and $yc\_csp\_max_{ijk}$).

What could be changed in crop management consistently to the preceding crop? What would be the consequences on yield?

What are the consequences on yield for a crop j grown in a soil type i of a return time l in comparison to the return time defined as a reference, without any changes in crop management? ($yc\_csr\_min_{ijl}$ and $yc\_csr\_max_{ijl}$).

What could be changed in crop management consistently to the return time; which consequences on yield?

Could you describe an alternative management for a crop j grown in a soil type i, contrasting to the management defined as a reference? (e.g., a low-input management).

What are the consequences on yield of such a management, for a crop j in a soil i after a preceding crop k, a return time l? ($yl\_cm\_min_{ijn}$ and $yl\_cm\_max_{ijn}$).

The second step aimed at reaching a consensus for each parameter, among the diversity of answers provided by all experts. Prior to the meeting, the information gathered from individual interviews was summarized. During the meeting, for each parameter, the distribution of answers given by experts was presented through minimum, mean, and maximum values. Attendees were asked to collectively agree on a single value. For Bourgogne and Eure-et-Loir case studies, two full-day meetings were necessary to discuss all parameters. For these two regions, about 6 months passed between the first interview and the last group meeting. For the Île-de-France case study, a collective meeting made no sense because of the limited number of experts interviewed. We thus arranged a meeting with experts from neighboring regions, additionally to the two experts interviewed: They were asked to give their opinion on the consistency of the parameterization. This meeting helped us to tailor some parameter values.

2.4 Assessment of the predictive capacity of PerSyst

The predictive capacity of PerSyst was assessed for the Île de France case study by comparing simulated yields with actual yields measured on two long-term experiments in OF in the Île-de-France region. The first experiment ("Boigneville") was located in the southern part of Île-de-France, under an intermediate (60–80-cm depth), non-hydromorphic loam-clay-calcareous soil. The 4.7-ha plot was divided into six sub-plots, each characterized by a 6-year crop sequence (Fig. 5). This experiment was set in 2007, and yields had been recorded over 5 years when the yield comparison was carried out. The second experiment ("La Motte") was located in the north-western part of Île-de-France, under a deep (> 100 cm) hydromorphic and beating loamy soil. The 64-ha plot was divided into eight sub-plots, each characterized by an 8-year crop sequence. This experiment took place in 2003, and 9 years of yields were used for the model assessment. This experiment, managed by a farmer on his own farm, was representative of on-farm conditions, with a cropping system close to the OF current practices in the region. In contrast, the "Boigneville" experiment took place on a site dedicated to experiments and was managed by a staff from a technical institute. The crop rotation was innovative, including crops not currently grown in the region. The crop management was also innovative; for example, the last cut of alfalfa was not taken away, to preserve soil fertility, which is not a widespread technique. For both sites, the average yields measured across years for each crop, as well as minimum and maximum observed yields, were provided by people in charge of experiments (who were not involved as experts to parameterize PerSyst). Each crop of the crop sequence was supposed to be grown every year, but both crop sequences showed flexibility within time. For example, the last crop of the rotation was most frequently a winter oat (*Avena sativa* L.) on the "La Motte" experiment, but it was another secondary cereal 4 years upon 9. Thus, the number of available yield values for a given crop was sometimes smaller than the duration of the experiment. The PerSyst model was then used to predict yields for these two cropping systems, each simulation involving 10 iterations. The predictive quality was assessed through the relative root-mean-square error of prediction (R-RMSEP), calculated for the average, minimum, and maximum values across years. The R-RMSEP was estimated, for each crop, across both experiments.

$$R\text{–RMSEP} = \frac{\sqrt{(Y\_A\_\mathrm{sim}-Y\_A\_obs)^2}}{Y\_A\_obs}$$

with

Y_A_obs Average or minimum or maximum observed yield across available years

Y_A_sim Average or minimum or maximum actual yield predicted with the PerSyst model from ten iterations.

3 Results and discussion

3.1 Estimation of the reference yield parameters of PerSyst

For each crop present in each region, *y_ref_min*, *y_ref_max*, and *y_ref_dist* parameters are shown for two soil types (a deep soil and a shallow one) in each case study (Fig. 4). Within a given case study, *y_ref_min* and *y_ref_max* showed differences between soil types. For instance, for winter wheat in Bourgogne, *y_ref_max* for the shallow soil (7.5 t ha^{-1}) was close to *y_ref_min* for the deep one (7.1 t ha^{-1}). For quite similar soil types among regions, these parameters also showed differences, according to the case study. For instance, for winter wheat in Bourgogne, *y_ref_min* was set at 7.1 t ha^{-1} and *y_ref_max* at 10.5 t ha^{-1} for deep clay loam soil, whereas these parameters were set respectively at 6.5 and 15 t ha^{-1} in Eure-et-Loir for a deep loam soil with similar maximum soil water content (SWC). These ranges are consistent with public statistics: Over the past 15 years, the average yield reached 6.6 t ha^{-1} (varying from 5 to 7.5 t ha^{-1}) in Bourgogne and 7.9 t ha^{-1} (varying from 6.3 to 8.6 t ha^{-1}) in the Eure-et-Loir (Agreste 2017). This highlights the need for a local parameterization of reference yield.

y_ref_dist also showed differences between soils or between case studies. For instance, for winter wheat in Bourgogne, a right-skewed distribution was chosen for deep soils, whereas a left-skewed one was chosen for shallow soils. To argue this difference, experts quoted a more frequent occurrence of low yields due to stronger drought in shallow soils than in deep ones because of a lower maximum SWC. Experts collectively agreed on the same form of distribution for all winter crops, all being similarly exposed to drought due to their growth cycle. In Eure-et-Loir, a left-skewed distribution was chosen for deep loam soils, consistently with a very high *y_ref_max* value chosen by experts, corresponding to exceptional yields. Unlike the Bourgogne region, there was no generic rule across crops concerning *y_ref_dist*, for instance, a normal distribution was chosen for winter wheat on clay-calcareous soils, whereas a left-skewed one was chosen for winter barley.

3.2 Estimation of the parameters dealing with yield change due to preceding crop

Contrary to the reference yield values, the values proposed by experts for winter wheat yield change due to the preceding crop were close among regions. In all case studies, experts

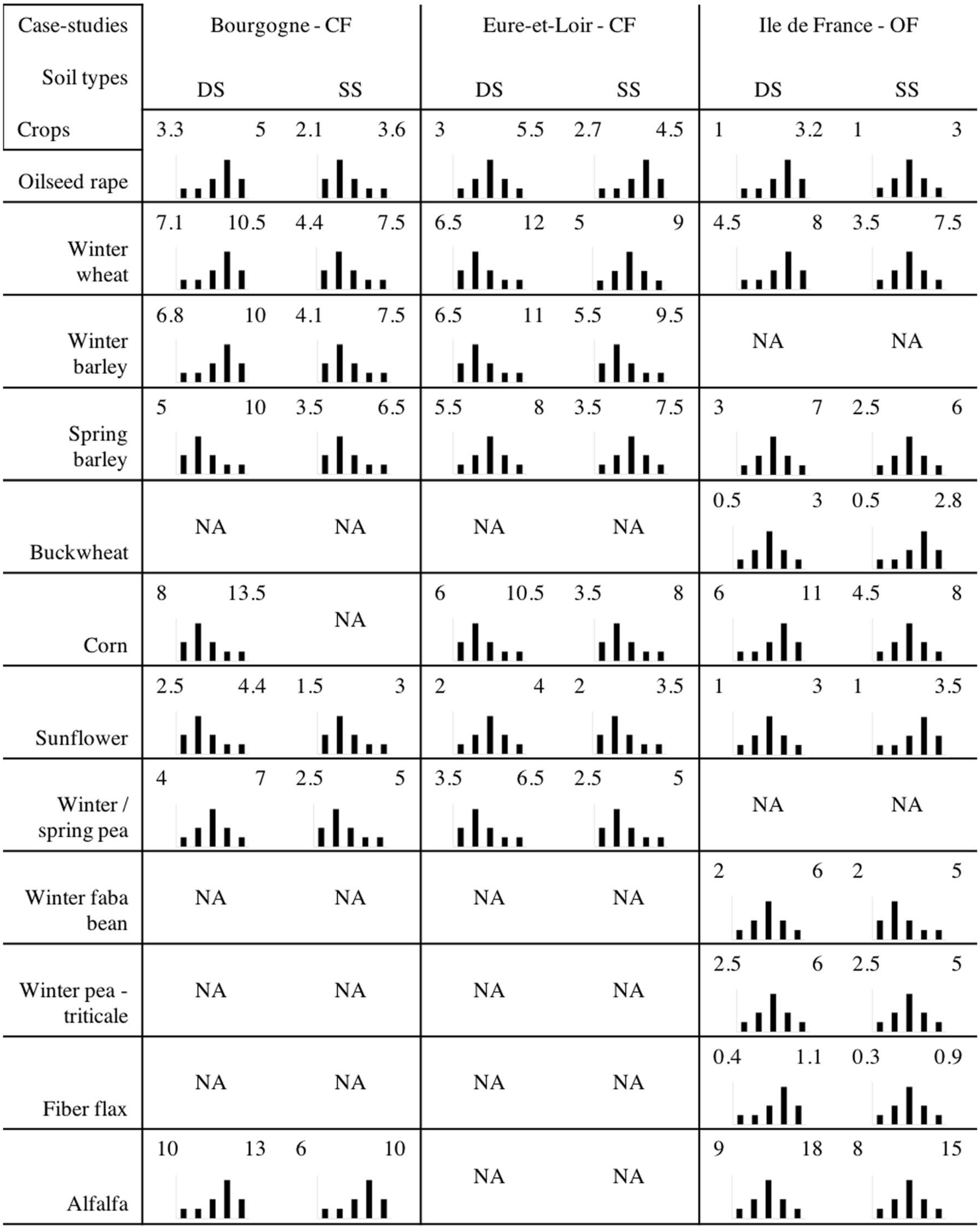


Fig. 4 *y_ref_min* (i.e., reference yield in years with unfavorable conditions, e.g., 3.3 t ha^{-1} for oilseed rape on DS in the Bourgogne region) *y_ref_max* (i.e., reference yield in years with favorable conditions, e.g., 5 t ha^{-1} for oilseed rape on DS in the Bourgogne region) and *y_ref_dist* (i.e., values distribution described by the bar plots*)* parameters for several crops and for a shallow soil type (SS) and a deep soil type (DS) among the three case studies. NA means non-parameterized crops, as the set of crops parameterized is not the same among case studies

chose a single value rather than a range of values. Consequently, in all case studies, *YC_csp_min* was equal to *YC_csp_max* for each *ijk* “crop × soil type × preceding crop” combination.

In addition, experts also chose to set the same value for all soil types in a case study. It could be a constant value, as in Bourgogne where the experts considered that yield change due to the preceding crop was independent of the reference yield, or a percentage of the reference yield, as in Eure-et-Loir or Île-de-France, where the experts considered that yield changes were correlated with the reference yield. To allow comparisons across case studies, and consistently with Schneider and Huyghe (2015) who presented preceding crop effects in decitonne per hectare, percentages were changed into constant values (Table 1), based on reference yield values shown in Fig. 4.

The crop defined as the reference preceding crop (i.e., the one that makes it possible to reach the reference yield) differed from one case study to another: oilseed rape (*Brassica napus* L.) in Bourgogne, spring pea (*Pisum sativum* L.) in Eure-et-Loir, and alfalfa (*Medicago sativa* L.) in Île-de-France. To allow comparisons across case studies, values were converted to the same baseline (oilseed rape) for all case studies (Table 1).

The values chosen by experts showed great consistency across case studies. In all case studies, cereals were set as the worst preceding crops for winter wheat with yield loss around 1 t ha^{-1}. This yield loss was explained by experts by an increase of diseases on the winter wheat following a cereal, as they are host crops for several foot- and root-borne pathogens (Colbach et al. 1997a; Colbach et al. 1997b). Experts also mentioned other factors causing yield decline in cropping systems with short rotations, such as deleterious rhizosphere microorganisms (Bennett et al. 2012). Corn (*Zea mays* L.) and sunflower (*Helianthus annuus* L.) were set as intermediate preceding crops, resulting in yield loss around 0.5 t ha^{-1}, except for Île-de-France for which it was defined as equivalent to straw cereals. In Bourgogne, as well as in Eure-et-Loir, winter and spring peas were defined as favorable preceding crops with yield gain around 0.2 t ha^{-1} compared to oilseed rape. In comparison to winter wheat, this represents a yield gain between 0.6 and 1.4 t ha^{-1}, which is consistent with Schneider and Huyghe (2015) who quantified an increase of 0.84 t ha^{-1} from on-farm data gathered in the north of France from 1991 to 2008 when pea was used as the preceding crop rather than a winter wheat. In addition, in the Île-de-France region, another annual grain legume—faba bean (*Vicia faba* var. *minor* Peterm.)—was given the same effect on yield of the following crop than oilseed rape. In Bourgogne and Île-de-France, alfalfa was defined as the most favorable preceding crop, with yield gains from 0.3 to 1.2 t ha^{-1}.

As yield changes due to the crop sequence were similar for the three case studies in terms of sign (positive or negative) and ranking, they could be estimated in a more generic way for other study areas. Data analysis on preceding crop effects in Europe, obtained from the LINK (Legume Interactive Network) project, has shown that these effects were close across regions (Pahl et al. 2000). Thus, using meta-analysis synthesizing published data to assess yield changes due to crop sequence (e.g., Philibert et al. 2012; Cernay et al. 2016) could compensate for the lack of expert knowledge in some study areas.

3.3 Estimation of the parameters describing yield change due to crop management of PerSyst

In the three case studies, the sub-model assessing yield change due to crop management presents many similarities, even if specific elements occur in each of them, as shown for the example of winter wheat on Fig. 3a. First, in all case studies, yield change due to crop management plan was broken down into: (i) change due to sowing practices and (ii) change due to pest and lodging management practices. Yield change due to sowing practices always involved the effects of sowing date, sowing rate, and cultivar choice. Yield change due to pest and lodging practices encompassed diseases, insects, and lodging for case studies in CF. In OF, experts considered that yield change due to weeds was so high that the other reducing factors were negligible. For winter wheat, diseases were

Table 1 *yc_csp_min and yc_csp_max* (t ha^{-1}) parameters for several winter wheat preceding crops and for a shallow soil type (SS) and a deep soil type (DS) among the three case studies. NA means non-parameterized crops, as the set of crops parameterized is not the same among case studies

Case-studies		Bourgogne—CF		Eure-et-Loir—CF		Île-de-France—OF	
Crops	Soil types	DS	SS	DS	SS	DS	SS
Oilseed rape		Reference		Reference		Reference	
Winter wheat		− 1	− 1	− 0.45	− 1.05	− 0.55	− 1.2
Winter barley		− 1	− 1	− 0.45	− 1.05	NA	NA
Spring barley		− 1	− 1	− 0.45	− 1.05	− 0.55	− 1.2
Buckwheat		NA	NA	NA	NA	0	0
Corn		− 0.3	− 0.3	− 0.20	− 0.50	− 0.55	− 1.2
Sunflower		− 0.4	− 0.4	− 0.25	− 0.60	0	0
Winter/spring pea		+ 0.2	+ 0.2	+ 0.15	+ 0.35	NA	NA
Winter faba bean		NA	NA	NA	NA	0	0
Winter pea—triticale		NA	NA	NA	NA	0	0
Fiber flax		NA	NA	NA	NA	0	0
Alfalfa		+ 0.3	+ 0.3	NA	NA	+ 0.5	+ 1.2

broken down into foliar diseases and soil-borne diseases, because they are not influenced by the same crop techniques. Foliar diseases depended on fungicide application as a curative technique, and on preventive techniques including sowing date, sowing rate, and cultivar choice. Soil-borne diseases differed in respect of the preventive techniques involved: In addition to tillage, the preceding crop was included to allow for compensation of an unfavorable preceding crop by an enhanced fungicide protection. Yield change due to insects included insecticides and sowing date effects. In Eure-et-Loir only, this variable also included cultivar choice as a preventive technique against orange blossom midge (*Sitodiplosis mosellana* Gehin), whereas in Bourgogne, this pest was considered negligible. Yield change due to lodging included growth regulators and, as preventive techniques, nitrogen fertilization, sowing rate, and cultivar choice.

Changes due to weeds were broken down into annual and perennial weeds, as they are not influenced by the same crop techniques (Fig. 3b). Crop techniques involved in this sub-model were weeding techniques (mechanical weeding only for OF case study) as well as other crop techniques that could affect weed dynamics or crop competitiveness (e.g., sowing date, sowing rate, plowing). In addition to crop techniques, this sub-model involved several crop rotation characteristics (e.g., presence of a pluriannual crop or diversity of sowing periods).

The various winter wheat management plans described by experts made it possible to fill in utility functions for each node of the tree, so that the tree ordered these management plans consistently.

The formalization of yield change due to crop management for other crops was adapted from the one developed for winter wheat, the most complete among all crops. Two types of adaptation were made. First, branches or leaves have been removed when not relevant (e.g., yield change due to diseases for corn, or nitrogen fertilization for legume crops). Second, utility functions have been adapted to translate the influence of various attributes on yield (e.g., yield change due to sowing practices was higher for spring crops than for winter crops, according to expert knowledge).

Implemented in three regions, this formalization seems to be robust enough to be used in many French regions, with minor adaptations. The PerSyst model is currently under parameterization in the Hauts-de-France region (north of France) for both CF and OF, using the crop management effect sub-models presented in this paper. It also presents a flexibility that allows it to be adapted for a wider variety of conditions. For example, it was possible to parameterize the PerSyst model for inland valleys of West Africa (Furian et al. 2015) thanks to changes in crop management sub-models, to adapt them to other reduction factors and other local crop techniques. However, additional work on PerSyst is under progress. First, the nitrogen requirement and management sub-models could take profit of recent studies on drivers of soil mineralization. Moreover, the three case studies developed in this paper involved rainfed cropping systems, thus not requiring to consider irrigation. PerSyst was also parameterized in the Midi-Pyrénées region, located in the South-West of France and with a large part of irrigated cropping systems. To take into account this technique, irrigated and rainfed crops were distinctly parameterized, with different potential yields (e.g., rainfed corn and irrigated corn). Including irrigation into crop management, sub-model would make it possible to consider the effect on yield of variations in irrigation rate, as well as interactions between irrigation and other techniques (e.g., disease management).

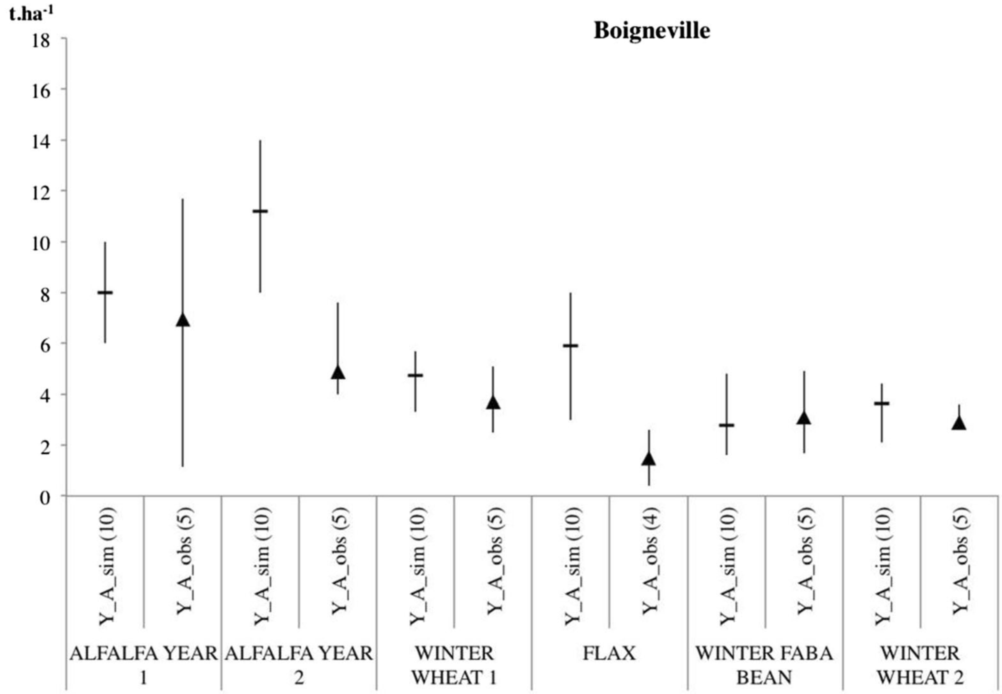
3.4 Assessment of the predictive capacity of PerSyst

Simulated yields fitted well with observed values for winter faba bean and winter wheat (Fig. 5), with average R-RMSEP on mean yield of 15% for faba bean as well as for winter wheat. This R-RMSEP was lower than those obtained for other crop models. For example, for wheat, RMSEP in conventional and low-input conditions amounted to 1.05 t ha^{-1} for the Azodyn model (David and Jeuffroy 2009) and to 1.59 t ha^{-1} for the STICS model (Brisson et al. 2002). As a comparison, with the PerSyst model, the 15% R-RMSEP mentioned above for wheat corresponds to a RMSEP of 0.50 t ha^{-1}. Besides, Plaza-Bonilla et al. (2015) quoted a R-RMSEP of 23% for grain yield simulated with the STICS model among three crop rotations, including sorghum (*Sorghum bicolor* L. Moench), sunflower, durum wheat (*Triticum durum* Desf.), soybean (*Glycine max* (L.) Merr.), and pea.

Simulated yields also correctly reported the variability of observed yields with average R-RMSEP on minimum and maximum yields of 18 and 14% for winter wheat, respectively. For winter faba bean too, average R-RMSEP on minimum and maximum yields was small, with 6 and 3%, respectively. However, R-RMSEP was not calculated for situations with observed yields equal to 0. As a result, it did not report that 1 year on the "La Motte" experiment, no faba bean was harvested because of a combination of factors reducing the yield to 0 t ha^{-1}, while at the same time, PerSyst predicted no yield under 2.1 t ha^{-1}.

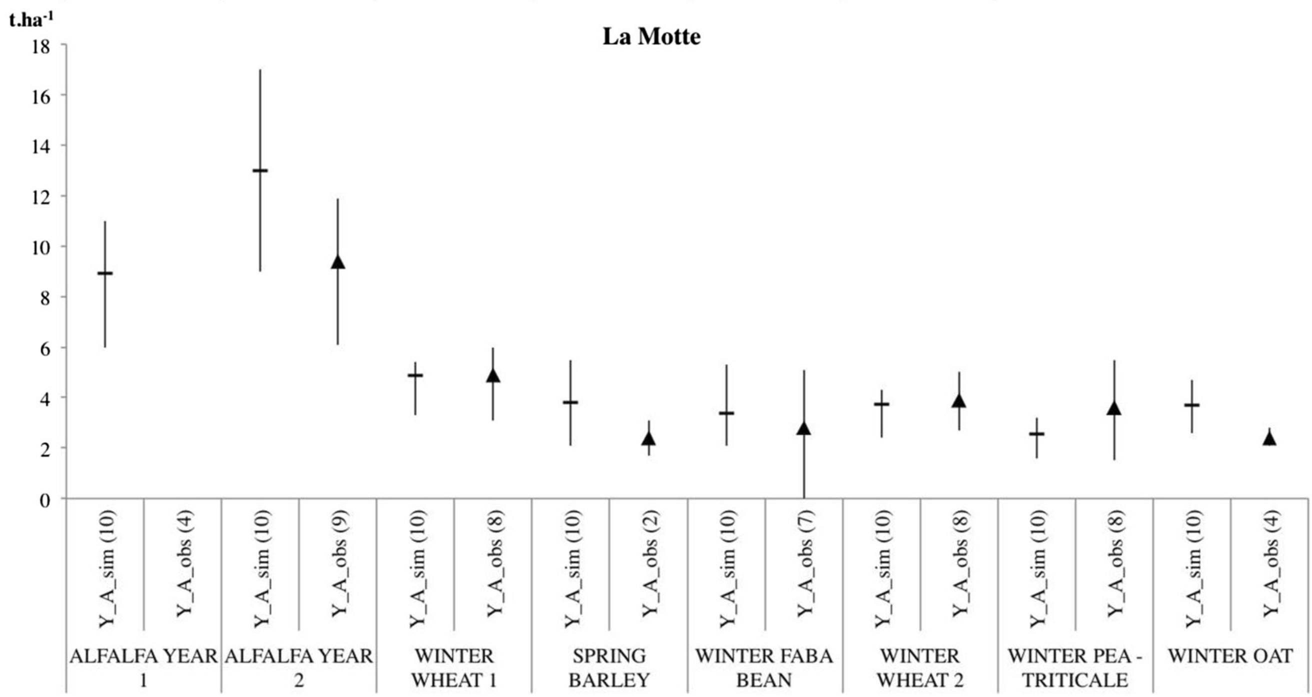
Relative RMSEP was higher for other crops: 29% for winter pea—triticale (*Triticosecale*) intercropped, 55% for winter oat, 58% for spring barley (*Hordeum vulgare* L.), 61% for alfalfa, and 293% for flax (*Linum usitatissimum* L.). PerSyst

Fig. 5 Mean yields predicted with the PerSyst model for Boigneville and La Motte experiments, and mean yields observed on the experiments (error bars represent the amplitude of yields predicted across iterations or observed across the duration of experiments) root-mean-square error of prediction (RMSEP) and relative RMSEP (in brackets) are given for minimum, mean, and maximum simulated yields) ▶



RMSEP - $t.ha^{-1}$ (R-RMSEP)

min	4,9 (426%)	4 (100%)	0,8 (32%)	2,6 (650%)	0,1 (6%)	0,6 (22%)
mean	**1 (15%)**	**6,3 (129%)**	**1 (28%)**	**4,4 (293%)**	**0,3 (10%)**	**0,8 (26%)**
max	1,7 (15%)	6,4 (84%)	0,6 (12%)	5,4 (208%)	0,1 (2%)	0,8 (22%)



RMSEP - $t.ha^{-1}$ (R-RMSEP)

min	-	2,9 (48%)	0,2 (6%)	0,4 (24%)	-	0,3 (11%)	0,1 (7%)	0,5 (24%)
mean	**-**	**3,6 (38%)**	**0,1 (1%)**	**1,4 (58%)**	**0,6 (20%)**	**0,2 (4%)**	**1,1 (29%)**	**1,3 (55%)**
max	-	5,1 (43%)	0,6 (10%)	2,4 (77%)	0,2 (4%)	0,7 (14%)	2,3 (42%)	1,9 (68%)

was parameterized to simulate fiber flax yields, whereas oilseed flax was grown in the "Boigneville" experiment, which explains the high value of relative RMSEP for this crop. Concerning the second year of growth of alfalfa, predicted yields were higher than observed yields, especially for the "Boigneville" experiment. In that experiment, at least the last harvest was mulched instead of being harvested, to increase nitrogen soil status, whereas the yield simulated by PerSyst assumed three annual harvests, thus explaining the gap between observed and simulated yields. Regarding these results, accuracy seems to depend on the amount of knowledge the experts have on each crop. It was especially good for winter wheat and winter faba bean, which are major crops in organic cropping systems of the Île-de-France region. Accuracy is lower for crops such as spring barley or winter oat, which are less widespread on farmers' fields and thus, for which expert knowledge may be more limited. Although it took place in one experiment, oilseed flax was even not parameterized because acreage at regional scale was so scarce that the experts had no sufficient knowledge about this crop. This could be a limitation to overcome to make the model relevant to assess highly innovative cropping systems. New methods mixing local expert knowledge with literature data need to be developed with this aim, as proposed by Laurent et al. (2015), to combine between-site and within-site information and thus to obtain information on a new crop which was not experimented at a given site.

Beside the capacity to predict accurate yield values, these results illustrate the capacity of the PerSyst model to correctly rank yields. Especially, simulations gave a good account of winter wheat yield according to its place within the crop sequence for both experiments: The first winter wheat had higher simulated yields than the second winter wheat, with a yield difference consistent with the yield difference observed. Among experiments and the position of winter wheat within the crop sequences, winter wheat yield changes due to the crop sequence sub-model varied from 0 to 0.9 t ha^{-1}. Changes due to the crop nitrogen management sub-model varied from 0.3 to 0.7 t ha^{-1}. Changes due to crop management sub-model varied from 0 to 0.9 t ha^{-1}. This result highlighted the importance of all sub-models. Indeed, the reference yield sub-model only enabled to differentiate yields for a given crop between sites, according to location and soil characteristics. However, it was not sufficient to differentiate yields for a given crop cultivated many times in a given site. This could be the case of a given crop occurring more than once in a cropping system, as observed for winter wheat for both experiments or the case of a given crop occurring in different cropping systems on a given site. However, it is necessary to assess the model on additional sites, including sites in conventional farming, for which incidence of various limiting and reducing factors on yield may be different. This assessment is currently in progress in the Hauts de France region, located in the north of France.

3.5 Experience-based analysis of the method

The parameterization of the PerSyst model for these three case studies illustrated that it is relevant to rely on expert knowledge to fill in parameters related to yield, especially the parameters related to reference yield. We have already discussed about one of the limitations encountered, i.e., considering new crops and new management techniques in PerSyst, and possibilities to overcome them. Yet, additional difficulties in gathering the required expertise could be noticed. As illustrated by the Île-de-France case study, it is not always possible to gather a minimum number of five experts, as recommended by O'Hagan et al. (2006). However, rather than the quantity of experts involved in the parameterization, our experience showed that the quality of their knowledge is much more important. Indeed, we managed to set an accurate parameterization for organic farming in Île-de-France, with only two experts. Our feeling was that in organic farming, agronomists and farmers have to deal with crop sequence effects and combine techniques to manage pests without chemicals, making the experts more experienced with the questions at the cropping system scale. In contrast, some experts interviewed in other case studies struggled to identify alternatives to the reference cropping system they described and consequences on yield. It is hard to draw further criterions to select experts, as their ability to answer our questions did not appeared directly linked to their age, the number of years of experience in the study area, or the institution they belong to. Thus, our recommendations to reproduce the method elsewhere are to interview all the experts motivated, and then to rely on the group discussions to set a consensus making sense for each parameter. In the Bourgogne and Eure-et-Loir case studies, where a large number of experts were involved, both groups expressed a strong satisfaction about these discussions. They particularly appreciated to share values about achievable yields for example, for which they had no shared reference documents. In this sense, PerSyst parameterization contributed to formalize and share tacit knowledge. Beside the knowledge of experts involved, the skills of the person leading the parameterization process are also critical for its success. Indeed, a background in agronomy of cropping systems is required to have a full comprehension of the answers given by experts, especially for filling in the crop management sub-model.

Our results first illustrated the feasibility of parameterizing a cropping system model from expert knowledge. Consistent results among case studies were obtained for yield change due to crop sequence and yield change due to crop management, highlighting possibilities to overcome local lack of knowledge. Second, the model and its expert-knowledge-based parameterization showed a good accuracy in predicting yields on two long-term experiments, giving account of crop sequence and crop management effect on yield. As yield is not the only relevant indicator to take into account for cropping system assessment, an evolution in progress is to implement in the model the calculation of indicators derived from yield (e.g., nitrogen losses, gross margin, workload). The use of this model by local stakeholders to assess a priori the interest of innovative cropping systems should be enhanced by adding such indicators, among those proposed by Sadok et al. (2008), allowing a multi-criteria assessment.

4 Conclusion

The PerSyst model was developed with the aim of simulating the yield of various crops within a cropping system. Taking into account the numerous effects of the combination of practices characterizing a cropping system (including rotation, sowing, soil tillage, pesticide applications, and fertilization), for a large number of crops, both in conventional and organic systems, was possible only by mixing expert and scientific knowledge in the algorithms and parameter estimation. A robust and reproducible method of expert elicitation to obtain the parameters for a region was proposed. Indeed, we showed that for some parameters (e.g., yield change due to crop sequence), close values were chosen among case studies. In addition, we demonstrated the good predictive capacity of the PerSyst model for organic farming in the Île-de-France region.

In the future, the PerSyst model could be improved by linking the climatic variability resulting in the yield distributions, with the weather conditions influencing pest or disease pressure and nitrate leaching, while keeping the parsimonious characteristics of PerSyst in terms of parameter number. This improvement could help to assess innovative cropping systems faced with climate change. Lastly, it could be interesting to use the PerSyst model to perform a general assessment of organic versus conventional systems, considering the whole cropping system.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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