Economic analysis of summer fallow management to reduce take-all disease and N-leaching in a wheat crop rotation[*]

Stéphane De Cara[†], Florence Jacquet[†], Arnaud Reynaud[‡], Gaël Goulevant[§], Marie-Hélène Jeuffroy[¶], Philippe Lucas[§], and Françoise Montfort[§]

Abstract: This paper addresses the question of summer cover crop adoption by farmers in presence of a risk of yield loss due to take-all disease and climate variability. To analyse the public incentives needed to encourage farmers to adopt summer cover crops as a means of reducing N leaching, we combine outputs from an economic, an epidemiological and an agronomic model. The economic model is a simple model of choice under uncertainty. The farmer is assumed to choose among a range of summer fallow managements and input uses on the basis of the expected utility criterion (HARA assumption) in presence of both climate and take all risks. The epidemiological model proposed by Ennaïfar et al. (2007) is used to determine the impact of take all on yields and N-uptake. The crop-soil model (STICS) is used to compute yield developments and N-leaching under various management options and climatic conditions. These models are calibrated to match the conditions prevailing in Grignon, located in the main wheat-growing area in France. Eight management systems are examined: 4 summer fallow managements: 'wheat volunteers' (WV), 'bare soil' (BS), 'early mustard' (EM), 'late mustard' (LM), and 2 input intensities. We show that the optimal systems are BS (WV) when the take-all risk is (not) taken into account by agents. We then compute the minimum payment to each system such that it emerges in the optimum. We thus derive the required amounts of transfer needed to trigger catch crop adoption. The results of the Monte Carlo sensitivity analysis show that the ranking of management systems is robust over a wide range of input parameters.

(version: 1.22 by: stdecara)

[†]INRA, UMR 210 Economie Publique INRA-AgroParisTech, BP01, 78850 Thiverval-Grignon

[‡]TSE (LERNA-INRA), Université Toulouse 1, Manufacture des Tabacs, 21, Allée de Brienne, 31000 Toulouse

[§]UMR BIO3P, Domaine de la Motte, BP35327, 35653 Le Rheu Cedex

[¶]UMR 211 Agronomie INRA-AgroParisTech, BP01, 78850 Thiverval-Grignon

1   Introduction

Nitrogen leaching is a major environmental concern, with consequences on water nitrate concentrations and on nitrous oxide emissions. The introduction of cover crops during the inter-cropping season has been advocated as one means of reducing N leaching (Meisinger et al., 1991). In the European Union, winter cover crops are mandatory in vulnerable zones under the Nitrate Directive (Council of the European Communities, 1991). They may also be part of agri-environmental schemes under which farmers are entitled to payments if they adopt cover crops outside the Nitrate Directive vulnerable zones and/or if they commit to manage the cover crop using a defined set of environmentally-friendlier practices. As an illustration, in France, such payments amount to 86 and 48 € per hectare, respectively (Ministère de l'Agriculture et de la Pêche, 2007).

The positive impact of catch crops with respect to N leaching has been widely demonstrated (Meisinger et al., 1991), especially before spring crops. They may also play an important role before a winter crop such as winter wheat, which represents one quarter of European cropland area and is characterized by low N uptake rate during the rainy season. Recent agronomic studies suggest that cover crops may also have a beneficial effect with respect to the development of some plant pathogens. Ennaïfar et al. (2005) show that summer fallow management affects the development of take-all root rot *Gaeumannomyces graminis tritici (Ggt)*, which poses a serious threat to wheat yield when wheat follows another cereal crop. In particular, the introduction of a cover crop before wheat may have a 'biofumigation' effect that reduces take all disease severity (see also Ennaïfar et al., 2005; Angus et al., 1994; Kirkegaard et al., 1994).

The adoption of a cover crop thus has consequences on the expected net returns and net-return variance of the following crop (through the effect on take-all severity), as well as on the environment (through the effect on N leaching). If those two effects are not taken into account by farmers, private incentives alone are generally not sufficient to prompt cover crop adoption before wheat because of increased costs and additional work to do just after harvest. Moreover, the choice of a particular summer fallow management results from a decision under uncertainty involving climate- and disease-related risks. In this paper, we assess how the incentives to introduce a cover crop are modified when the biofumigation effect on take-all and its interaction with N leaching risks are accounted for.

There is a large body of literature addressing the issue of N leaching, both in economics and in agronomy. Some studies have combined approaches from both disciplines. This is the case in Lacroix et al. (2005). The authors use a biophysical model (STICS) and an economic framework in which uncertainty is explicitly taken into account. They consider cover crops as part of a set of measures to control N leaching. However, in their analysis, the authors do not account for the possibility of diseases such as take all. Roberts et al. (2004) estimate the effect of take-all severity and fertilization sources/timing on wheat yield mean and variance. Using experimental data, they analyze the risk-return trade-offs for risk averse farmers. In their study, the authors do not include the impact of summer fallow management on disease severity.

To our knowledge, the trade-offs between N leaching and disease risk management in the decision of adopting (or not) a cover crop before wheat has not been studied in the economic literature. The novel aspect of our paper is to address this question by combining results from a crop-soil model (STICS), an epidemiological model, and an economic framework of choice under uncertainty. We focus on the second wheat in a wheat-wheat succession. Maximum feasible wheat yield and N-leaching are derived from STICS simulations. STICS is parameterized using soil and climate data from Grignon, located in the main wheat growing area in France, and pertaining to years 1978-2007. Eight management practices (four summer fallow management, including two types of cover crop, times two levels of input intensity) are simulated. The epidemiological model is based on Ennaïfar et al. (2007) from which we infer the yield loss associated to various disease ratings and choices of summer fallow management options. The simulated distributions of climate-related impacts on yield and take-all severity are then introduced in an economic model that determines the optimal management system on the basis of expected utility.

Equipped with this framework, we examine the optimal management choice of a risk averse farmer. We compare the situations when the yield loss risk due to take-all is taken into account and when it is not. We analyze the impact of price instruments aimed at combating N leaching and discuss the minimum payment needed for cover crop to be profitable in each case. This payment includes the differences in costs and revenues associated with each management system, as well as the relative risk premium associated to each management system. Last, we examine the robustness of our results with respect to a wide range of values of input parameters using a Monte Carlo sensitivity analysis.

The rest of the paper is organized as follows. Section 2 presents the economic model underlying the choice of summer fallow management for a (risk-averse) farmer producing wheat. In Section 3, we describe the data used in the calibration of the biophysical, epidemiological and economic models. Optimal managements with and without taking into account the take-all disease risk are presented in Section 4. We also examine the impact of various economic instruments on farmer's optimal choice. Section 5 presents the results of the Monte Carlo sensitivity analysis. We discuss in particular the distribution of the minimum payment needed to trigger the adoption of each summer fallow management (including cover crops) for a wide range of input parameters values. Section 6 concludes.

2   A model of cover-crop adoption under climate and take-all risks

We consider a (risk-averse) farmer who produces wheat and has to choose among various input intensities (indexed by i) and summer fallow managements (SFM, indexed by k). Two types of risks potentially affect wheat yield: a climate risk (denoted by $\tilde{\epsilon}_c$) and a take-all risk ($\tilde{\epsilon}_d$). We denote by F_c and F_d the cumulative distribution probabilities of the climate and the take-all risks. Agronomic evidence suggest that those two risks are independent.

For a given type of SFM and a given level of input use intensity, the realisation of the climate risk determines a maximum feasible yield $Y_{\max}(\tilde{\epsilon}_c, k, i)$, which is defined as the maximum agronomic yield for the management system (k, i) without taking into account the impact of the take-all disease. We denote by $\phi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)$ the share of yield that is lost due to the take-all disease. This share depends upon the type of climate year realized. The realized wheat yield is:

$$Y(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i) = Y_{\max}(\tilde{\epsilon}_c, k, i)\big(1 - \phi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)\big) \tag{1}$$

We denote by $c(k, i)$ the per hectare cost of production as a function of the SFM and the level of input intensity. As we shall examine policy instruments on fertilizer use, we distinguish between fertilizer costs and other costs :

$$c(k, i) = wx(i) + c_{\mathrm{SFM}}(k) + c_0(k, i) \tag{2}$$

where $x(i)$ denotes the per-hectare nitrogen use, w is the unit nitrogen fertilizer price, $c_{\mathrm{SFM}}(k)$ are SFM-specific costs, and $c_0(k, i)$ denotes all other costs. Absent any public

regulation, the profit of the farmer is thus:

$$\Pi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i) = a\Big[pY(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i) - c(k, i)\Big] \tag{3}$$

where p represents the price of wheat received by the farmer[1] and a the wheat area.

We assume that the farmer's attitude toward risk can be fully characterized by a utility function $U(.)$ with $U'(.) > 0$ and $U''(.) < 0$. CRRA and CARA utility functions have been commonly used in the literature examining expected utility based decisions. However, these assumptions are somewhat restrictive with respect to the slope of absolute and relative risk aversion measures. In this paper, we retain a hyperbolic absolute risk aversion (HARA) function, which provides a more general functional form of utility function (see Merton, 1971):

$$U(\Pi) = \frac{1-\gamma}{\gamma}\left(\frac{\beta\Pi}{1-\gamma} + \eta\right)^{\gamma} \tag{4}$$

where β, η, and γ are parameters subject to the restrictions $\gamma \neq 1$, $\beta > 0$, and $\eta = 1$ if $\gamma = -\infty$. The measure of absolute risk aversion (λ) is locally given by:

$$\lambda(\Pi) = \left(\frac{\Pi}{1-\gamma} + \frac{1}{\beta}\right)^{-1} \tag{5}$$

The slopes of the absolute and relative risk aversion measures for this functional form can be made positive or negative with appropriately selected values for the three parameters. Equation (4) reduces to a CRRA functional form when the parameter η is equal to 0 ; as the parameter γ goes to infinity, the utility function is asymptotically identical to a CARA form.

The problem of the farmer is then to select the combination of SFM and input use intensity that maximizes his/her expected utility of profit. The optimal combination (k^*, i^*) is thus defined by:

$$(k^*, i^*) \in \arg\max_{k \in \{\text{BS,WV,EM,LM}\}, i \in \{\text{C,L}\}} \Big\{ EU\left(\Pi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)\right) \Big\} \tag{6}$$

where E denotes the expectation operator over the joint distribution of climate and take-all risks.

---

[1] Note here that wheat price is assumed to be certain and known to the farmer. A simple extension of the model would be to explicitly include a price risk, by treating the wheat price as a stochastic component in the farmer's program. This, however, would blur the trade-off between take-all and N-leaching that we focus on in this paper. The sensitivity analysis conducted in Section 5 provides some static comparative results with respect to the effect of output price.

The optimal choice depends on the farmer's risk preferences, climate and the take-all risks, production costs and wheat price. Notice that if the farmer does not internalize the impact of his/her production choices on the take-all risk, the solution of the farmer's decision problem is simply obtained by replacing $Y(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)$ by the maximum feasible yield, $Y_{\max}(\tilde{\epsilon}_c, k, i)$, in equation (3).

The solution of (6) corresponds to a situation in which no policy instrument is in place. In particular, the social cost of N-leaching is not internalized by the farmer. As we shall consider policy instruments later on in the paper, we introduce a regulated version of the farmer's program (6):

$$(\hat{k}, \hat{i}) \in \arg \max_{k \in \{BS, WV, EM, LM\}, i \in \{C, L\}} \left\{ EU \left(\Pi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i) + G \right) \right\} \qquad (7)$$

where G denotes the level of public intervention and can be positive (subsidy) or negative (tax). We shall examine three policy instruments in Section 4 and 5.

The first instrument we examine is a tax on N leaching. We denote by $n(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)$ the level of per hectare N leaching. N leaching depends on the farmer's management choices (fertiliser use and SFM), take all (a high prevalence of the take-all disease implies a lower N uptake by wheat), and climate realization (in particular autumn and winter rain). The introduction of a standard Pigovian tax τ implies that $G = -\tau(an(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i))$.

Second, we consider a tax t on fertilizer use. The rationale for adopting such an input-based instrument is that it might be difficult in practice for the regulator to compute the effective level of N leaching and that fertilizer use is less costly to observe. This indirect instrument would translate into (7) by $G = -t(ax(i))$. Notice that, in our framework, taxing the quantity of fertilizer is equivalent to taxing the conventional use of input (relative to the low input use case) since nitrogen quantities differ across input intensity levels but not across SFM types. Compared to the case of a Pigovian tax on N leaching, taxation of nitrogen induces an efficiency loss since for the same quantity of nitrogen $x(i)$, the level of N-leaching varies across SFM types.

The last instrument we consider is a direct payment $G = as(k, i)$ to each combination of SFM and input use (a tax if $s(k, i) < 0$). Compared to the use of a Pigovian tax, the loss of efficiency is due to the fact that N-leaching for EM or LM varies according to input intensity (conventional or low nitrogen use).

In Sections 4 and 5, we shall also determine the minimum per hectare payment required for a particular management system to emerge in the optimum. Formally, we shall compute $\underline{s}(k, i)$ such that:

$$EU\big(\Pi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i) + G + a\underline{s}(k, i)\big) = EU(\Pi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, \hat{k}, \hat{i}) + G) \text{ for all } (k, i) \qquad (8)$$

where $(\hat{k}, \hat{i})$ is the optimum combination resulting from program (7).

3   An empirical application to France

In this section, we present the data and models used to represent the conditions of a typical wheat-producing farm in Grignon (48°50'N; 1°57'E). Grignon is located in the Paris Basin, the main French wheat growing area.

3.1   Summer fallow and input use management

Summer fallow (SF) management	Input intensity	(k, i)
Bare soil	conventional	(BS,C)
Bare soil	low input	(BS,L)
Wheat volunteers	conventional	(WV,C)
Wheat volunteers	low input	(WV,L)
Early mustard destruction	conventional	(EM,C)
Early mustard destruction	low input	(EM,L)
Late mustard destruction	conventional	(LM,C)
Late mustard destruction	low input	(LM,L)

Table 1: Farmer's summer fallow management and input intensity choices

Four types of SFM are considered ($k \in$ {BS, WV, LM, EM}). They vary according to the type of soil tillage, the sowing date, and the nature of the cover crop (see Table 1). The first type of SFM is bare soil (BS) from harvest of preceding wheat to sowing of the following wheat. The second option available to the farmer is to allow wheat volunteers (WV) from harvest of preceding wheat to sowing of the following wheat. With WV, soil is not tilled until the next wheat sowing. The third and fourth types of SFM correspond to the introduction of a catch crop, namely white mustard. To account for the influence of the length of the mustard growth cycle on N leaching, we further distinguish between two options, whether the wheat sowing date *(i)* is the same as in the two previous cases and catch crop destruction occurs just before this date (early mustard destruction, EM), or *(ii)* is delayed, thus permitting a later destruction of the mustard (LM).

In addition, the farmer may opt for conventional or low input use ($i = \{C, L\}$). The conventional (C) and low input (L) practices differ according to wheat yield targets that define fertilizer use, sowing density, and chemical protection. The conventional crop management is defined according to a 10 t.ha^{-1} yield target, which imposes a high sowing density (275 grains.m^{-2}), high levels of N fertilization to meet high nitrogen requirements (300 kgN.ha^{-1}), and high chemical protection. The low-input is defined for a medium yield target (7.5 t.ha^{-1}), involving a 60% lower sowing density than under conventional management, nitrogen requirements of 225 kgN.ha^{-1} and less chemical protection. Fertilization is calculated using the N balance at the end of winter and is based on N requirements, mineralized N, final soil residual nitrogen objective at harvest of 40 kgN.ha^{-1} (Goulevant et al., 2008).

Table 2 synthesizes the assumptions regarding summer fallow and wheat management retained in the simulations. A detailed discussion of the underlying assumptions from an agronomic standpoint can be found in Goulevant et al. (2008).

3.2   Maximum yields

The maximum feasible wheat yield, $Y_{\max}(\tilde{\epsilon}_c, k, i)$ is obtained from STICS simulations. STICS is a generic crop-soil model simulating the crop growth from sowing to harvest at a daily time scale (Brisson et al., 1998). It is based on biomass accumulation and radiation use efficiency concepts. Given input parameters defining climate, soil, cultivar, and crop management, STICS calculates the quantity and quality of harvested grains, drainage and nitrate leaching, and outputs related to the evolution of the soil characteristics under the influence of the crop. STICS has been validated and parameterized for various crops and a wide range of pedo-climatic conditions[2]. Parameterizations of STICS for white mustard (growth, N mineralization from decomposition of residues) are available and have been validated under field conditions (Dorsainvil, 2002; Justes and Mary, 2004; Justes et al., 2004).

The pedo-climatic parameters used in the simulations pertain to a deep and silty soil, with 190 mm of plant-available water. The simulations were initialized with soil residual nitrogen at harvest of the preceding crop of 40 kg ha^{-1}. The preceding crop for all simulations is winter wheat. The climate database includes the daily minimum and

---

[2]More information on the STICS model can be found at `www.avignon.inra.fr/stics/`.

(a)

SFM	Input Intensity	Summer fallow period			Implantation		
		Wheat residue management	Cover crop sowing	Cover crop crushing	Mouldboard ploughing	Wheat sowing	Insecticide / Herbicide
BS	C	3 stubble ploughing August-September	/	/	15th of October	16th of October	1 dose / 1 dose
	L						/
WV	C	/	Emergence from 15th of August	/	15th of October	16th of October	1 dose / 1 dose
	L						/
EM	C	1 stubble ploughing 4th of August	5th of August	14th of October	15th of November	16th of November	1 dose / 1 dose
	L						/
LM	C	1 stubble ploughing 24th of August	25th of August	14th of November	15th of November	16th of November	/
	L						

(b)

	Fertilization			Spring input		
	1 month before Ear 1cm (19th of February)	Ear 1cm (19th of March)	1 month before flowering (23rd of April)	Growth regulator (mid-March)	Herbicide (March)	Fungicide (March-May)
C	NH_4NO_3 50kgN.ha^{-1}	NH_4NO_3 adjusted dose (see text)	NH_4NO_3 50kgN.ha^{-1}	1 dose	1 dose	3 doses
L	/			/		2 half doses

Table 2: Description of summer fallow and wheat management options.

maximum temperatures, rainfall, global radiation, and potential evapotranspiration for thirty years from 1978 to 2007. The average temperature calculated during the whole year is 11ºC, annual global radiation is 4117 MJ.m^{-2}, annual rainfall is 605 mm, and annual evapotranspiration is 725 mm.

The maximal feasible yield at harvest is simulated for each year by STICS. Simulations have been run over thirty years (1978-2007) for each combination of SFM and input intensity. Summary statistics of $Y_{\max}(\tilde{\epsilon}_c, k, i)$ are presented in Table 3. Absent any impact of take-all, the highest average yield is obtained with conventional input use and a bare soil during summer. This management option is also characterized by the lowest variability among conventional input use systems. In accordance with the above discussed assumption governing the level of N fertilization, input intensity has a significant impact on wheat yield, with low input systems leading to 26% lower yields on average than conventional ones.

		Mean	Std dev.	Max	Min
BS	C	9.10	1.56	11.10	5.09
	L	7.13	1.11	8.47	4.42
WV	C	9.00	1.73	11.19	4.32
	L	7.12	1.22	8.50	3.86
EM	C	8.98	1.76	11.22	4.19
	L	7.01	1.25	8.54	3.63
LM	C	8.94	1.87	11.33	4.19
	L	7.10	1.31	8.52	3.71

Table 3: Wheat yields (in t.ha^{-1}) from STICS Simulations 1978-2007

3.3   Economic parameters

Unit costs associated with the eight management options are given in Table 4. These costs include fixed and variable costs associated with summer fallow managements, fertilization, and other field operations (sowing, chemical protection) described in Table 2.

Fertilizer cost is based on a fertilizer price assumption of 1 €.kg^{-1} and on quantities corresponding to the respective yield target of conventional and low input systems. The unit cost of production ranges from 369 €.ha^{-1} for WV with low level of input intensity to 737 €.ha^{-1} in the case of EM with a conventional level of input. The cost advantage of WV is mainly due to the absence of costs during the summer fallow period. Therefore, it allows savings compared to BS, which requires three stubble ploughing during summer.

k	i	Unit costs[*] (c)	N-fertilizer costs [**] (wx)			SF management (c_{SF})	Other costs (c_0)
			Mean	Min	Max		
		($\text{\euro}.\text{ha}^{-1}$)	($\text{\euro}.\text{ha}^{-1}$)			($\text{\euro}.\text{ha}^{-1}$)	($\text{\euro}.\text{ha}^{-1}$)
BS	C	728	198	170	220	60	470
	L	435	123	95	145	60	252
WV	C	656	201	180	210	-	455
	L	369	126	100	135	-	243
EM	C	737	211	200	225	71	455
	L	451	137	125	150	71	243
LM	C	671	214	195	225	71	386
	L	453	139	115	150	71	243

[*] Using average quantity of fertilizer use. [**] Based on a fertilizer price of 1 $\text{\euro}.\text{kgN}^{-1}$ (see text).

Table 4: Costs of production

The cost of a mustard cover crop includes one stubble ploughing in August, the sowing of the cover crop and the destruction of the cover crop (in mid October and mid-november for EM and LM, respectively). The SFM choice induces some minor differences in the other production costs. The late mustard cover crop implies lower production costs in C management due to the assumption of late sowing excluding the need for chemicals during implantation.

The wheat price effectively paid to farmers (p, in $\text{\euro}.\text{t}^{-1}$) varies according to the protein content (r_p, in percent). Based on the information provided by a large grain cooperative in the area of study (2008), we use a price scheme, whereby a high (low) protein content triggers a premium (penalty) relative to some reference price (p_i):

$$p = \begin{cases} p_i - 5 & \text{if } r_p < 10\% \\ p_i - 2(11 - r_p) & \text{if } 10\% \leq r_p \leq 11\% \\ p_i + 2(r_p - 11.5) & \text{if } 11.5\% \leq r_p \leq 12.5\% \\ p_i + 2 & \text{if } r_p > 12\% \end{cases} \tag{9}$$

r_p is calculated by STICS and depends on climatic conditions and the wheat crop management. In the base simulations (see Section 4), p_i is set to 200 $\text{\euro}.\text{t}^{-1}$ and wheat area is set to one hectare ($a = 1$). These assumptions will be relaxed in the sensitivity analysis presented in Section 5.

In the base simulations, we set the parameters defining the farmer's utility function to satisfy the usual properties of farmer's risk preferences, including decreasing absolute and relative risk aversion (see Chavas and Holt, 1996). γ, β and η are set to -3, 0.1, and 1, respectively. For a total profit equal to 5,000$\text{\euro}$, the levels of absolute and relative risk

aversion are respectively 0.08 and 0.49 which is compatible with a moderately risk-averse farmer. In Section 5, a wider range of these values will be explored.

3.4 Take-all incidence and yield loss

Ennaïfar et al. (2007) have developed several models to predict the incidence of take-all disease on winter wheat as a function of crop management, soil characteristics, and climate. The models have been built and validated on a large database, which includes data on the area of study. It has been shown that the use a disease measurement at a very early stage of the plant cycle greatly improves the prediction of the models. In our simulations, we chose StatL1+ , an additive static model with one of the best predictive value (Ennaïfar et al., 2007).

This disease score (Fsem30) is the percentage of plants with diseased seminal roots at the leaf shealth erect stage of the crop cycle (GS30). From this score, the epidemiological model predicts the percentage of wheat yield loss.

Other variables of the epidemiological model include climatic variables, soil texture, field crop history (two preceding crops and tillage management), sowing density, amount of ammonium in nitrogen fertilization applications.

Ennaïfar et al. (2005) have showed that the type of the cover crop has a strong influence on the Fsem30 value of the following wheat. Following Ennaïfar et al. (2005), the range of expected Fsem30 values for each are set to (0, 20, 40) for BS, (20, 35, 50) for LM, (40, 55, 70) for EM, and (70, 85, 100) for WV. In the base simulations, the two extreme realizations of the FSem30 ranges are assigned the same probability (1/6), whereas the central value is assigned a probability of 2/3. The climatic parameters are drawn randomly among the set of climatic years. Each year is assigned the same probability.

The take-all related yield loss $\phi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)$ is calculated for each year, each SFM, each level of input intensity, and each value of Fsem30. Summary statistics of the resulting values are provided in Table 5.

As expected, the lowest reduction in wheat yield obtained under BS management, whereas WV is the most vulnerable SFM. The introduction of catch crop (either EM or LM) lead to intermediate performances in term of wheat yield.

		Mean	Std dev.	Max	Min
BS	C	7.96	6.17	22.71	0.00
	L	7.68	6.05	22.27	0.00
WV	C	35.50	6.21	46.11	20.94
	L	35.15	6.28	45.93	20.50
EM	C	21.50	7.09	36.03	7.45
	L	21.06	7.07	35.65	7.14
LM	C	15.10	6.38	28.75	4.16
	L	13.66	6.21	27.07	3.11

Table 5: Yield loss (in %) due to the take-all disease Simulations 1978-2007 for the three level of FSEM30 per summer fallow × crop management

3.5 N-leaching estimations and its implementation in the economic model

N leaching is obtained by combining simulations both from the agronomic and the epidemiological model. N-leaching depends on the amount of soil mineral nitrogen during the period of high rainfall and low vegetation growth (autumn and winter). Two components play a role in N leaching: *(i)* initial soil residual nitrogen after the harvest of the preceding crop, and *(ii)* N uptake during and after the inter cropping season. The introduction of a cover crop tends to increase N uptake. Wheat management (in particular N-fertilization), climatic conditions and take-all disease severity have an impact on N-uptake and on final soil residual nitrogen, which in turn may result in N-leaching the following year. As our approach is static, we have to take into account the variations between initial and final residual nitrogen in the soil, which represents a potential N-leaching. To this effect, we distinguish between two components in total N-leaching:

$$n(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i) = n_L(\tilde{\epsilon}_c, k, i) + b(k) \left(\text{HRN}(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i) - \text{HRN}_{\text{init}} \right) \tag{10}$$

In Equation (10), $n_L(\tilde{\epsilon}_c, k, i)$ represents the 'direct' (per hectare) N-leaching, which depends only on the initial soil nitrogen after the preceding wheat harvest and on the cover crop management[3]. n_L is obtained from STICS simulations results. HRN_{init} is the initial soil residual nitrogen at harvest, assumed to be 40 kg.ha^{-1}. $\text{HRN}(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)$ is the soil residual nitrogen. It accounts for the quantity of nitrogen that has not been absorbed because of the disease. We use the same assumptions as Goulevant et al. (2008) with regard to the share of this quantity of nitrogen that remains in soil. Last, $b(k)$ is the

---

[3]This component may also depend, albeit to a very limited extent, on wheat management because of minor differences in implantation techniques between management systems.

SFM-specific N-leaching effect of the residual nitrogen in soil. It is obtained from an estimation of the relationship between the N-leaching and the soil residual nitrogen at harvest, through simulations using STICS over thirty years under different soil residual nitrogen levels and for the different cover crop managements (Goulevant et al., 2008).

		Mean	Std dev.	Max	Min
BS	C	8.183	13.730	49.930	-5.520
	L	8.175	14.147	51.310	-5.290
WV	C	6.841	11.221	36.200	-5.200
	L	6.607	11.558	37.800	-5.200
EM	C	5.538	9.085	32.920	-4.420
	L	5.661	9.522	34.600	-4.420
LM	C	5.741	9.226	27.740	-5.520
	L	5.801	9.571	27.555	-5.290

Table 6: Total N-leaching (in kg ha^{-1}) from STICS simulations 1978-2007 including the impact of take-all disease

The effective N-leaching by SFMs and by level of input intensity are given in Table 6. As expected, using a white mustard as a catch crop results in the lowest average N-leaching. White mustard has been proved to reduce leaching by a fast growth rate and a high N-uptake (Atallah and Lopez-Real, 1991). This is reinforced by its impact on take-all disease (Angus et al., 1994; Ennaïfar et al., 2005). Conversely, 'bare soil' is the worst SFM in terms of N-leaching. With a BS soil tillage simply consists in some stubble ploughings during the summer period, at given depth. As a result, the risk of N-leaching from harvest of the preceding wheat to sowing is high. Yet, as shown by Ennaïfar et al. (2007), BS significantly reduces the risk of take-all. Wheat volunteers systems play a role in reducing nitrate leaching (see also Macdonald et al., 2005). However, such systems increase take-all incidence and severity on the following wheat crop (Ennaïfar et al., 2005).

4   Results

The base scenario assumptions regarding input parameters discussed in Section 3 are summarized in Table 7 (column 'Base'). Wheat and fertilizer prices correspond to observed levels in 2007. The distribution of the probability of occurrence of one particular Fsem30 value (out of three) plays a key role in the assessment of the impact of take-all risks. In absence of sufficient experimental evidence, we assume that the central value of the range given by Ennaïfar et al. (2007) for each management system is associated with a

	Assumptions		
	Base	Sensitivity analysis	
Economic parameters			
Wheat price (p_i)	200 €.t^{-1}	[90; 290]	(Uniform)
Area (a)	1 ha	[1; 50]	(Uniform)
Fertilizer price (w)	1 €.kgN^{-1}	[0.5; 4]	(Uniform)
N-leaching tax (τ)	0 €.kgN^{-1}	[0; 4.5]	(Uniform)
Utility function			
β	-0.1	[0.1; 2]	(Uniform)
η	1	[5; 10]	(Uniform)
γ	-3	[−3; −1]	(Uniform)
Range of FSem30			
(f_1, f_2, f_3)	BS: (0, 20, 40); WV: (70, 85, 100); EM: (40, 55, 70); LM: (15, 30, 45)		
Probability of each FSem30 *			
(P_1, P_2, P_3)	(1/6, 2/3, 1/6)	$P_1 \in [0; 1/3]$, $P_1 = P_3$, $P_2 = 1 - P_1 - P_3$	(Uniform)

* P_i denotes the probability of Fsem30 being equal to f_i.

Table 7: Input parameters: Assumptions in the base scenario and in the Monte Carlo sensitivity analysis

probability $P_2 = 2/3$ and that the probabilities that the two extreme values occur are equal to $P_1 = P_3 = 1/6$.

Economic indicators for each of the eight management systems examined under the base asumptions are presented in Table 8. We first consider the situation in which the risk of a take-all outbreak is not taken into account by the farmer. The impact of take-all on yield ($\phi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)$) is thus set to 0 for all management systems. It follows that $Y(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)$ is assumed to be equal to $Y_{\max}(\tilde{\epsilon}_c, k, i)$ for all (k, i) in this case; the only remaining risk faced by the farmer therefore results from climate variability. Columns 3 to 5 in Table 8 present the corresponding results in terms of expected utility and mean and variance of profit. Columns 7 to 9 refer to the case where the farmer's optimization program includes the take-all effect $\phi(\tilde{\epsilon}_c, \tilde{\epsilon}_d, k, i)$. The latter is computed based on the relationships given by Ennaïfar et al. (2007).

Under the base assumptions and when the risk of yield loss due to take-all is ignored by the farmer, WV (wheat volunteers) combined with conventional input use yields the highest expected utility. This system is associated with low costs and relatively high yield (absent any take-all impact). However, this system is also the most vulnerable to the development of the take-all disease. It is therefore not chosen when take-all related yield loss is accounted for. In the latter case, the optimal summer fallow management consists

k	i	Without take-all risk				With take-all risk			
		$EU(\Pi)$	$E(\Pi)$	$V(\Pi)$	$\underline{s}$	$EU(\Pi)$	$E(\Pi)$	$V(\Pi)$	$\underline{s}$
			(k€.ha^{-1})		(k€.ha^{-1})		(k€.ha^{-1})		(k€.ha^{-1})
BS	C	-1.233	1.066	7.642	0.051	**-1.245**	0.930	7.238	.
	L	-1.241	0.968	3.926	0.147	-1.251	0.866	3.738	0.063
WV	C	**-1.228**	1.118	9.460	.	-1.286	0.483	4.717	0.445
	L	-1.236	1.029	4.731	0.086	-1.281	0.534	2.441	0.394
EM	C	-1.236	1.030	9.761	0.088	-1.271	0.649	6.975	0.281
	L	-1.245	0.928	4.968	0.187	-1.272	0.636	3.606	0.291
LM	C	-1.230	1.095	10.938	0.024	-1.254	0.828	8.732	0.102
	L	-1.243	0.945	5.345	0.170	-1.261	0.755	4.513	0.173

Table 8: Expected utility, expected profit, variance of profit, and minimum subsidy under base assumptions with (right) and without (left) taking into account take-all risk. The highest expected utility in each case is indicated in bold.

of bare soil from harvest of the preceding crop to sowing. In both cases, conventional input use is preferred.

Obviously, our assumptions regarding the parameters of the utility function matter in the ranking of management systems. The base combination of assumptions for β, γ, and η leads to a quite moderate risk-aversion. As an illustration, regardless of the role of take-all on yields, the preferred management system pertains here to the highest expected profit, as well as a relatively high level of variance.

In order to compare management systems yielding profits that differ in both expected levels and variability, we compute the minimum payment $\underline{s}$ for each management system such that it emerges in the optimum. $\underline{s}$ is thus the solution of Equation (6) and embeds not only the differences in profitability, but also the risk premium differential. The results without and with take-all risk are presented in columns 6 and 10 of Table 8, respectively.

Absent any yield loss due to take-all, $\underline{s}$ ranges from 24 to 187 €.ha^{-1}. (By (8), the minimum subsidy for the optimal system $(\hat{k}, \hat{i})$ under the base assumptions is zero). The implementation of a mustard combined with late crushing, late sowing of wheat, and combined with conventional management (LM,C) requires a payment of only 24 €.ha^{-1} to secure the same expected utility as (WV,C). This low level of $\underline{s}$ can be explained by the cost advantage of (LM,C) that compensates low yields and a high variance of profit. At the other end of the spectrum, early mustard (EM) combined with low input use requires the highest payment to match the expected utility associated with (WV,C). Whatever the type of SFM, low-input management systems require higher payments than

conventional management, reflecting the absence of incentives to internalize environmental externalities.

When accounted for, the risk of a take-all outbreak greatly modifies the ranking of management systems based on expected utility. This changes explained by the change in both absolute levels of profit and probability distribution. From the results presented in Table 8, one can note that the choice of SFM matters more than input management in this ranking. As WV-based systems are the most vulnerable to take-all risk, the payment needed for these systems to yield the same expected utility as (BS, C) is markedly higher than without take-all risk. It reaches 394 and 445 €.ha^{-1} in the case of low and conventional input use, respectively. Interestingly, low-input management requires a smaller payment than conventional management when combined with wheat volunteers. This is due to a lower variance of yields in this case.

As it lowers the farmer's exposure to take-all risks, bare soil-based systems plays the role of an insurance and clearly outperforms all other SFM systems. Even combined with low input use, 'bare soil' yields higher expected utility than any other management system. For all other SFM, the payment needed to match BS expected utility is greater than in the case without take-all risk. At least 102 €.ha^{-1} are needed for a catch crop to emerge in the optimum. Such a level of subsidy would allow a late crushing mustard combined with conventional input management to break even with (BS,C). Again, this reflects a cost advantage of LM over EM that offsets the yields differential. An additional payment of 71 €.ha^{-1} is needed for farmers to adopt LM in combination with low-input management systems.

As SFM and input management systems have contrasted impacts on the environment, we examine how farmers' optimal choice might be affected by policy instruments. We first introduce a tax on N-leaching. We assume that N-leaching can be observed and computed using equation (10). The examined tax varies from 0 to 4.5 €.kgN^{-1} by steps of 0.5€. The corresponding results are presented in Figures 1.a and 1.b. Again, we distinguish between whether take-all risks are accounted for (right) or not (left) by the farmer.

Even for high levels of the tax on N-leaching, the ranking of SFM and input management systems is not modified. This suggests that the differences in N-leaching are not sufficiently large to offset differences in cost and yield differential. Of course, the profit is reduced by the introduction of the tax. But the ranking of expected utilities is not

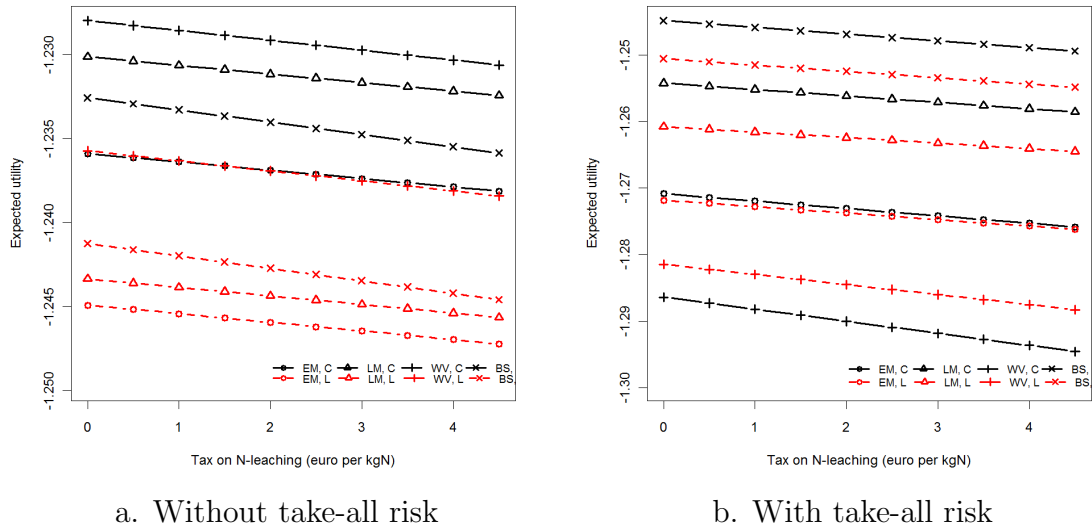| a. Without take-all risk | b. With take-all risk |

Figure 1: Impact of an N-Leaching tax on expected utility

modified to the extent that it triggers a change in optimal management under the base assumptions.

The picture is different when a tax on fertilizer use is introduced. Figures 2.a and 2.b present the results (without and with take-all risk, respectively) for a tax on fertilizer ranging from 0 to 2.25 €.kgN^{-1}. Practices that rely on conventional wheat management are relatively more penalized by such a tax. The relative profitability of low-input management systems therefore increases with respect to the fertilizer tax. For a given SFM, the tax triggers a switch from conventional to low-input systems for levels of the tax above 0.75 €.kgN^{-1}. Two exceptions are however noteworthy when take-all risks are taken into account: WV, for which low-input management dominates conventional management without any tax on fertilizer, and EM, for which a small tax is sufficient for low-input systems to yield a higher expected utility than conventional management.

Nevertheless, the introduction of a fertilizer tax does not modify the optimal choice of summer fallow management. The latter is robust to relatively large changes in N-input prices. Under our base assumptions and whatever the level of the tax, WV yields the highest levels expected utility when yield losses due to take-all are not taken into account, and BS remains preferable when this risk is accounted for by the farmer. The only change triggered by the fertilizer tax is a switch from conventional to low-input systems. This occurs for a tax in the neighborhood of 1.25 and 0.75 €.kgN^{-1} for WV (without take-all) and BS (with take-all), respectively.

18

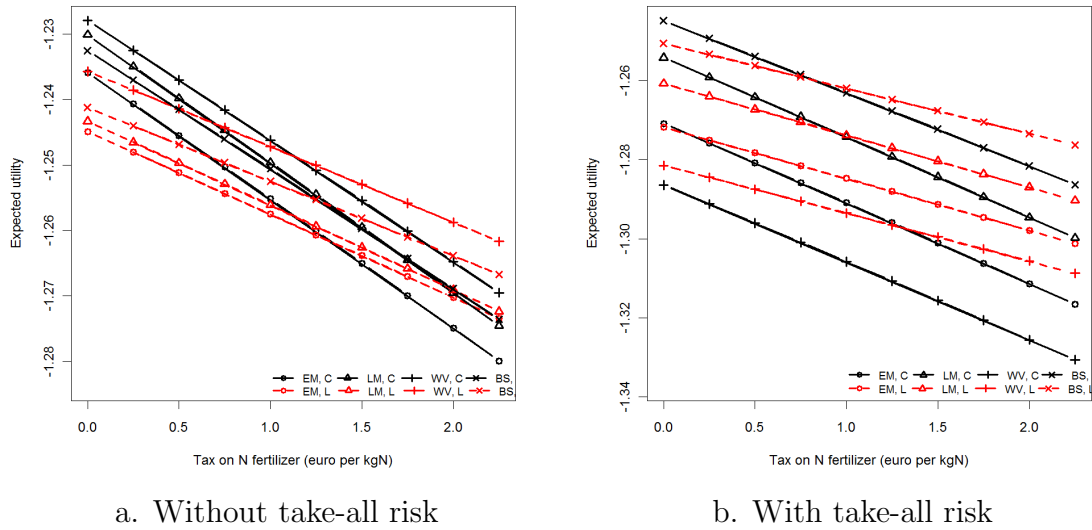a. Without take-all risk   b. With take-all risk

Figure 2: Impact of a tax on N fertilizer on expected utility

5 Sensitivity analysis

In order to assess the robustness of the SFM choices, we conduct a sensitivity analysis. As experimental data are not sufficient to set the input parameters based on observed ranges for all the relevant parameters, we rely on Monte Carlo simulations.

Three main categories of input parameters are examined: economic parameters, the probability of occurrence of extreme realisations of Fsem30, and the farmer's attitude toward risk as summarized by the parameters defining the utility function (see equation (4)). The ranges and distribution used in the Monte Carlo sensitivity analysis are summarized in the last column of Table 7.

The wheat price range (before adjustment for protein content) is set slightly wider than the maximum spread in observed farm prices over the period 2000-2007. The range assumed for fertilizer price is also admittedly wide compared to historic and current prices. This assumption has been made in order to accommodate for the possibility of a fertilizer tax, the introduction of which is formally equivalent to an increase of the nitrogen price in the model. In addition, we consider the possibility of a tax on N-leaching. The combination of a tax on N-leaching and potentially high nitrogen price tends to favor the adoption of low input management systems in comparison to the base simulations. Total farm-level wheat area was normalized to unity in the base scenario. It is now allowed to vary from 1 to 50 ha to account for the impact of wealth on the farmer's risk aversion.

The probability that a particular value of Fsem30 occurs (out of three possible outcomes for each SFM) affects the expected utility through its impact on wheat yield. We relax the assumption about the distribution made in the base scenario. However, we maintain that the central value of Fsem30 provided by plant pathologists remains the mode ($P_2 \geq \frac{1}{3}$). Furthermore, we assume that the two extreme outcomes of FSem30 are equiprobable ($P_1 = P_3$). The corresponding probabilitues are randomly drawn from $[0; \frac{1}{3}]$.

The parameters defining $U(.)$ are randomly drawn, and chosen such that the conditions implied by the HARA functional forms are fulfilled. Instead of imposing *a priori* restrictions on the values of β, η, and γ, we draw these values from independent distributions and retain only the combinations that ensure that $U(.)$ is defined with the appropriate properties.

The set of input parameters is constructed by iteratively and independently drawing their values from uniform distributions, which ranges are given in Table 7. 10,000 sets of parameters are contructed. 8,180 are kept after discarding the combinations that do not fulfill the conditions given in Section 2. The simulations are replicated with two sets of parameters. In both sets, the parameters have the same values except for the take-all related yield loss and its impact on N-leaching, which is set either to 0 ("without take all") or computed by the take-all model ("with take-all").

The results confirms the advantage of wheat-volunteers (WV) when the take-all risk is ignored. This SFM yields the highest expected utility in a vast majority of the simulations (95%, 69% combined with low input and 26% combined with conventional management). In the remaining 5%, BS emerges as the optimal SFM in almost all the cases combined with a conventional input management system. When the probability of yield loss due to take-all is accounted for, the dominance of BS is also confirmed. Over the whole set of conducted simulations, this SFM is the only one that emerges in the optimum. It is combined with low input management in 69% of the simulations.

Figures 3.a and 3.b summarize the distribution of the minimal subsidy needed for each management system to yield the maximal expected utility (see also Figures 4 and 5 in appendix). For all management systems but BS, the distribution of the minimum subsidy is shifted upward in the "with take-all" case relatively to the "without take-all". This indicates that the relative efficiency of BS in terms of preserving the crop from a disease outbreak is large compared to the effect on leaching of alternative management

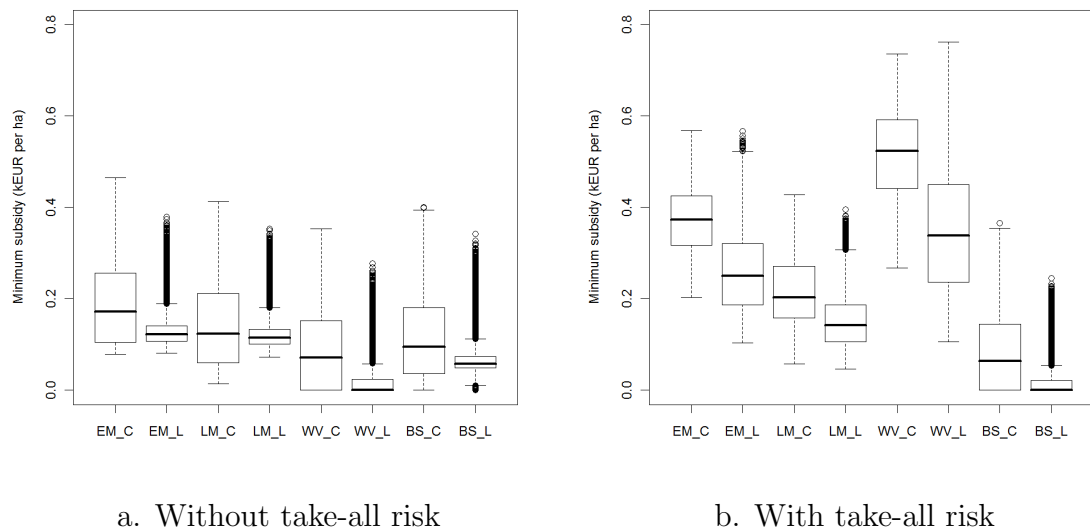| a. Without take-all risk | b. With take-all risk |

Figure 3: Monte Carlo sensitivity analysis: Summary of the distributions of $\underline{s}$ with (right) or without (left) take-all risk

systems. The insurance effect of a bare soil between the harvest of the preceding crop and the sowing of wheat clearly dominates other yield and cost considerations for a wide range of parameter values.

On average, the adoption of mustard would require a minimum subsidy amounting to 127 €.ha^{-1} absent any risk of take-all, and 152 €.ha^{-1} if take-all risks are accounted for. In both cases, these amounts would be sufficient (on average) for a mustard with a late destruction date and low-input management to compete with the optimal management. Interestingly, the minimum subsidy associated to this type of SFM is also characterized by a relatively low variance in comparison to other SFM. It could thus be considered as a potential candidate for a policy encouraging the adoption of catch crop in the area of study.

6   Concluding remarks

The choice of the type of summer fallow management in between a wheat-wheat succession involves trade-offs between *(i)* standard private interests as reflected in yields and costs, *(ii)* environmental impacts on water quality through N-leaching, and *(iii)* risk management of a disease outbreak potentially detrimental to the crop. In this paper, we have combined results from economics, plant pathology, and agronomy to shed some light on this type of situations.

		Without take-all risk				With take-all risk			
		Mean	Std dev.	Min	Max	Mean	Std dev.	Min	Max
			(€.ha^{-1})				(€.ha^{-1})		
BS	C	114	92	0	400	84	87	0	365
	L	74	50	0	342	22	44	0	244
WV	C	87	86	0	353	514	99	267	736
	L	24	48	0	277	349	138	105	762
EM	C	189	91	78	465	373	74	202	568
	L	136	48	80	379	260	90	103	567
LM	C	142	92	13	412	216	77	56	428
	L	127	44	72	353	152	62	45	396

Table 9: Monte Carlo sensitivity analysis: Summary statistics of $\underline{s}$ with (right) or without (left) take-all risk

The case study examined in this paper is illustrative of such trade-offs. If the risk of disease is ignored by farmers, the type of summer fallow management favored by private incentives alone ("wheat volunteers", WV) is also the 'worst' practice with respect to the development of the disease, possibly leading to significant yield losses. At the same time, the practice that yields the highest expected utility to farmers fully aware of the disease risk ("bare soil", BS) is also the 'worst' with respect to its impact on water quality through N-leaching.

Between those two management systems, adoption of a catch crop may appear as an interesting alternative choice as it provides higher environmental benefits than BS (through reduction of N leaching), as well as a lower exposure to take-all risk than WV because of the 'biofumigation' effect. The results of the simulations conducted in this paper tend to confirm that private incentives alone are not sufficient to prompt farmers to adopt mustard as a catch crop. However, the results also show that a standard price instrument on N leaching might not be sufficient to trigger adoption either, even for high tax levels compared to current nitrogen prices and even when take-all risks are fully taken into account by farmers.

The main reason is that the beneficial effect of BS in preventing the development of the disease provides a protection to the farmer against yield loss. This beneficial (private) impact offsets the negative (and public) consequences on nitrogen leaching. Hence, any incentive scheme meant to convince farmers to switch away from BS must therefore compensate for the increase in risk, not only for increased costs and/or lower yields.

From a public policy perspective, N leaching concern and/or take-all risk manage-
ment alone do not justify subsidies, in the context of our case study, to encourage catch
crop adoption within a wheat-wheat succession. Should such payments be implemented,
they should be motivated by the presence of other externalities (soil erosion, water man-
agement, preventing loss of soil organic matter). One finding of the paper is that the
minimum compensation required for farmers to implement a white mustard instead of
BS (when combined with some policy instruments affecting the nitrogen input price) lies
in a range that is comparable to existing CAP-related environmental payments. In this
case, the combination of a catch crop that is destroyed late in the season and a low-input
management may be chosen by risk-averse farmers and would provide some environmental
benefits (reduction of N leaching).

This work can be extended in several directions. The introduction of the possibility of
seed treatment in the economic framework is one. Another is to explicitly account for the
dynamic nature of the problem, both regarding the nitrogen cycle and crop rotation. This
would involve to endogenously determine, rather than impose, the post harvest residual
nitrogen and thus initial soil nitrogen for the following crop. This is left for further
research as it requires a full coupling of the economic and crop-soil models.

References

Angus, J., Gardner, J., Kirkegaard, J., and Desmarchelier, J. (1994). Biofumication:
isothiocyanates released from Brassica roots inhibit growth of take all-fungus. *Plant
and Soil*, 162:107–112.

Atallah, T. and Lopez-Real, J. (1991). Potential of green manure species in recycling
nitrogen, phosphorus and potassium. *Biological Agriculture & Horticulture*, 8:53–65.

Brisson, N., Mary, B., Ripoche, D., Jeuffroy, M.-H., Ruget, F., Nicoullaud, B., Gate, P.,
Devienne-Barret, F., Antonioletti, R., Durr, C., Richard, G., Beaudoin, N., Recous,
S., Tayot, X., Plenet, D., Cellier, P., J-M., M., Meynard, J.-M., and Delécolle, R.
(1998). STICS: A generic model for the simulation of crops and their water and nitro-
gen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie*,
18:311–346.

Chavas, J. and Holt, M. (1996). Economic behavior under uncertainty: A joint analysis of risk preferences and technology. *Review of Economics and Statistics*, 78:329–335.

Council of the European Communities (1991). Council directive concerning the protection of waters against pollution caused by nitrates from agricultural sources. Council Directive 91/676/EEC, Council of the European Communities.

Dorsainvil, F. (2002). *Evaluation, par modélisation, de l'impact environnemental des cultures intermédiaires sur les bilans d'eau et d'azote dans les systèmes de culture.* PhD thesis, INA P-G, Paris, Paris, France. 124 pp.

Ennaïfar, S., Lucas, P., Meynard, J.-M., and Makowski, D. (2005). Effects of summer fallow management on take-all of winter wheat caused by gaeumannomyces graminis var. tritici. *European Journal of Plant Pathology*, 112:167–181.

Ennaïfar, S., Makowski, D., Meynard, J.-M., and Lucas, P. (2007). Evaluation of models to predict take-all incidence in winter wheat as a function of cropping practices, soil, and climate. *European Journal of Plant Pathology*, 118:127–143.

Goulevant, G., Jeuffroy, M., Lucas, P., Montfort, F., De Cara, S., Jacquet, F., and Reynaud, A. (2008). Combining crop and epidemiological models to simulate the impact of summer fallow management between two consecutive winter wheat crops on n-leaching and take-all disease incidence: application to two regions of france. Technical report, INRA.

Justes, E., Dorsainvil, F., Alexandre, M., and Thiébeau, P. (2004). Simulation with STICS soil-crop model of catch crop effect on the nitrate leaching during fallow period and N release for the succeeding main crop. Controlling nitrogen flows and losses. In *12th Nitrogen Workshop*, pages 122–130, Exeter, UK. University of Exeter.

Justes, E. and Mary, B. (2004). N mineralisation from decomposition of catch crop residues under field conditions: measurement and simulation using the STICS soil-crop model. Controlling nitrogen flows and losses. In *12th Nitrogen Workshop*, Exeter, UK. University of Exeter.

Kirkegaard, J., Gardner, P., Angus, J., and Koetz, E. (1994). Effect of brassica break crops on the growth and yield of wheat. *Australian Journal of Agricultural Resources*, 45:529–545.

Lacroix, A., Beaudoin, N., and Makowski, D. (2005). Agricultural water nonpoint pollution control under uncertainty and climate variability. *Ecological Economics*, 53:115–127.

Macdonald, A., Poulton, P., Howe, M., Goulding, K., and Powlson, D. (2005). The use of cover crops in cereal-based cropping systems to control nitrate leaching in SE England. *Plant and Soil*, 273:355–373.

Meisinger, J., Hargrove, W., Mikkelsen, R., Williams, J., and Beson, V. (1991). Effects of cover crops on groundwater. In Hargrove, W., editor, *Cover crops for clean water*, pages 57–68, Jackson, Tennessee, USA. Soil and Water Conservation Society.

Merton, R. C. (1971). Optimum consumption and portfolio rules in a continuous-time model. *Journal of Economic Theory*, 3:373–413.

Ministère de l'Agriculture et de la Pêche (2007). Programme de developpement rural hexagonal. tome 4, annexe 2 Dispositions spécifiques à la mesure 214, French Ministry of Agriculture and Fisheries, Paris, France. 261 p.

Roberts, R. K., Walters, J. T., Larson, J. A., English, B. C., and Howard, D. D. (2004). Effects of disease, nitrogen source, and risk on optimal nitrogen fertilization timing in winter wheat production. *Agrononomy Journal*, 96(3):792–799.
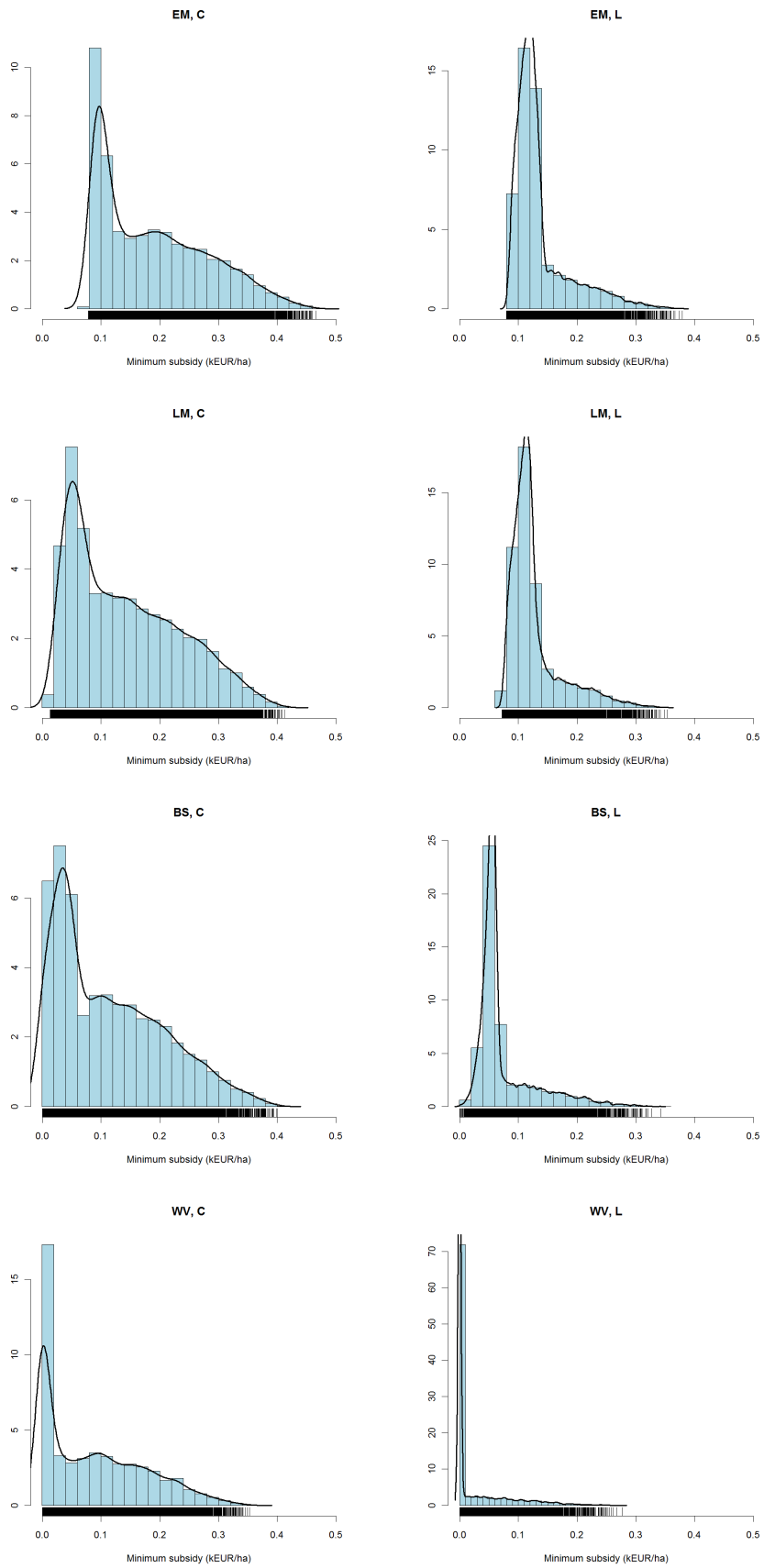
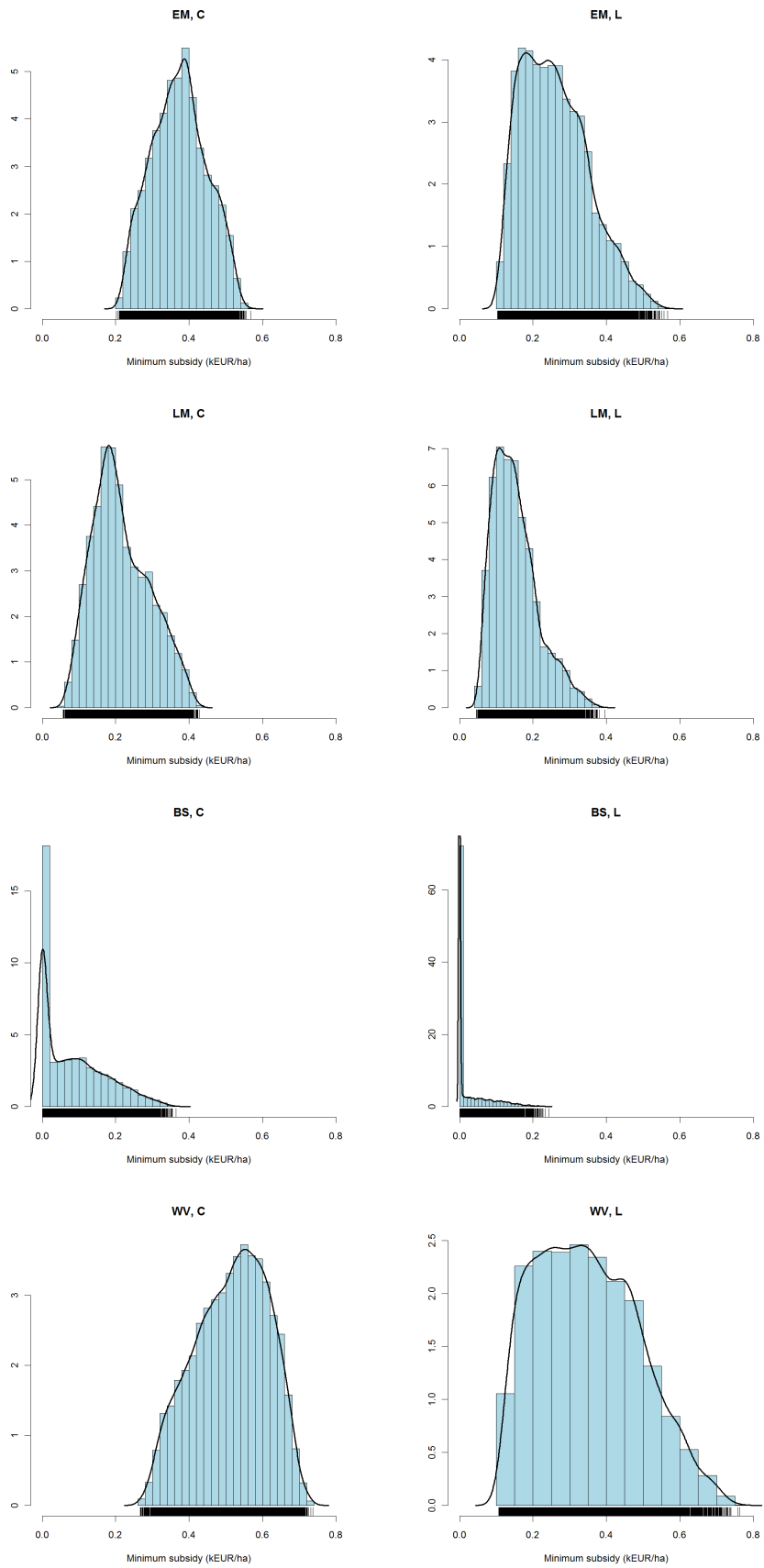Figure 4: Monte Carlo sensitivity analysis: Distribution of $\underline{s}$ without take-all risk

Figure 5: Monte Carlo sensitivity analysis: Distribution of $\underline{s}$ with take-all risk