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### ► To cite this version:

Sabine-Karen Lammoglia, Marc C. Kennedy, Enrique Barriuso, Lionel Alletto, Eric Justes, et al.. Assessing human health risks from pesticide use in conventional and innovative cropping systems with the BROWSE model. *Environment International*, 2017, 105, pp.66-78. 10.1016/j.envint.2017.04.012 . hal-01522976v2

HAL Id: hal-01522976

<https://hal.science/hal-01522976v2>

Submitted on 28 Nov 2024

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# Assessing human health risks from pesticide use in conventional and innovative cropping systems with the BROWSE model

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**Lammoglia SK, Kennedy MC, Barriuso E, Alletto L, Justes E, Munier-Jolain N, Mamy L, 2017.** Assessing human health risks from pesticide use in conventional and innovative cropping systems with the BROWSE model. **Environment International, 105: 66-78.**  
**<http://dx.doi.org/10.1016/j.envint.2017.04.012>**

## HIGHLIGHTS

- Risks for human health due to pesticides use in various cropping systems are compared
- The risk for each pesticide was assessed with the BROWSE model
- A method was proposed to assess the overall pesticides risk for one cropping system
- Low input and no herbicide systems reduce risks for human health compared to conventional ones
- On the contrary, conservation tillage systems lead to unacceptable risks for human health

## ABSTRACT

*Background:* Reducing the risks and impacts of pesticide use on human health and on the environment is one of the objectives of the European Commission Directive 2009/128/EC in the quest for a sustainable use of pesticides. This Directive, developed through European national plans such as Ecophyto plan in France, promotes the introduction of innovative cropping systems relying, for example, on integrated pest management. Risk assessment for human health of the overall pesticide use in these innovative systems is required before the introduction of those systems to avoid that an innovation becomes a new problem.

*Objectives:* The objectives of this work were to assess and to compare (1) the human exposure to pesticides used in conventional and innovative cropping systems designed to reduce pesticides needs, and (2) the corresponding risks for human health.

*Methods:* Humans (operator and residents) exposure to pesticides and risks for human health were assessed for each pesticide with the BROWSE model. Then, a method was proposed to represent the overall risk due to all pesticides used in one system. This study considers 3 conventional and 9 associated innovative cropping systems, and 116 plant protection products containing 89 different active substances (i.e. pesticides).

*Results:* The modelling results obtained with BROWSE showed that innovative cropping systems such as low input or no herbicide systems would reduce the risk for human health in comparison to the corresponding conventional cropping systems. On the contrary, BROWSE showed that conservation tillage system would lead to unacceptable risks in the conditions of our study, because of a high number of pesticide applications, and especially of some herbicides. For residents, the dermal absorption was the main exposure route while ingestion was found to be negligible. For operators, inhalation was also a predominant route of exposure. In general, human exposure to pesticides and human health risks were found to be correlated to the treatment frequency index TFI (number of registered doses of pesticides used per hectare for one cropping season), confirming the relationship between the reduction of pesticide use and the reduction of risks.

*Conclusions:* Assessment with the BROWSE model helped to identify cropping systems with decreased risks from pesticides for human health and to propose some improvements to the cropping systems by identifying the pesticides that led to unacceptable risks.

### *Keywords:*

BROWSE model, Human exposure, Plant protection products, Risk assessment, Cropping system

## **1. Introduction**

The European Commission Directive 2009/128/EC (2009) established a framework to achieve sustainable use of pesticides by reducing the risks and impacts of pesticide use on human health and on the environment, and by promoting the use of integrated pest management (IPM) or alternative approaches of pest control or techniques (i.e. non-chemical alternatives to pesticides). This Directive should be applied in each European country with the development of specific programs, such as the Ecophyto plan in France (Ecophyto, 2015). Consequently, this obligation has led to the development and introduction of new cropping systems built on agronomic, mechanical, physical, and biological principles which all contribute to the reduction of the reliance on pesticides (Barzman et al., 2015). The assessment of the impacts of innovative systems is a prerequisite to their effective implementation and adoption to avoid that an innovation becomes a new problem (Diederer et al., 2003; Lançon et al., 2007). Evaluating the sustainability of such cropping systems is a complex task which has focused, so far, on the economic, environmental or social impacts (Lechenet et al., 2014; Sadok et al., 2008; Sadok et al., 2009; Vasileiadis et al., 2013).

Humans are exposed to pesticides by a number of routes: during manufacture, mixing/loading, spraying, harvest, and by consumption of treated crops derived products (Damalas and Eleftherohorinos, 2011; Damalas and Koutroubas, 2016; Maroni et al., 1999). The estimation or measurement of human (i.e. operator, worker, resident and bystander) exposure to pesticides is mandatory for their registration (Regulation EC No 1107/2009, 2009). Regulators of EU member states evaluate the levels of exposure and the toxicological risks of each pesticide (i.e. active substance) and plant protection product (PPP, i.e. containing one or more active substances, in the form in which they are supplied to the user) for their intended uses to ensure they have no harmful effect on humans. Risk assessment is mainly based on laboratory studies using animal species, generally the rodent (Damalas and Eleftherohorinos, 2011; Regulation EC No 1107/2009, 2009). When available, medical data relating to clinical cases and poisoning incidents are also used. The assessment of human exposure also relies on predictive modeling approaches. Several models are used such as the EUROPOEM (EUROpean Predictive Operator Exposure Model) (van Hemmen, 2001), the UK approach (Chemical Regulation Directorate, 2008), or the German model (Martin et al., 2008). Recently, a European project has delivered BROWSE (Bystanders, Residents, Operators and WorkerS Exposure models for plant protection products) (Butler Ellis et al., 2017a; Butler Ellis et al., 2017b; Kennedy and Butler Ellis, 2017), an improved modelling framework for human exposure which integrates large European guidance and regulatory databases to refine the assessment of human exposure. BROWSE has been tested and led to more realistic exposure predictions than the existing models because of improvements in

modelling: incorporation of many exposure routes, short term and long term exposures (Butler Ellis et al., 2017b). By using probability distributions to represent realistic variability in model parameters, instead of fixed high quantiles, the resulting exposure distributions output by the BROWSE software are considered to represent more realistic worst case scenarios with an appropriate level of conservatism (Butler Ellis et al., 2017b).

The exposure of humans to pesticides is usually assessed separately for each substance, even though humans can be exposed to a number of substances since several pesticides are commonly used to control various weeds, pests or diseases in the cropping systems. One study, that of Reganold et al. (2001), assessed the risks related to the overall use of pesticides in various apples perennial production systems using an environmental index which includes assessment of potential worker and consumer exposure to pesticides. They showed that organic systems ranked first in environmental sustainability, followed by integrated then conventional systems (the economic sustainability was also assessed and followed the same ranking). However, to the best of our knowledge, no risk assessment for human health of the overall pesticide use in cropping systems based on arable crops has been done. Thus, the objectives of this work were to assess and to compare, with the BROWSE model, (1) the human exposure to pesticides used in 3 conventional and 9 associated innovative cropping systems designed to reduce pesticide needs and (2) the corresponding risks for human health. As BROWSE considers only single pesticide usage per run, a method is proposed to represent the results obtained for all pesticides used in one system. This method enables to assess the overall pesticides risk for one system and then to compare various systems. The results will allow to identify the most efficient cropping systems to reduce the risks from pesticides for human health. The environmental (i.e. pesticides leaching), agronomic and technical (weed infestation, crop yield...), and economic performances of the systems will also be considered to determine whether the results obtained in this work are consistent with the recommendations based on the assessment of these other performances.

## **2. Material and methods**

### *2.1. BROWSE model*

BROWSE is a mechanistic model developed by the European project BROWSE ([www.browseproject.eu](http://www.browseproject.eu)) to predict human exposure from liquid and solid (including seed treatment) formulations of pesticides for the operators, workers, bystanders, and residents. From the amounts of pesticides humans are exposed to, BROWSE then estimates those that are likely to be absorbed through inhalation, dermal contact and ingestion. Finally, the model assesses the risk for human health due to the absorbed amounts of pesticides. This is explained in more details in section 2.1.3.

The model uses a probabilistic approach allowing the determination of a distribution of exposures. This approach also ensures that the worst case exposures, obtained by consideration of the higher percentiles, are simulated in rare cases, and is meant to represent more realistic scenarios (Butler Ellis et al., 2017a; Kennedy and Butler Ellis, 2017). Conservative assumptions are built into the BROWSE model, for example when real data are not available to parameterise the model.

### *2.1.1 Definition of operator and residents groups*

Operators are persons who are involved in activities relating to the application of a PPP: mixing/loading, application, emptying/cleaning the machinery after use, etc. They may be either professionals or amateur users (EFSA, 2014). Workers are persons who, as part of their employment, enter an area that has previously been treated with a PPP or who handle a crop that has been treated with a PPP (EFSA, 2014). In the BROWSE model, there is no scenario of workers exposure for arable crops because these crops are harvested with machines, therefore workers are not considered in this work.

Contrary to the EFSA definitions (EFSA, 2014), for the purposes of the BROWSE model, residents and bystanders are considered as a single group of persons (named here as “residents”). This group could be located within or directly adjacent to the area where PPP application or treatment is in process or has recently been completed; their presence is quite incidental and unrelated to work involving PPP, but their position might lead them to be exposed, irrespective of whether they live there or just visit the site. BROWSE also makes the distinction between adults and children (Butler Ellis et al., 2017a).

### *2.1.2 Assessment of operator and residents exposure to pesticides*

For operator, BROWSE considers three main routes of personal exposure: inhalation (via respiratory tract), dermal (via skin) and ingestion (via mouth). The dermal exposure is the most complex route of exposure and occurs through three potential pathways, i.e. deposition from the air, contacts of the hands and body with surfaces, direct transfer through splashes or dripping (from liquids) and impaction (from solids) (Damalas and Eleftherohorinos, 2011; Damalas and Koutroubas, 2016). The effects of work clothing and personal protective equipment (PPE) can be taken into account through coverage factors and pesticide migration factors through clothing and PPE.

For residents, BROWSE determines exposure to spray drift from boom sprayers during a spray application, as well as exposure to vapour and deposited spray drift following an application, assuming residents are immediately downwind of the application. For humans exposed during spray application, the routes of exposure

are spray coming into contact with their skin (direct dermal exposure) and spray being inhaled (inhalation exposure). For humans exposed after spraying, the routes are breathing in vapour which is emitted from the crop after application (inhalation exposure) and drifting spray settling on the ground followed by skin contact with the contaminated ground (indirect dermal exposure). In both situations, hand-to-mouth contact (ingestion exposure) can also be considered. Total exposure for residents includes all routes of exposure, added together probabilistically. Acute exposure over a period of up to 24 h is considered for people who are downwind and between 2 to 20 m from the treated area. Longer term exposure is considered for people who are in locations surrounded by fields on all sides at a distance of between 2 and 20 m, and remain there for 365 days a year (Butler Ellis et al., 2017a). The exposure to resident individuals is provided in the BROWSE output as short-term exposures, in addition to the long-term exposures. For residents, the PEARL-OPS module can provide inputs for estimating dermal and inhalation exposure by means of estimates of the dislodgeable foliar residue and the concentration of the substance in the air, respectively (van den Berg et al., 2016). The PEARL model describes the fate of the pesticide in the soil-plant system, while OPS simulates atmospheric dispersion and dry deposition of pollutants at the local scale. This module was not used in this work, so inhalation exposures were only calculated during mixing/loading procedures and from spray droplets.

### *2.1.3. Human health risk assessment*

As indicated above, the BROWSE model predicts exposure to pesticide that is likely to be absorbed through inhalation, dermal contact and ingestion. These routes are then summed together to produce a total exposure (Butler Ellis et al., 2017b). The output distributions (i.e. exposure) can be summarized by selecting a preferred quantile (Kennedy and Butler Ellis, 2017): the 50<sup>th</sup> percentile were retained in this work to avoid too high (90<sup>th</sup> percentile) or too low (10<sup>th</sup> percentile) exposure values that could be unrealistic.

From the amounts of pesticides humans are exposed to, BROWSE estimates the absorbed amounts taking account of protection by clothing, dermal absorption, and oral and inhalation absorption if appropriate (Butler Ellis et al., 2017b). We assumed that the operator uses the most protective PPE (see 2.3 Parameterization) and handle pesticides as advised in the safety information. PPE items provide effective protection only if they are adequate for the risk factor they are addressed to, in good condition of maintenance, and used in a proper way. We also assumed that PPE used for mixing/loading and application were similar for the different PPPs, although PPPs may have specific PPE requirements (Perry et al., 2002).

Finally, BROWSE calculates a “Human health risk index” (HR) dividing the absorbed amounts of each pesticide by the corresponding values of pesticide AOEL (Acceptable Operator Exposure Level). When the HR is higher than 100 %, the risk for humans (operator and residents) health is not acceptable. On the contrary, when the HR is lower than 100 %, the risk is considered acceptable. Specific AOEL values per compound allow for variations in toxicity to be accounted for when assessing health risks.

BROWSE considers only single pesticide usage per run. Therefore, to assess the overall pesticides risk for one system and then to compare various systems, all pesticides HR obtained with BROWSE for one system are presented as boxplots. This allows displaying the distribution of the HR and identifying the pesticides that may lead to unacceptable risks. The systems were compared from the maximum HR that were obtained and from the number of pesticides that exceeded the 100% threshold.

## *2.2. Cropping systems*

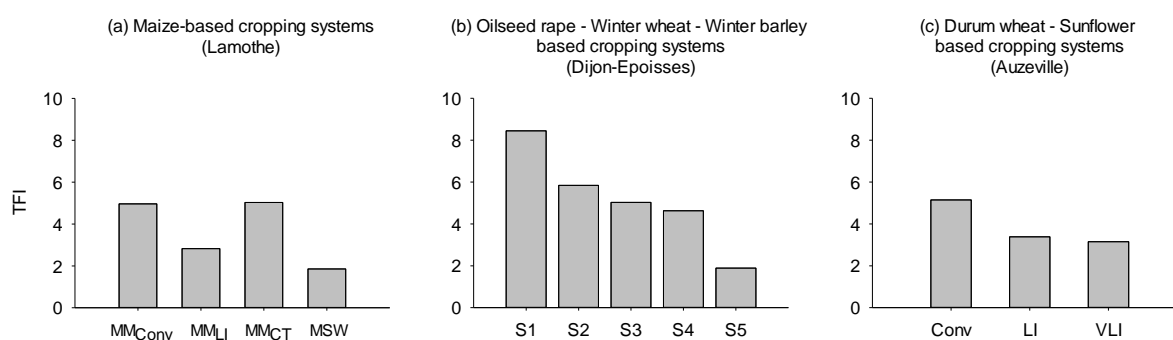
Twelve cropping systems (3 conventional and 9 innovative) tested in three French experimental sites have been selected to cover a wide diversity of (1) crops (alfalfa, barley, faba bean, maize, oilseed rape, pea, soybean, sorghum, sugar beet, sunflower, triticale, wheat), (2) cropping practices (cover crops, intercropping, conservation tillage, diversified crop rotation, mechanical weeding...), and (3) pesticide use. In total, 116 different PPPs containing 89 different active substances (i.e. pesticides) were used in the 12 systems (Tables 1 and 2). The number of pesticide applications in each system and the corresponding treatment frequency index (TFI) were considered to study the relationship between pesticide use and human exposure and human health risks. The TFI corresponds to the number of registered doses of pesticides used per hectare for one cropping season. For each system, an average TFI of all studied cropping seasons was then calculated (see 2.2.1 to 2.2.3). The innovative cropping systems are only compared to their reference conventional cropping systems and not among them because the durations of the rotations are different (Table 1).

### *2.2.1. Maize-based cropping systems*

The pesticide uses related to the maize-based cropping systems were obtained from the French Lamothe experimental site (INP-EI Purpan). This site was set up since 2011 with the objective to develop and evaluate the agronomic, environmental, and socio-economic performances of different maize-based cropping systems. One conventional irrigated maize monoculture and three low input maize-based cropping systems were designed and experimented. This study considers the four cropping systems from 2011 to 2014.



The “Conventional maize production” system ( $MM_{Conv}$ ) was designed to maximize the gross margin, according to the conventional system practiced in the Southwest France. In order to avoid water, nitrogen and macronutrients stresses, inputs were adjusted to yield targets objectives. The main agricultural operations consisted of a conventional tillage with a spring mouldboard ploughing (25 - 28 cm depth). A bare soil, without green cover but with maize residues cover, was kept in winter during the fallow period. From 2011 to 2014, 27 applications of pesticides were done, and the TFI was 4.9 (Fig. 1a, Table 1, Supplementary Table S1) (Giuliano et al., 2016).



**Fig. 1.** Treatment frequency index (TFI) of (a) maize-based cropping systems of Lamothe (mean TFI from 2011 to 2014.  $MM_{Conv}$ : Conventional system;  $MM_{LI}$ : Low input system;  $MM_{CT}$ : Conservation tillage system; MSW: Integrated maize rotation system), (b) oilseed rape – winter wheat – winter barley based cropping systems of Dijon-Epoisses (mean TFI from 2003 to 2014. S1: Conventional system; S2: Integrated weed management (IWM) reduced tillage system; S3: IWM without mechanical weeding system; S4: IWM with mechanical weeding system; S5: IWM no herbicide system), and (c) durum wheat – sunflower based cropping systems of Auzeville (mean TFI from 2011 to 2015. Conv: Conventional system; LI: Low input with cover crops system; VLI: Very low input with intercrops and cover crops system).

The “Low input maize monoculture” system ( $MM_{LI}$ ) was designed to reduce the use of N fertilizer by 25 %, herbicides by 50 % (thanks to mechanical weeding and on-row band spraying), and irrigation water by 25 % (using an early variety to reduce water needs and post-harvest drying costs). Soil and water protection was reinforced by using a cover crop (Giuliano et al., 2016) (Table 1). From 2011 to 2014, 16 applications of pesticides were done on this system corresponding to a TFI of 2.8 (Fig. 1a, Table 1, Supplementary Table S1).

**Table 1**

Description of the cropping systems based on maize monoculture (Lamothe), oilseed rape – winter wheat – winter barley rotation (Dijon-Epoisses), and durum wheat – sunflower rotation (Auzeville), and corresponding number of pesticide applications and treatment frequency index (TFI). Cover crops are written in *italic*. IWM: Integrated weed management.

Experimental site	Cropping systems	Crops sequence	Number of pesticide applications
Lamothe (2011 – 2014)	Conventional (MM <sub>Conv</sub> )	Maize – Maize – Maize – Maize	27
	Low input maize monoculture (MM <sub>LI</sub> )	Maize – <i>Hybrid ray grass + Red clover</i> – Maize – <i>Hybrid ray grass + Red clover</i> – Maize – <i>Hybrid ray grass + Egyptian clover</i> – Maize	16
	Conservation tillage maize monoculture (MM <sub>CT</sub> )	Maize – <i>Vetch + Phacelia + Oat</i> – Maize – <i>Vetch + Phacelia + Oat</i> – Maize – Faba bean + Sorghum – Maize	24
	Integrated maize rotation (MSW)	<i>Purple vetch + Phacelia</i> – Maize – Oat – Soybean – <i>Mustard</i> – Winter wheat	16
Dijon-Epoisses (2003 – 2013)	Conventional (S1)	Winter barley – Oilseed rape – Winter wheat – Winter barley – Oilseed rape – Winter wheat – Winter barley – Oilseed rape – Winter wheat – Winter barley – Oilseed rape	106
	IWM reduced tillage (S2)	Oilseed rape – Winter wheat – Spring barley – Sorghum – Faba bean – <i>Mustard</i> – Triticale – Oilseed rape – Winter wheat – <i>Oat + Vetch – Phacelia</i> – Spring barley – Oat – Soybean – Winter wheat	69
	IWM without mechanical weeding (S3)	<i>Mustard</i> – Winter wheat – Oilseed rape – Winter wheat – Triticale – Maize – Faba bean – Winter wheat – Spring barley – Oilseed rape – Winter wheat – Soybean – Triticale	71
	IWM with mechanical weeding (S4)	Winter wheat – Sugar beet – Triticale – Faba bean – Winter wheat – Oilseed rape – Winter wheat – Maize – Winter wheat – Spring barley – Triticale + Pea	63
	IWM no herbicide (S5)	Winter barley – Faba bean – Triticale – Oilseed rape – Winter wheat – Sorghum – Faba bean – Winter wheat – Alfalfa – Maize – Alfalfa – Winter wheat	25
Auzeville (2011 – 2015)	Conventional	Durum wheat – Sunflower – Durum wheat – Sunflower	24
	Low input with cover crops (LI)	<i>Phacelia + Purple vetch</i> – Sorghum – Sunflower + <i>Alfalfa + Egyptian clover + Red clover</i> – Durum wheat – <i>Mustard + Vetch</i> – Sorghum	17
	Very low input with intercrops and cover crops (VLI)	Triticale + Faba bean – <i>Mustard + Purple vetch</i> – Durum wheat + Pea – <i>Vetch + Oat</i> – Sunflower + Soybean – Durum wheat + Pea	15

The objectives of the “Conservation tillage maize monoculture” system ( $MM_{CT}$ ) were both to reduce pesticide leaching by 50 % and to reduce energy consumption and associated greenhouse gas emissions by 40 % compared to the “Conventional” system  $MM_{Conv}$ . To reach these objectives, conservation tillage practices were implemented and maize was either sown after strip tillage (2011 and 2012) or directly in no-tillage system (2013), and a cover crop was sown immediately after maize harvest. In this system, weeds were chemically controlled with the objective to reduce, if possible, the use of herbicides in comparison to the conventional system. A slight gross margin reduction of 10 % was accepted as compared to  $MM_{Conv}$  as a compensation of human labour reduction (Giuliano et al., 2016). The number of pesticide applications (24) and the TFI (5.0) were close to those of the conventional system (Fig. 1a, Table 1, Supplementary Table S1).

Finally, the “Integrated maize rotation” system (MSW) included a three-year rotation of maize – soybean – winter wheat and was designed to reduce, at the rotation level, the inputs of herbicides, irrigation water, and N fertilizer by 50 % compared to  $MM_{Conv}$ . The maize prioritized the same input reduction objectives as  $MM_{LI}$ , reducing the use of herbicides by 50 % and the use of N fertilizer and irrigation water by 25 %, while MSW aimed at maintaining the same gross margin as the  $MM_{Conv}$  (Giuliano et al., 2016). A total of 16 applications of pesticides was done, with a TFI of 1.9 (Fig. 1a, Table 1, Supplementary Table S1).

### *2.2.2. Oilseed rape – winter wheat – winter barley based cropping systems*

The data for the oilseed rape – winter wheat – winter barley based cropping systems were obtained from the INRA experimental site of Dijon-Epoisses. This site was set up in 2000 with the objective to study the economic, social, and environmental impacts of one conventional system and four associated innovative cropping systems based on integrated weed management (IWM) principles, aiming at gradually reducing the reliance on herbicides as compared to the conventional cropping system (Chikowo et al., 2009). In this work, a 10-year crop management period was studied (2003 to 2013).

The “Conventional” cropping system (S1) is an oilseed rape – winter wheat – winter barley rotation, one of the two most common crop rotations in France (Fuzeau et al., 2012). This system was designed to maximize the financial returns and emphasized the use of chemical herbicides for weed control. Mouldboard ploughing was carried out each year during summer and herbicides were chosen following the recommendations of extension services (Chikowo et al., 2009). One hundred and six applications of pesticides were done (Table 1, Supplementary Table S2). The corresponding TFI was high, being 8.4 (Fig. 1b).

The “IWM reduced tillage” cropping system (S2) was designed to reduce labour requirement. Time consuming operations such as mouldboard ploughing, rotary harrowing and mechanical weeding were excluded. All the other IWM techniques were used (diversified crop rotation, false-seed bed, late cereal sowings, competitive cultivars). This system is under no-till since 2006 (Chikowo et al., 2009). From 2003 to 2013, 69 applications of pesticides were done, and the TFI was 5.8 (Fig. 1b, Table 1, Supplementary Table S2).

The “IWM without mechanical weeding” system (S3) used mouldboard ploughing and other soil tillage operations to manage the soil seed bank, but excluded mechanical weeding considered as potentially too time consuming for some farmers, and/or difficult to implement in farms that do not have the proper equipment (Chikowo et al., 2009). A total of 71 pesticide applications was done leading to a TFI of 5.0 (Fig. 1b, Table 1, Supplementary Table S2).

The “IWM with mechanical weeding” system (S4) used all the prophylactic measures available to reduce the potential weed infestations. In this system, scarce herbicide applications were combined with mechanical weeding, using flex-tine harrow in cereals, flex-tine harrow followed by hoe in oilseed rape, and hoe in crops with large row spacing such as sugar beet, sunflower or faba bean. The crop rotation included sugar beet once in six years to test the possibilities of reducing the reliance on herbicide of this crop (which usually requires high amounts of herbicides) using in-crop mechanical weeding associated with on-rows herbicide application (band spraying) (Chikowo et al., 2009). Sixty-three pesticides were applied on this system (Table 1, Supplementary Table S2). The TFI was 4.6 (Fig. 1b).

Finally, an “IWM no herbicide” system (S5) was experimented. This system excluded the use of any herbicide, thus relying only on other physical and cultural means to control weed infestations. Fertilization was based on mineral fertilizers and the use of insecticides, fungicides and molluscicides was allowed when necessary (Chikowo et al., 2009). Twenty-five applications of pesticides were done, and the corresponding TFI of 1.9 was the lowest one (Fig. 1b, Table 1, Supplementary Table S2).

### *2.2.3. Durum wheat – sunflower based cropping systems*

The pesticide use related to the durum wheat – sunflower rotation were obtained from the INRA experimental site of Auzeville. This field trial was set up in 2010 with the objective to study innovative low input cropping systems designed as alternatives to the traditional durum wheat – sunflower rotation under rainfed conditions in southwest France (Peyrard et al., 2016). Three cropping systems with a gradient in N fertilizer and pesticide use, combined with the use of cover crops during fallow period were compared from 2011 to 2015.

The “Conventional” cropping system (Conv) consisted of durum wheat – sunflower rotation with bare soil during the fallow period. The soil management was based on conventional, inversion tillage with mouldboard plough. Twenty-four applications of pesticides were done from 2011 to 2015 leading to a TFI of 5.1 (Fig. 1c, Table 1, Supplementary Table S3).

The “Low input with cover crops” system (LI) was designed to reduce nitrate leaching as well as pesticide use (reduction of 50 % of the treatment frequency index TFI compared to the “Conventional” system). The three-year rotation conducted under integrated pest management included sorghum in addition to durum wheat and sunflower. The cover crops were Egyptian clover, purple vetch or mustard (Table 1). The reduction in pesticide use rested on mechanical weeding and on-row band spraying. Fungicides were allowed when necessary, according to decision rules (Peyrard et al., 2016). Seventeen applications of pesticides were done, corresponding to a TFI of 3.4 (Fig. 1c, Table 1, Supplementary Table S3).

The objectives of the “Very low input with intercrops and cover crops” system (VLI) were to reduce N-fertilizer use and TFI by 75 % compared to the “Conventional” system. To reach such objectives, legumes were introduced in the rotation, and mechanical weeding and resistant wheat varieties were used (Peyrard et al., 2016). A total of 15 applications of pesticides was done (Table 1). The TFI was found to be the lowest one: 3.1 (Fig. 1c).

### 2.3. Parameterization

The input parameters required to run the BROWSE model are given in Table 2 and in Supplementary Tables S1 to S4. These include the management techniques, the physicochemical properties of the sprayed pesticides, and the machinery setup (sprayed volume, use of fans, tractor speed, etc.) as well as residents characteristics and operator PPE use (Table 2). For input parameters not mentioned, default values as proposed by the model were used.

The required characteristics of the sprayed pesticide are molar mass, water solubility, temperature at which water solubility was measured, saturated vapour pressure, temperature at which vapour pressure was measured, soil adsorption coefficient corrected for soil organic matter content ( $K_{om}$ ), AOEL, degradation half-life on adjacent vegetation ( $DT50_{vegetation}$ ) and the dermal, oral and inhalation absorption coefficients (Supplementary Table S4). These characteristics were taken from two databases: Agritox (2016) and PPDB (2016).

The  $K_{om}$  were calculated from  $K_{oc}$  (soil adsorption coefficient corrected for soil organic carbon content) values as follows:

$$K_{om} = K_{oc} / 1.72 \quad (1)$$

**Table 2**

BROWSE input parameters related to scenario, operator Personal Protective Equipment (PPE), activity, and mixing and loading methods, and resident characteristics

Input name	Option selected	Unit
<i>Scenario<sup>a</sup></i>		
Wind speed at 2 m above ground	2.8	m s <sup>-1</sup>
Forward speed	7.5	km h <sup>-1</sup>
Spray quality	Medium	-
Drift reduction	0	%
Boom height above crop	0.7	m
Boom width	24	m
<i>Operator (male) PPE<sup>b</sup></i>		
Breathing rate	Moderate intensity	-
Hands migration factor - mixing & loading	0.85	%
Hands migration factor - boom spraying	3.14	%
Body migration factor - mixing & loading	0.1	%
Body migration factor - spraying	0.1	%
Head migration factor - mixing & loading	5	%
Head migration factor - boom spraying	5	%
Respiratory migration factor - mixing & loading	10	%
Respiratory migration factor - spraying	10	%
<i>Operator - Activity<sup>c</sup></i>		
Vehicle-sprayer type	Averaged-sized tractor (John Deere 2 series)	-
Cabin	Cabin with pressurised/filtered ventilation	-
Front-mounted boom	No	-
Boom shielding	No	-
<i>Operator - Mixing and loading<sup>c</sup></i>		
Mixing and loading method	Closed transfer systems (CTS)	-
Location	Outdoors	-
<i>Resident characteristics<sup>a</sup></i>		
Adult body weight	60	kg
Child body weight	10	kg
Adult short-term breathing rate	2.4	m <sup>3</sup> h <sup>-1</sup>
Child short-term breathing rate	1.9	m <sup>3</sup> h <sup>-1</sup>
Adult chronic long-term breathing rate	13.8	m <sup>3</sup> d <sup>-1</sup>
Child chronic long-term breathing rate	10.7	m <sup>3</sup> d <sup>-1</sup>
Clothing penetration	0.9	%
Closest distance to sprayed area	2	m
Furthest distance from sprayed area	20	m
Surface area of hand contacting mouth	0.1	m <sup>2</sup>
Percentage of hand area making contact with mouth	0.009	%
Skin to mouth transfer factor	43	%
Adult duration of exposure (post-application)	2	h
Child duration of exposure (post-application)	2	h
Transfer coefficient for adult	N(18.24, 4.06)	m <sup>2</sup> h <sup>-1</sup>
Transfer coefficient for child	N(18.24, 4.06)	m <sup>2</sup> h <sup>-1</sup>
Frequency of hand-to-mouth contact, short term	20	Number h <sup>-1</sup>
Frequency of hand-to-mouth contact, long term	9.5	Number h <sup>-1</sup>
Number of upwind passes	3	-
Standard deviation of boom height distribution	0.14	-
Droplet evaporation	None	-

<sup>a</sup> BROWSE default values.

<sup>b</sup> Values corresponding to the certified PPE used in Lamothe, Dijon and Auzeville experimental sites.

<sup>c</sup> Averaged value observed in Lamothe, Dijon and Auzeville experimental sites.

When Koc was available for several soil types, we selected the soil with organic carbon content close to that of the experimental site.

When dermal absorption values were missing in the pesticides databases, the EFSA default values were used (EFSA, 2012): EFSA recommends dermal absorption coefficients of 25 % for concentrate products (75 % if active substance content is < 5 %) and 75 % for spray dilution. When no data was available, a worst-case value of 100 % was used for oral and inhalation absorption (Supplementary Table S4).

For some active substances, the  $DT50_{\text{vegetation}}$  was not available, so the relationship provided by Juraske et al. (2008) was used to determine its value from the degradation in soil ( $DT50_{\text{Soil}}$ ):

$$DT50_{\text{vegetation}} = DT50_{\text{Soil}} / 4 \quad (2)$$

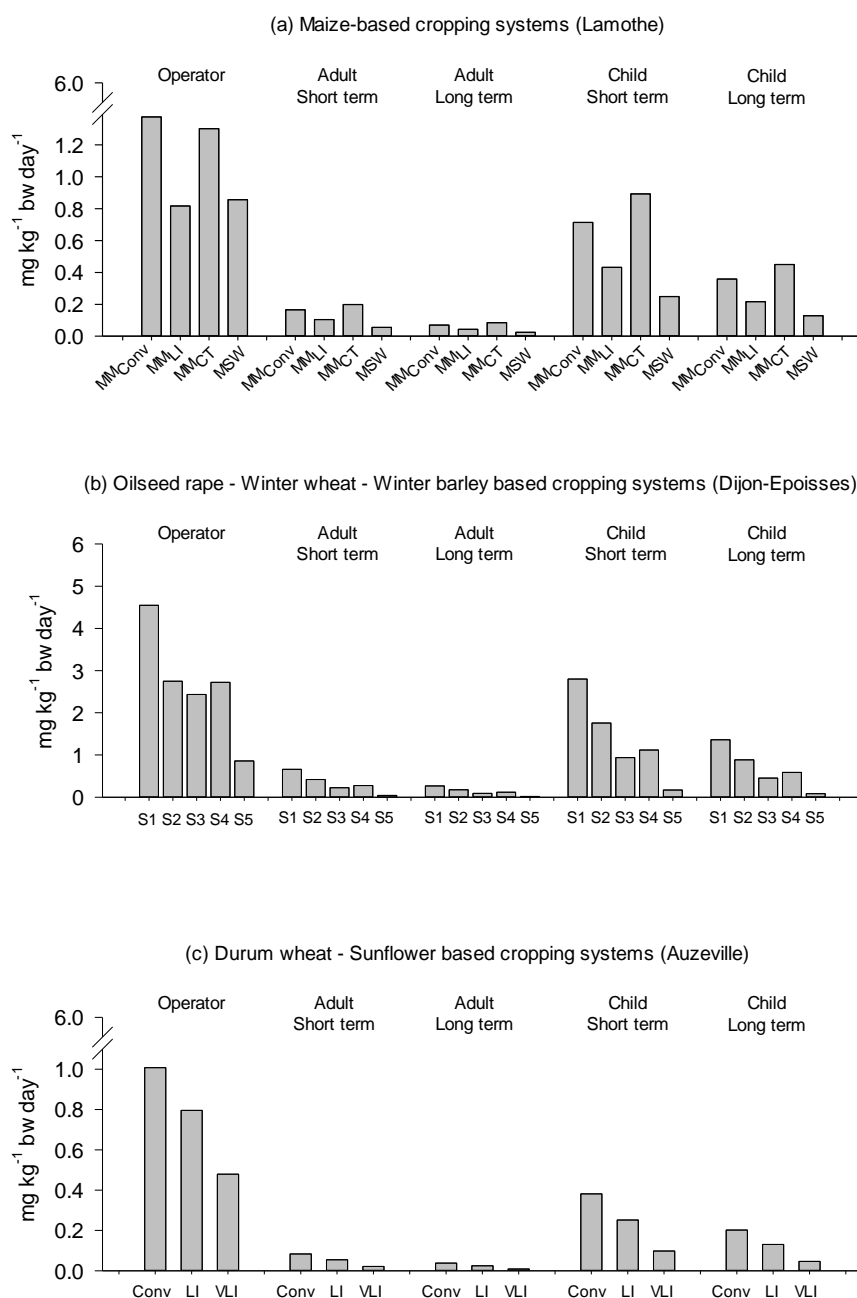
For all simulations, we assumed that operators wore the following protective PPE: nitrile gloves, certified body PPE items, hood and visor, and full face masks. The use of these PPE (gloves and respirators) reduces the proportion of potential exposure that becomes actual exposure. The area of a hand making contact with the mouth was assumed to be 0.1 m<sup>2</sup> (Goede et al., 2014).

For residents, exposure and risk were assessed both at short term (24 h) and long term (7 days after pesticide application). For operators, exposure and risk assessment are only relevant at short term (24 h), otherwise they are considered as residents.

### **3. Results and discussion**

#### *3.1. Assessment and comparison of human exposure to pesticides used in conventional and innovative cropping systems*

For all cropping systems, the results obtained with BROWSE showed that the highest cumulated human exposure to pesticides was for the operator, followed by the child at short term then long term, and the adult at short term then long term (Fig. 2). The higher exposure of a child compared to that of an adult is mainly due to their different body weights.



**Fig. 2.** Cumulative exposure of human (operator, adult and child in short and long terms) to pesticides for (a) maize-based cropping systems of Lamothe (MM<sub>Conv</sub>: Conventional system; MM<sub>LI</sub>: Low input system; MM<sub>CT</sub>: Conservation tillage system; MSW: Integrated maize rotation system), (b) oilseed rape – winter wheat – winter barley based cropping systems of Dijon-Epoisses (S1: Conventional system; S2: Integrated weed management (IWM) reduced tillage system; S3: IWM without mechanical weeding system; S4: IWM with mechanical weeding system; S5: IWM no herbicide system), and (c) durum wheat – sunflower based cropping systems of Auzeville (Conv: Conventional system; LI: Low input with cover crops system; VLI: Very low input with intercrops and cover crops system).



For the maize-based cropping systems of Lamothe, the lowest operator exposure was found for the “Low input maize monoculture” system ( $MM_{LI}$ ) with a decrease in exposure to pesticides of 41 % compared to the “Conventional system”  $MM_{Conv}$ , while for residents (both adult and child), the lowest exposure was found for the “Integrated maize rotation” system (MSW) which led to a decrease in the amounts of pesticides they are exposed to between 64 and 67 % compared to  $MM_{Conv}$ . On the contrary, the highest human exposure was observed for the “Conservation tillage maize monoculture” system ( $MM_{CT}$ ) (Fig. 2a). This system involved almost as many pesticide applications as  $MM_{Conv}$ , but the total amount of pesticides applied was higher than that of  $MM_{Conv}$  because of glyphosate applications needed for weed control in this conservation tillage system (Table 1, Supplementary Table S1). In general, the exposure was found to decrease with the TFI (Fig. 1a and Fig. 2a).

For the oilseed rape – winter wheat – winter barley based cropping systems (Dijon-Epoisses), the lowest human exposure to pesticides was obtained for the “IWM no herbicide” system (S5), while the highest exposure was obtained for the “Conventional” system S1 (Fig. 2b). As for Lamothe, the exposure decreased with the TFI (Fig. 1b and Fig. 2b). The “IWM no herbicide” system allowed reductions in human exposure of 81 % for the operator and 94 % for the residents (adult and child at short term and long term) as compared to S1.

Finally, for the durum wheat – sunflower system (Auzeville), the highest human (both operator and residents) exposure was logically found for the “Conventional” system while the lowest exposure was found for the “Very low input” system VLI (Fig. 2c). Similarly to Lamothe and Dijon-Epoisses, the decrease in exposure followed the decrease in TFI (Fig. 1c and Fig. 2c). The VLI system led to a decrease in total exposure of 52 % for the operator and a decrease of between 74 and 77 % for the residents as compared to the “Conventional” system.

However, high human exposure to pesticides should not necessarily represent a risk for human health as it depends on the toxicity of pesticides. This is discussed in the following section.

### *3.2. Human health risk assessment of pesticide use*

#### *3.2.1. Amounts of pesticides absorbed by humans*

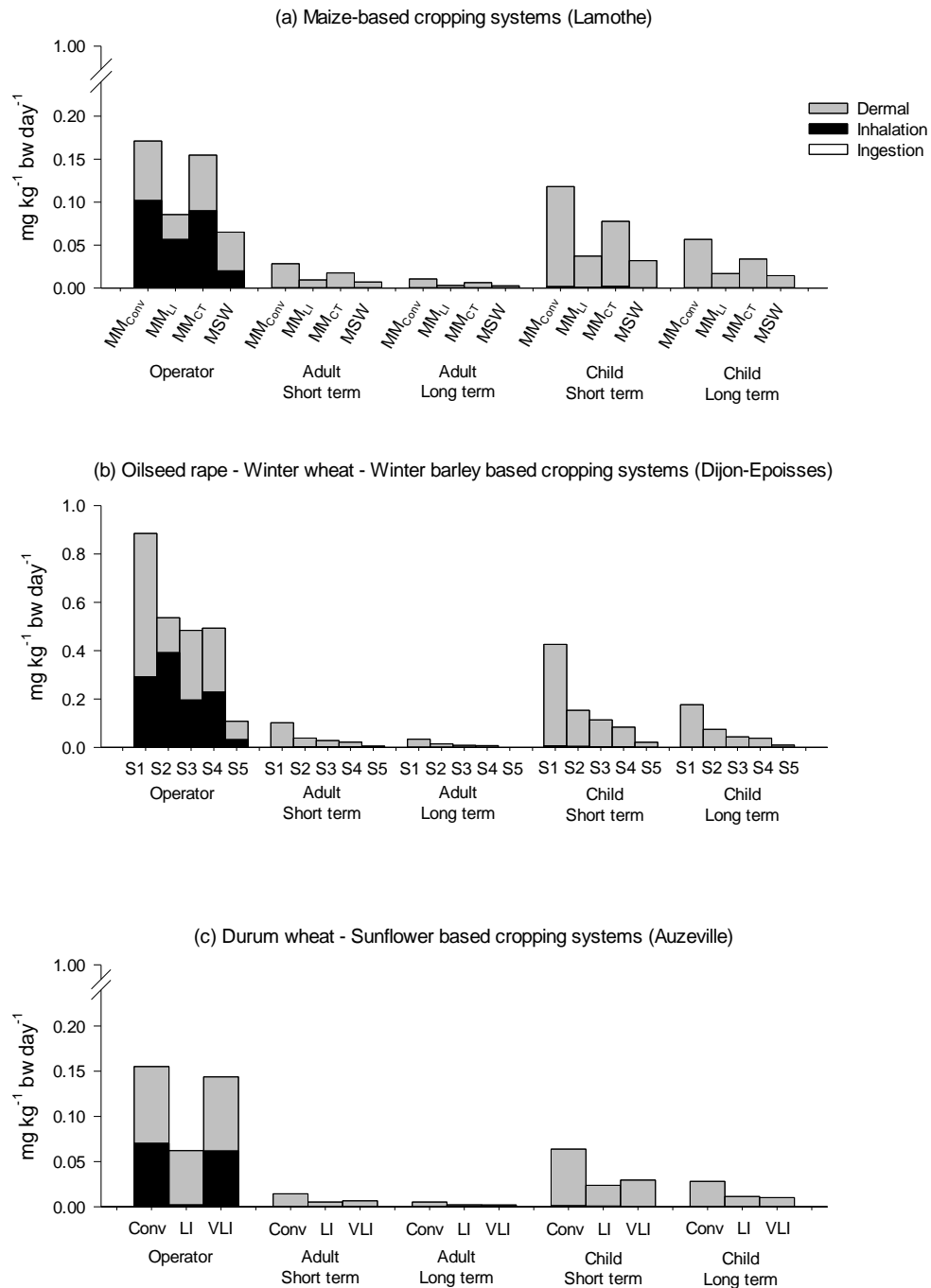
In each case, according to the BROWSE model, the highest amounts of absorbed pesticides were still found for the operator, followed by the child at short term then long term, and the adult at short term then long term (Fig. 2). Despite the operators were wearing PPE, they are directly exposed to concentrated PPP during mixing and loading, and then to significant amounts of pesticides during PPP application. Damalas and Koutroubas (2016) reported that the total exposure during pesticide application might exceed that incurred during mixing and loading, given that pesticide application typically takes more time than the tasks of mixing and loading. However, in this work,

the greatest level of exposure was found to occur during mixing/loading operations (data not shown). For residents, the total amounts of pesticides absorbed 7 days after application were lower than after 24 h following application (Fig. 3) mainly because of the degradation of pesticides.

In general, dermal absorption was found to be the predominant route of exposure (Fig. 3). Indeed, dermal exposure is one of the most common and effective routes through which applicators are exposed to pesticides (Anderson and Meade, 2014; Berthet et al., 2014; MacFarlane et al., 2013). Moreover, inhalation via volatilization was not taken into account in this work, as inhalation exposure was only considered during mixing/loading procedures from spray droplets.

In general, for the maize-based cropping systems (Lamothe), the amounts of absorbed pesticides were most often lower for the two low input maize cropping systems ( $MM_{LI}$  and MSW) than for the “Conventional” one ( $MM_{Conv}$ ). For the operator, the amounts of absorbed pesticides were higher for the conservation tillage maize monoculture ( $MM_{CT}$ ) than for the “Conventional” system  $MM_{Conv}$  (Fig. 3a). The lowest absorbed amounts of pesticides were systematically found for the integrated maize rotation (MSW), with a decrease of 62 % compared to  $MM_{Conv}$  for the operator, and of 73 to 75 % for the residents, which is consistent with the lowest human exposure to pesticides of this system (Fig. 2a). Dermal penetration ranged from 97 to 99 % for the residents (adult and child), and from 34 to 69 % for the operator. For the latter, inhalation was also significant (from 30 to 65 %) (Fig. 3a).

For the oilseed rape – winter wheat – winter barley based cropping systems (Dijon-Epoisses), the total amounts of absorbed pesticides decreased from the “Conventional” system S1 to the “IWM no herbicide” system S5, both for the operator and the residents (Fig. 3b). The “IWM no herbicide” system (S5) was found to be the best system in reducing the amounts of pesticides that are absorbed by humans with an 88 % decrease in absorbed amounts for the operator compared to S1, and a decrease of 95 % for the residents (adult and child in short and long terms) (Fig. 3b). Dermal penetration ranged from 27 to 70 % for operator, and from 97 to 99 % for residents (Fig. 2b). Inhalation was found to be the second most important exposure route for operator, ranging from 30 to 73 % (Fig. 3b).



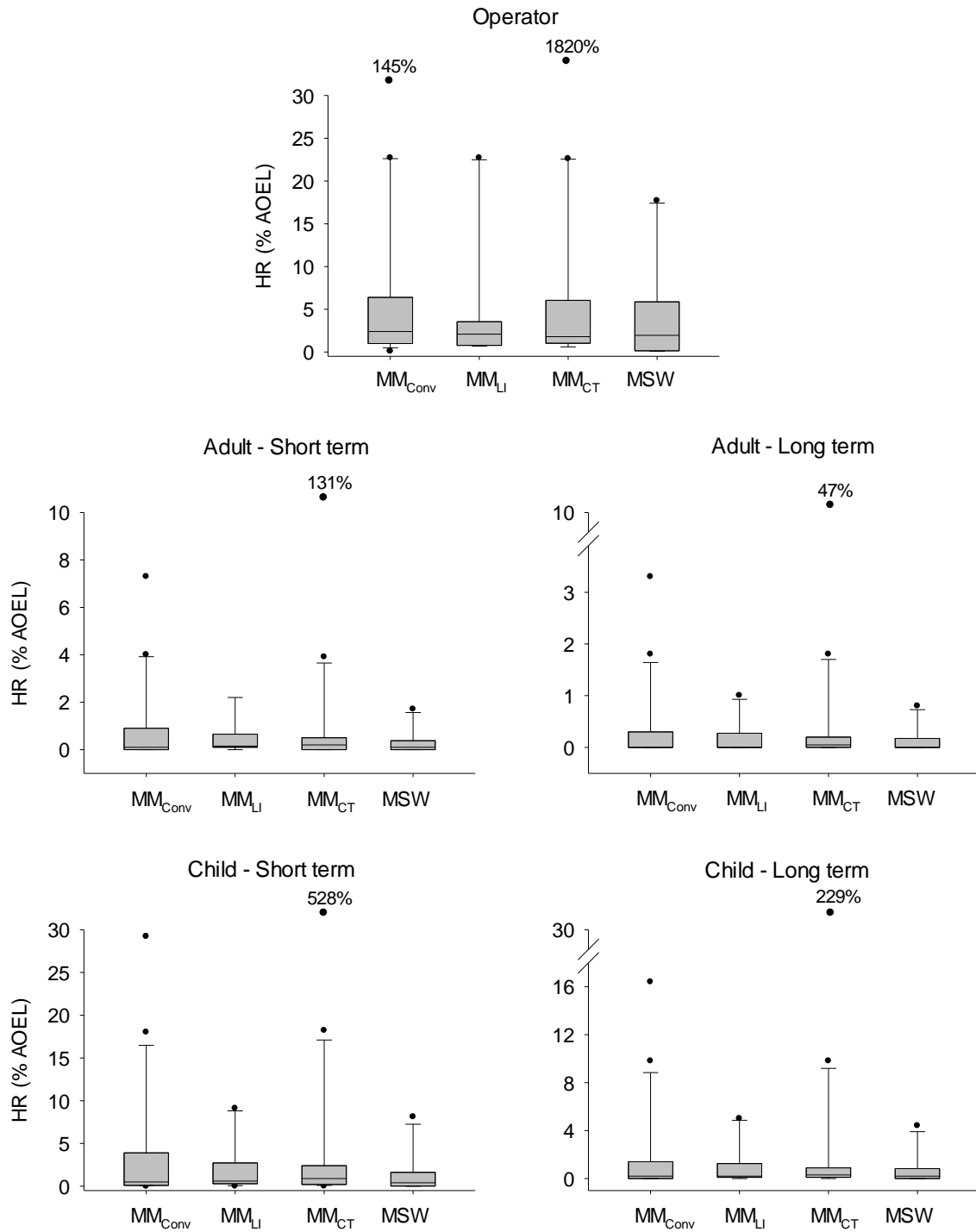
**Fig. 3.** Cumulative amounts of pesticides absorbed via the dermal, ingestion and inhalation routes for human (operator, adult and child in short and long terms) for (a) maize-based cropping systems of Lamothe ( $MM_{Conv}$ : Conventional system;  $MM_{LI}$ : Low input system;  $MM_{CT}$ : Conservation tillage system; MSW: Integrated maize rotation system), (b) oilseed rape – winter wheat – winter barley based cropping systems of Dijon-Epoisses (S1: Conventional system; S2: Integrated weed management (IWM) reduced tillage system; S3: IWM without mechanical weeding system; S4: IWM with mechanical weeding system; S5: IWM no herbicide system), and (c) durum wheat – sunflower based cropping systems of Auzeville (Conv: Conventional system; LI: Low input system; VLI: Very low input system with intercrops).

For the durum wheat – sunflower based cropping systems (Auzeville), the total amounts of absorbed pesticides by humans for the LI and VLI systems decreased as compared to the “Conventional” system. As observed for the systems experimented in Lamothe and Dijon-Epoisses, dermal penetration was the most important exposure route. It represented 55 to 97 % for the operator, and more than 98 % for the residents (Fig. 3c). Absorption of pesticides by inhalation was significant for operator in conventional and VLI systems (45 % and 43 %, respectively) but not in LI system (only 2 %) (Fig. 3c). For the residents, the LI and VLI systems allowed a reduction of the amounts of absorbed pesticides by 54 to 64 %, respectively, as compared to the “Conventional” system. For the operator, the amounts of absorbed pesticides were 60 % lower in LI than in the conventional and VLI systems. Contrary to what was expected, as the human exposure to pesticides was lower for VLI than for LI (Fig. 3c), the total amounts of absorbed pesticides were higher for VLI than for LI (Fig. 3c). This result can be explained mainly by differences in the total applied amounts of two fungicides and by their corresponding dermal absorption of in use dilution: prothioconazole (dermal absorption of 100 %) and metalaxyl-M (dermal absorption of 19 %) (Supplementary Table S4). Nevertheless, the LI and VLI systems both allowed a decrease of the amounts of pesticides absorbed by humans compared to the “Conventional” system.

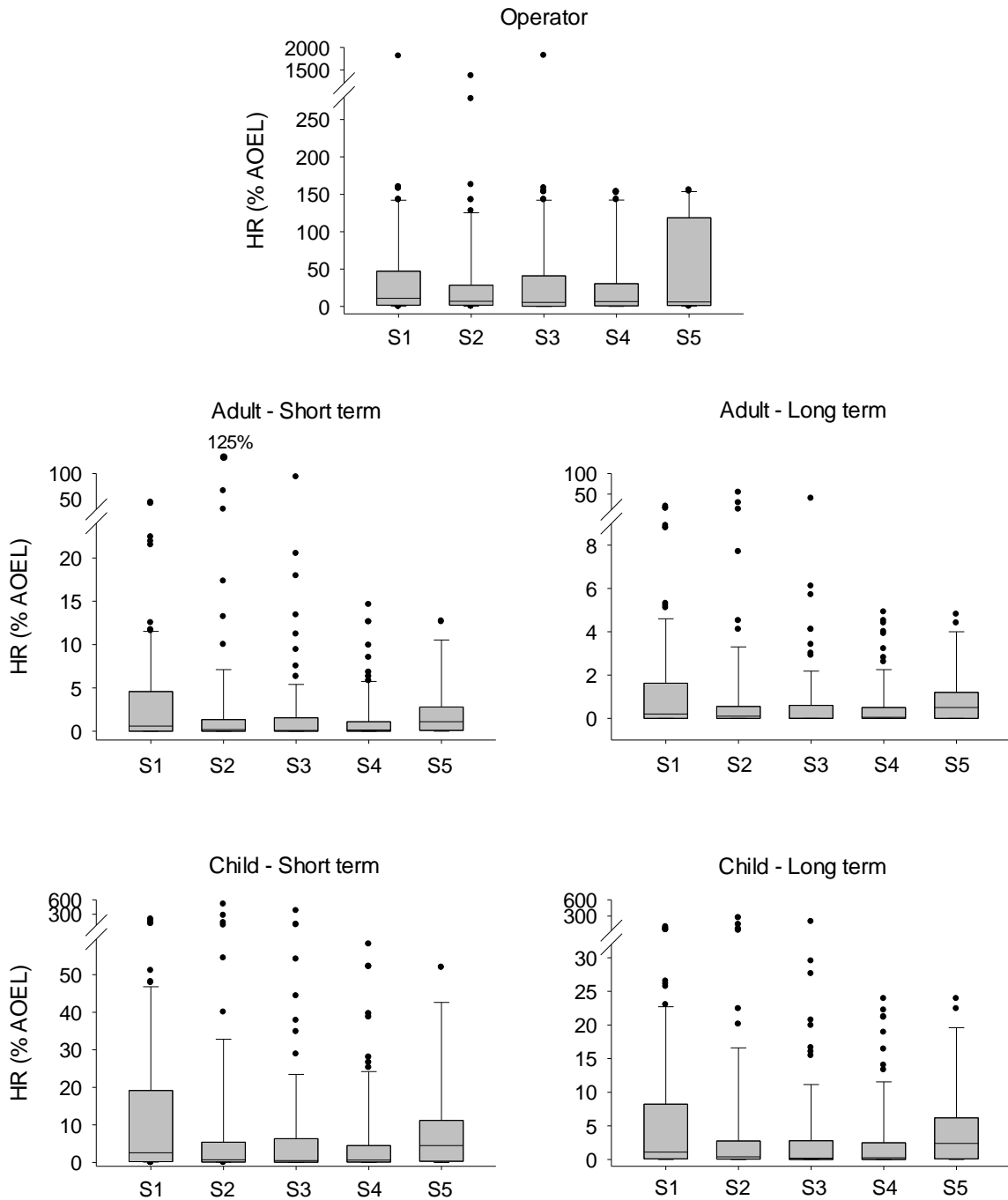
### 3.2.2. Human health risk assessment

To compare the risks of the overall pesticide use of each system, all pesticides “Human health risk index” (HR) obtained with BROWSE for one system are presented as boxplot (Figs. 4 to 6).

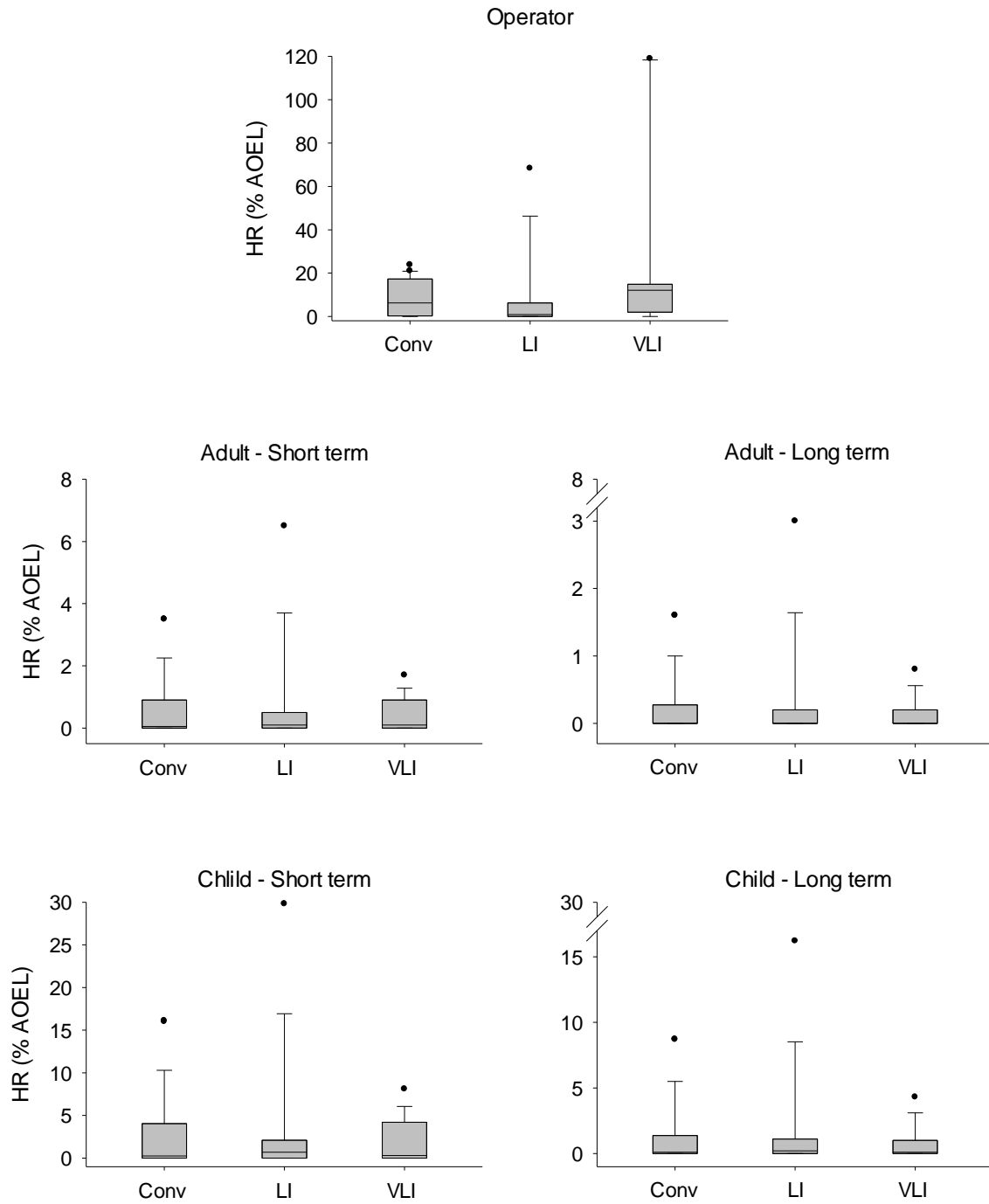
For the Lamothe systems, the HR ranged from 0 to 145 % of AOEL for the MM<sub>Conv</sub> system, from 0 to 23 % for the “Low input maize monoculture” system MM<sub>LI</sub>, from 0 to 1820 % for the “Conservation tillage” system MM<sub>CT</sub>, and from 0 to 18 % for the “Integrated maize rotation” system MSW (Fig. 4). For the operator, the lambda-cyhalothrin insecticide (applied the 13 June 2014) was the only pesticide used in MM<sub>Conv</sub> leading to an absorbed amount above the AOEL (145 %) (Fig. 4, Supplementary Table S1). In MM<sub>CT</sub>, the highest HR of 1820 % was due to tembotrione herbicide applied on 20 June 2014, then the HR of 120 % was due to cymoxanil applied the 15 October 2014 (Fig. 4, Supplementary Table S1). Indeed, tembotrione has a very high toxicity (AOEL of 0.0007 mg kg<sup>-1</sup> bw d<sup>-1</sup>) as well as cymoxanil (0.01 mg kg<sup>-1</sup> bw day<sup>-1</sup>) (Supplementary Table S4). The results also showed that PPP containing 960 g L<sup>-1</sup> of S-metolachlor and applied at 1344 g ha<sup>-1</sup> was more hazardous for the operator health than PPP which contained 400 g L<sup>-1</sup> of S-metolachlor and was applied at 1520 g ha<sup>-1</sup> (Supplementary Table S1). BROWSE considers that operator exposure is proportional to pesticide concentration (Goede et al., 2014), consequently a high concentration of active substance in the PPP generated a high risk for the operator health.



**Fig. 4.** Distribution of the “Human health risk index” (HR), calculated as the ratio of the absorbed amount to the AOEL (in %), for each active substance applied on the maize-based cropping systems of Lamothe (MM<sub>Conv</sub>: Conventional system; MM<sub>LI</sub>: Low input system; MM<sub>CT</sub>: Conservation tillage system; MSW: Integrated maize rotation system).



**Fig. 5.** Distribution of the “Human health risk index” (HR), calculated as the ratio of the absorbed amount to the AOEL (in %), for each active substance applied on the oilseed rape – winter wheat – winter barley based cropping systems of Dijon-Epoisses (S1: Conventional system; S2: Integrated weed management (IWM) reduced tillage system; S3: IWM without mechanical weeding system; S4: IWM with mechanical weeding system; S5: IWM no herbicide system).



**Fig. 6.** Distribution of the “Human health risk index” (HR), calculated as the ratio of the absorbed amount to the AOEL (in %), for each active substance applied on the durum wheat – sunflower based cropping systems of Auzeville (Conv: Conventional system; LI: Low input with cover crops system; VLI: Very low input with intercrops and cover crops system).

This is in agreement with the findings of Wester and Maibach (1985). For the residents, none of the PPPs applied on MM<sub>Conv</sub>, MM<sub>LI</sub> and MSW, would induce a risk for their health. However, tembotrione applied the 20 June 2014 on MM<sub>CT</sub> showed unacceptable risks: the HR values were 131, 528 and 229 % of AOEL for adult at short term, and child at short term and long-term, respectively (Fig. 4). None of the other PPPs applied on MM<sub>CT</sub> led to unacceptable risk for the residents health. As a summary, the “Integrated maize rotation” system MSW led to the lowest risks for human health, followed by the “Low input maize monoculture” system MM<sub>LI</sub>. This ranking follows that of TFI, i.e. of pesticide usage (Fig. 1a and Fig. 2). The MM<sub>CT</sub> system would lead to unacceptable risks (except for adult in the long term), but mainly because of tembotrione herbicide (Supplementary Table S1). Reducing the use of this herbicide could help to make human health risks acceptable for this system.

For cropping systems in Dijon-Epoisses, most of the HR values corresponded to acceptable risks, except for some PPPs (Fig. 5). These PPPs involved the following active substances: 4 fungicides, carbendazim, cymoxanil, epoxiconazole, and vinclozolin; 3 insecticides, alpha-cypermethrin, isofenphos and lambda-cyhalothrin; and 2 herbicides, bromoxynil octanoate and isoproturon. Among these pesticides, carbendazim, epoxiconazole, isoproturon, and lambda-cyhalothrin are identified as “candidates for substitution” by the European Commission (European Commission, 2015). The highest risks were systematically found for isofenphos and vinclozolin, however both pesticides were withdrawn from the market since their application in the experiment (PPDB, 2016). The isofenphos insecticide was applied as seed treatment in S1, S2 and S3 and exceeded the AOEL for short and long terms child exposure (104 to 368 %), and for the operators (1365 to 1806 %). Vinclozolin fungicide applied the 29 March 2004 (S2) exceeded the AOEL for adult in the short term (125 %), and child in short and long terms (506 and 269 %, respectively). Isoproturon was also found to be one of the pesticides leading to the highest risk for human health. It was applied several times as winter wheat and winter barley herbicide in S1 (Supplementary Table S2), and it exceeded the AOEL for the operator (139 to 141 %) and for the child at short term (102 to 166 %) (Fig. 5). As a conclusion, the system that showed the highest reduction in the risks for human health was found to be the “No herbicide IWM” system S5. This result is consistent with the lowest TFI and the lowest human exposure to pesticides used in this system.

For Auzeville, only two applications of PPPs done in the “Very low input” system VLI in November 2011 and November 2012 led to unacceptable risks for the operator health (Fig. 6). This high risk was found for seed treatments with the cymoxanil fungicide (Supplementary Tables S3 and S4). All other PPP applications led to acceptable risk for human health whatever the system (Fig. 6). From these results, the VLI system could offer a good alternative to the conventional durum wheat – sunflower rotation, if the use of cymoxanil is reduced.



It has to be underlined that this work only evaluates the active substances, and does not take into account the degradation products. In addition, we did not use the PEARL-OPS module of BROWSE to assess the effect of pesticide volatilization from plant surfaces on human health. Despite dermal absorption being the main route of exposure to pesticides, inhalation could appear as an important one too. The BROWSE model and the derivation of the AOEL both in theory have conservatism built in, so the exposure estimates and risk classifications may be overestimated in each case. However, these factors are the same across all the cropping systems considered so the relative human risks reported here remain valid. Further extension of the model is also required to deal with more realistic distributions of compound mixtures (Kennedy and Butler Ellis, 2017).

### *3.3. Summary of human health risks and identification of the most efficient cropping systems considering their environmental, agronomic, technical and economic performances*

Human health risks from pesticide use in the 12 studied cropping systems was never assessed before. However, the environmental, agronomic, technical, and economic performances of these systems were previously studied (Deytieux et al., 2012; Giuliano et al., 2016; Pardo et al., 2010; Plaza-Bonilla et al., 2016). Therefore, the objective of this section was to determine if the ranking of the cropping systems from the human health risk assessment done with the BROWSE model is consistent with the recommendations based on the assessment of these other performances.

Regarding the maize-based cropping systems,  $MM_{LI}$  and MSW were the most interesting ones to reduce the risks for human health. On the other hand,  $MM_{LI}$  was found to be the most technical and practical solution to transfer to farmers, able to reduce harmful impacts on the environment while maintaining the economic profitability (Giuliano et al., 2016). Therefore, this system could be proposed as a good alternative to conventional maize monoculture. Conversely, the “Conservation tillage” system  $MM_{CT}$  should not be recommended in its current form as an alternative to the conventional system. It presented the highest risk for human health (Fig. 4) because of greater use of pesticides, but it also had the largest weed infestation, the worst gross margins, and the objective of 50 % reduction in pesticides leaching was not reached (Giuliano et al., 2016).

For the cropping systems based on oilseed rape and cereals, the risk for human health decreased steadily from the “Conventional” system S1 to the “IWM no herbicide” system S5 (Fig. 5). These results are consistent with those of Deytieux et al. (2012) who performed a life cycle assessment analysis to compare the Dijon-Epoisses systems. These authors also showed that the IWM-based systems S2, S3 and S5 required less energy input, contributed less to the global warming potential and contributed less to ozone formation than S1. However, the

mean crop yields were reduced in the four S2 to S5 systems as compared to S1, both because the crop management techniques could induce yield reductions in some crops, and because spring crops with relatively low yielding potential were introduced in the crop rotation for diversifying sowing dates and therefore increasing the selection pressure on weed species. The saving of the cost of herbicides and of other pesticides did not offset the reduction in mean yields, so the economic profitability was affected in IWM-based cropping systems as compared to the conventional one (Pardo et al., 2010). The final selection of the most efficient system in such a production situation should be done considering the weights assigned to (1) protection of human health, (2) using the land and maintaining the landscape, (3) producing agricultural goods, (4) providing incomes to the farmers (Deytieux et al., 2012).

Among the cropping systems based on durum wheat – sunflower in Auzeville, the “Very low input” system VLI was found to be the most favourable to reduce the risk for the residents health (Fig. 6). For the operator health, the risks could be acceptable if the use of cymoxanil as seed treatment is avoided (see above) (Fig. 6). In addition, as this system has the lowest TFI compared to the LI and to the conventional ones (Fig. 1c), it will help to decrease the use of pesticides and consequently the pesticide pressure on the environment. Comparing the systems experimented in Auzeville, Plaza-Bonilla et al. (2016) showed that the use of cover crops did not have a negative impact on the yield, and on C and N mobilization into the grain of the subsequent crops. Cover crops play an important role in maintaining soil organic matter and crop productivity by recycling N from legumes and increasing the amount of C returned to the soil. Therefore, the VLI cropping system, including cover crops, appeared promising to replace the conventional durum wheat – sunflower system.

#### **4. Conclusion**

The objective of this work was to assess and to compare, using the BROWSE model, the risks for human health of various pesticide uses in 3 conventional and 9 associated innovative cropping systems. To the best of our knowledge, this is the first time the performances of cropping systems based on arable crops are assessed from the point of view of the risks for human health of overall pesticide use. The BROWSE model offers the advantages of being sufficiently flexible to allow the wide range of application practices and crops to be addressed, of including realistic scenarios, of using a probabilistic approach which avoids over-conservative approach, and of allowing consideration of mitigation measures to reduce exposure (Butler Ellis et al., 2017a). BROWSE showed that, for residents, the dermal absorption was the main exposure route while ingestion was negligible. For the operator, inhalation was also a predominant route of exposure. In general, human exposure to pesticides and human health

risks were found to be correlated to the treatment frequency index TFI, confirming the relationship between the reduction of pesticide use and the reduction of risks. The results showed that innovative low input cropping systems would reduce the human health hazard in comparison to the corresponding conventional cropping systems. On the contrary, conservation tillage system would lead to unacceptable risks for human health because of a high number of pesticides applications, and especially of some herbicides. However, avoiding the use of such herbicides could help to make the human health risks of these systems acceptable. This work also allowed to propose some improvements of the cropping systems to decrease the risks of pesticide use on human health by identifying the pesticides that led to unacceptable risks. In general, the systems leading to the lowest human health risks also had the best agronomic, environmental, technical, and economic performances. Thus, the best maize-based cropping systems appeared to be the low input maize monoculture. For the oilseed rape – winter wheat – winter barley based cropping systems, the “IWM reduced tillage”, “IWM without mechanical weeding” and “IWM no herbicide” systems were found to be the most interesting ones. The choice of the most efficient system has to be a compromise between protection of human health and of environment, agricultural production and incomes for farmers. Finally, for the durum wheat – sunflower based cropping systems, the very low input system could offer a good alternative to the conventional system. The BROWSE model was used to investigate relative risks, not actual risks. This model is an approximation to the true risk which includes conservative assumptions. As with any model, there is an unknown degree of uncertainty about the true error but the model captures many of the processes involved and was developed using the best available data and scientific knowledge. Therefore, risks assessment for human health, based on the BROWSE model, represents a step forward in the estimation of the performances of cropping systems. This approach could be extended to various arable crops based cropping systems and also to perennial crops (orchards, vineyards...). To complete the comparison of the cropping systems, the assessment of dietary exposure to pesticide residues could also be considered.

### **Acknowledgement**

The authors are grateful to Pascal Farcy (INRA, UE Domaine d’Epoisses, Bretenière), Catherine Bonnet, Eric Bazerthe, Patrick Bruno, André Gavaland, Benoît Gleizes, Pierre Perrin, Didier Raffailac (INRA, UMR AGIR), Simon Giuliano, Gaël Rametti and François Perdrieux (INP-EI Purpan), and Arnaud Coffin and Frédéric Lombard (Université Bourgogne Franche-Comté, AgroSup Dijon, UMR 1347 Agroécologie) for providing field experimental data. This work was supported by the French Ecophyto plan, managed by the ONEMA, through two French research programs: “For the Ecophyto plan (PSPE1)” funded by the Ministry in charge of Agriculture

(Perform project), and “Assessing and reducing environmental risks from plant protection products” funded by the French Ministries in charge of Ecology and Agriculture (Ecopest project), and by the ANR Systerra (ANR-09-STRA-06, Mic-Mac Design project). Sabine-Karen Lammoglia was supported by INRA (SMaCH metaprogram) and by the Perform project.

## **Appendix A. Supplementary data**

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.envint.2017.04.012>

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