Titre : Approche systémique pour gérer les bioagresseurs du blé
Title: System approach to manage wheat pests

Programme Evaluation et réduction des risques liés à l'utilisation des Pesticides APR 2009 « Programme Evaluation et réduction des risques liés à l'utilisation des pesticides »

Rapport final- Juin 2004

Jean-Noël Aubertot
UMR AGIR
BP 52627
31326 Castanet Tolosan Cedex

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RAPPORT SCIENTIFIQUE

*Dans le rapport scientifique, nous vous prions de fournir des **éléments méthodologiques** présentés succinctement et clairement afin de pouvoir avoir une vision des limites des résultats*

Titre du projet : ASPIB : Approche systémique pour gérer les bioagresseurs du blé

APR 2009 Programme « Evaluation et réduction des risques liés à l'utilisation des pesticides»

Nom du responsable scientifique du projet
Jean-Noël Aubertot
UMR AGIR
BP 52627
31326 Castanet Tolosan Cedex

Noms des autres partenaires scientifiques bénéficiaires
Marie-Hélène Robin-Bonnemé
Ecole d'Ingénieurs de PURPAN
75 voie du TOEC – BP57611
31076 Toulouse Cedex 3

Très peu de travaux de modélisation s'intéressent à une approche réellement systémique de la protection des cultures et prennent en considération les dimensions horizontale et verticale de la Protection Intégrée des Cultures. Il semble pourtant incontournable de devoir privilégier cette approche compte tenu des enjeux futurs de la production agricole. Il nous a donc semblé pleinement justifié de retenir cette démarche en choisissant d'appréhender et de modéliser la diversité et la complexité du profil de bioagresseurs au sein d'un agrosystème afin de proposer des stratégies de gestion intégrée moins dépendante des pesticides.

1. Les objectifs du projet

- Le premier objectif du projet ASPIB est **l'analyse des effets de l'interaction entre le système de culture et la situation de production sur le profil de dégâts sur blé d'hiver**. Afin de permettre la réalisation de cet objectif ambitieux, le choix a été fait de ne pas embrasser l'ensemble de la complexité des agroécosystèmes abordés. Tout d'abord, l'échelle d'espace considérée a été celle de la parcelle, même si certaines dynamiques biotiques ont lieu à des échelles supérieures. Les effets des niveaux supra-parcellaires peuvent en effet être intégrés au travers de variables simples décrivant les effets des espaces interstitiels et du territoire (représentation non explicite). De même, l'échelle temporelle abordée est celle de l'itinéraire technique, même si l'effet du précédent voire de l'antéprécédent a été être pris en compte pour les organismes endocycliques. Nous avons choisi de considérer la culture du blé comme étude de cas du fait de sa contribution forte à l'utilisation des pesticides au niveau national compte tenu des surfaces emblavées, mais aussi parce que les connaissances scientifiques disponibles sont nombreuses (notamment en termes de références pour la conduite du blé, de modélisation de son écophysiologie, et de ses bioagresseurs). Au-delà des avancées sur la protection intégrée du blé, les enjeux tant conceptuels que méthodologiques portés par le projet sont génériques, de sorte que les retombées du projet devront pouvoir concerner d'autres cultures. Pour cela, un cadre conceptuel générique pour la gestion des bioagresseurs a été développé.

- Le second objectif du projet porte sur le **développement d'un outil de simulation** permettant de représenter les interactions au sein des agroécosystèmes conduisant à différentes pressions biotiques. A terme, cet outil, combiné à un modèle de nuisibilité, pourra contribuer à la conception de systèmes de culture moins à risque vis-à-vis des pressions biotiques et donc moins dépendants des pesticides. Dans cet objectif, un modèle de simulation a été développé et évalué pour représenter les effets de l'ensemble des pratiques agricoles sur les profils de dégâts dans une situation de production donnée, et pour la culture du blé d'hiver (Injury Profile SIMulator-Wheat).

2. Méthode de travail

2.1. Schéma conceptuel, hypothèses de travail, méthode de modélisation

La première étape du travail a donc été de réaliser un schéma conceptuel représentant le fonctionnement d'un agroécosystème et la multiplicité des interactions en son sein pour les questions relatives à la protection des cultures (Aubertot et Robin, 2013). Afin de pouvoir appréhender la complexité des dégâts et des régulations biologiques, le système étudié a été restreint au blé d'hiver (tendre et dur) et non à l'ensemble des cultures présentes dans un système de culture.

Le choix de la méthode de modélisation s'est porté sur une démarche pouvant intégrer un niveau de complexité élevé, soit un outil s'intéressant aux différentes méthodes de gestion de différents bioagresseurs présents simultanément. L'option retenue a donc été une démarche de modélisation qualitative, qui permet plus facilement de répondre à l'enjeu scientifique d'appréhension d'un plus haut niveau de complexité lié à l'avènement de l'Agroécologie dans la recherche agronomique française. De plus, ce choix permet d'atteindre un niveau de généricité indispensable à la recherche actuelle et la simplicité de l'outil permettra une appropriation par les acteurs de la recherche/développement aisée.

La première hypothèse sous-jacente de ce concept est que la combinaison d'une situation de production (caractéristiques physiques, chimiques, biologiques d'une parcelle, en dehors du peuplement cultivé, et de son environnement) et d'un système de culture (à une échelle pluriannuelle) détermine complètement le profil de dégâts rencontré. Ce schéma est le cadre conceptuel du modèle IPSIM (Injury Profile SIMulator (Aubertot et Robin, 2013). Les sorties du modèle sont les sévérités finales des dégâts causés par un complexe de bioagresseurs et les entrées sont structurées en trois grands groupes de variables : les pratiques culturales, le pédoclimat et l'environnement.

L'objectif à terme est qu'IPSIM puisse contribuer à la conception de systèmes de culture à base de blé moins soumis aux pressions biotiques et donc moins sensible aux pertes de rendement, en utilisant les sorties du modèle (les profils de dégâts rencontrés dans une situation de production), comme variables d'entrée d'un modèle de simulation de la nuisibilité (**Figure 1**).

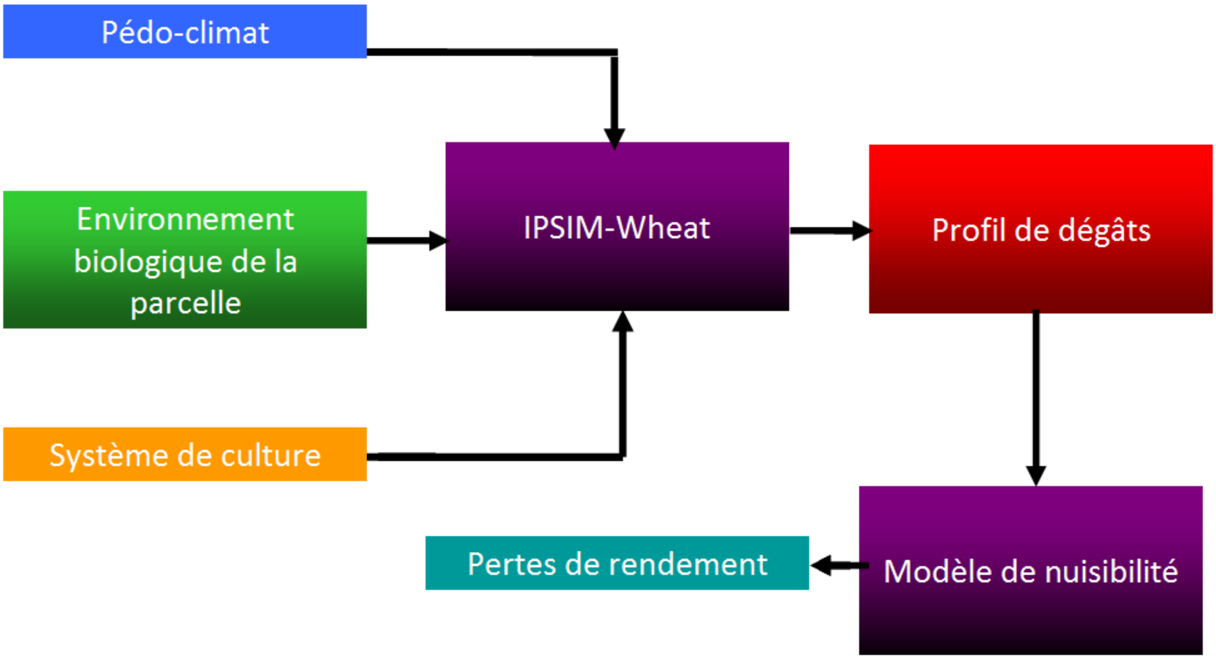


Figure 1 : Couplage d'IPSIM avec un modèle de nuisibilité

Associé à un module économique et à un module caractérisant les performances environnementales, ce couplage permettra l'étude, *in silico*, des performances multicritères (économiques, sociales et économiques) de différents systèmes de culture dans des situations de production données.

2.1. Démarche de construction d'IPSIM

2.1.1. *Bibliographie et expertise*

Afin de pouvoir développer un modèle de simulation à partir du schéma conceptuel IPSIM, des analyses bibliographiques aussi exhaustives que possibles ont été conduites et synthétisées dans des tableaux. La littérature scientifique internationale ainsi que la littérature technique a été analysée afin de pouvoir décrire, comprendre finement et hiérarchiser les effets des facteurs agronomiques, pédoclimatiques et paysagers sur les dynamiques des principaux bioagresseurs du blé d'hiver. L'aide d'experts a pu compléter cette synthèse des connaissances disponibles.

2.1.2. *Construction du modèle sous DEXi*

Les sous-modèles développés dans le cadre du modèle IPSIM ont été réalisés en utilisant la méthode DEX et implémentés avec le logiciel DEXi, logiciel d'analyse et d'évaluation multicritères permettant de prendre des décisions (Bohanec, 2003). Il permet une représentation qualitative et hiérarchique pour l'aide à la décision. DEXi est basé sur la décomposition d'un problème complexe en sous-problèmes plus faciles à évaluer et son champ d'application est très vaste. Cet outil, en général utilisé pour construire des modèles de décision a été utilisé ici de manière originale pour développer des modèles de simulation. Dans notre cas, cette méthode a permis de renseigner un profil de dégâts (sortie du modèle) selon la combinaison de 3 attributs : les pratiques culturales, l'environnement de la parcelle et le pédoclimat. Ensuite, chacun de ces trois attributs a été décomposé en différents attributs, eux-mêmes décomposés en attributs de base (entrées du modèle) décrits à un niveau inférieur (structure en arborescence).

La figure 2 représente la structure générique d'IPSIM pour un seul bioagresseur (Aubertot et Robin, 2013).

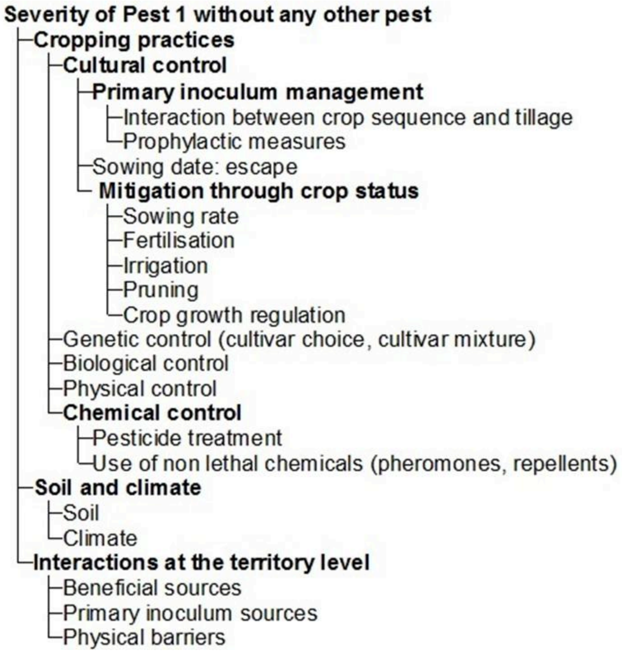
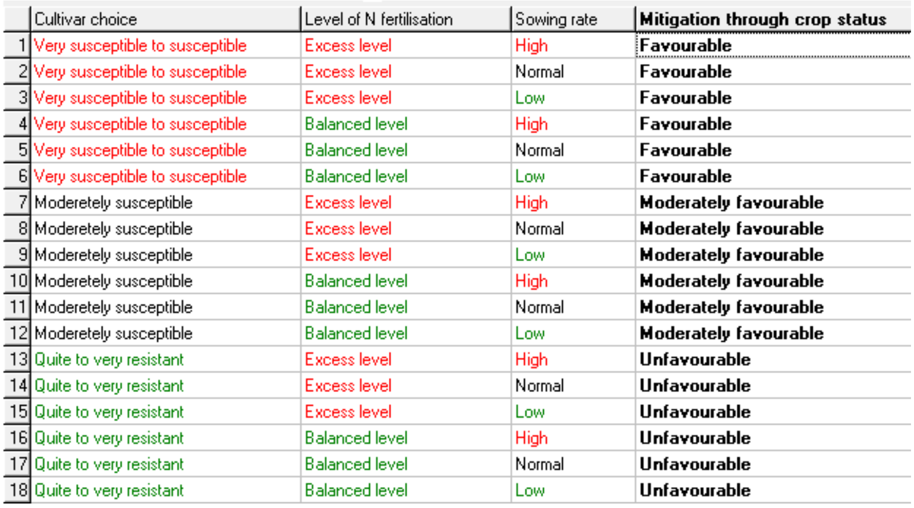


Figure 2. Structure générique d’un module d’IPSIM (Aubertot et Robin, 2013).

Les attributs de base sont des variables qui permettent de renseigner d’autres variables en utilisant une fonction d’agrégation (de type : « si…alors … »). Les fonctions d’agrégation sont présentées sous forme de tables et les attributs de base sont renseignés de manière qualitative (variables nominales ou ordinales).

La valeur d’un attribut agrégé est déterminée par les valeurs des attributs de niveau inférieur dans des tables d’agrégation telle que celle figurant ci-dessous dans le cas du piétin-verse (Robin et al, 2013).



	Cultivar choice	Level of N fertilisation	Sowing rate	Mitigation through crop status
1	Very susceptible to susceptible	Excess level	High	Favourable
2	Very susceptible to susceptible	Excess level	Normal	Favourable
3	Very susceptible to susceptible	Excess level	Low	Favourable
4	Very susceptible to susceptible	Balanced level	High	Favourable
5	Very susceptible to susceptible	Balanced level	Normal	Favourable
6	Very susceptible to susceptible	Balanced level	Low	Favourable
7	Moderetely susceptible	Excess level	High	Moderately favourable
8	Moderetely susceptible	Excess level	Normal	Moderately favourable
9	Moderetely susceptible	Excess level	Low	Moderately favourable
10	Moderetely susceptible	Balanced level	High	Moderately favourable
11	Moderetely susceptible	Balanced level	Normal	Moderately favourable
12	Moderetely susceptible	Balanced level	Low	Moderately favourable
13	Quite to very resistant	Excess level	High	Unfavourable
14	Quite to very resistant	Excess level	Normal	Unfavourable
15	Quite to very resistant	Excess level	Low	Unfavourable
16	Quite to very resistant	Balanced level	High	Unfavourable
17	Quite to very resistant	Balanced level	Normal	Unfavourable
18	Quite to very resistant	Balanced level	Low	Unfavourable

Figure 3. Exemple de table d’agrégation utilisée dans le modèle IPSIM-Wheat-Eyespot (Robin et al, 2013). Le niveau d’atténuation en culture du piétin verse du blé n’est déterminé que par la sensibilité variétale. Le niveau de disponibilité en azote et la densité de semis figurent néanmoins dans cette table de manière à être cohérent avec la structure d’autres modules du modèle IPSIM-Wheat.

Rappelons que les variables retenues, les valeurs de classe, et les fonctions d’agrégation ont été identifiées et caractérisées grâce à la bibliographie et à l’expertise. Seuls les facteurs facilement renseignés et ayant des conséquences majeures sur les bioagresseurs ont été retenus.

Ainsi une structure générique, quelle que soit la culture visée, IPSIM, a été développée (Aubertot et Robin, 2013).

Afin de représenter le profil de dégâts sur la culture retenue, le blé d’hiver, il a été nécessaire de concevoir par la suite autant de sous-modèles que de bioagresseurs principaux du blé d’hiver en mobilisant la structure IPSIM décrite précédemment.

D’après le travail bibliographique, nous avons donc retenu comme organismes les plus préoccupants en termes d’occurrence et d’évolution de fréquence les 12 bioagresseurs du blé d’hiver suivants.

Parmi les **maladies :**

- le piétin-verse
- le rhizoctone
- le piétin-échaudage
- la fusariose de la tige
- l'oïdium
- la septoriose
- la rouille jaune
- la rouille brune
- la fusariose des épis
- la jaunisse nanisante de l'orge transmise par les pucerons d'automne

Parmi les **ravageurs** :

- les pucerons de printemps

Les **adventices** à envisager dans leur globalité bien qu'elles regroupent une grande diversité.

Ces 12 sous-modèles ont été ou sont en voie de construction. Ils seront réunis en un modèle final IPSIM-Wheat, en tenant compte des interactions potentielles connues entre organismes (Aubertot et Robin, 2013). Pour ce faire, le concepteur du modèle doit renseigner une matrice décrivant les interactions potentielles connues entre organismes (forte facilitation, facilitation modérée, aucune interaction, compétition modérée, forte compétition).

Le modèle complet IPSIM-Wheat permettra ainsi d'appréhender les dimensions verticales et horizontales de la PIC pour un meilleur contrôle du profil de dégâts sur blé d'hiver.

2.1.3. Recueil des données

- Une base de données nationale pour les principaux bioagresseurs du blé a été constituée. Elle servira par la suite à l'évaluation du modèle et à l'amélioration de sa qualité prédictive.

Cette base de données regroupe des résultats croisant des données sur les pratiques culturales et les bioagresseurs du blé. Les données collectées permettent de fournir :

- des valeurs d'entrée du modèle (ou variables explicatives), qui se décomposent en trois groupes : le pédoclimat, les pratiques culturales et l'environnement biologique.

- des variables de sortie du modèle (ou variables expliquées) en terme de sévérité finale pour chaque bioagresseur retenu.

Dans un premier temps, le travail a consisté à inventorier, recueillir et classifier les données existantes au niveau national puis à les sélectionner selon un cahier des charges établi d'après les exigences du modèle. Un travail d'analyse et d'homogénéisation des données a été nécessaire afin de pouvoir les utiliser avec le modèle. Par la suite, les variables quantitatives ont dû être converties en variables qualitatives pour être intégrées dans les différents modules.

Cette base de données a été constituée à partir de résultats expérimentaux provenant de centres de recherche ou d'expérimentation, d'instituts techniques, d'associations et groupements d'agriculteurs, d'entreprises (coopératives ou privées), de réseaux formalisés ou informels.

- Cette base de données nationale, constituée à partir de résultats non conçus dans le cadre de la démarche IPSIM donc souvent incomplets ou inadaptés pour certaines variables, a été complétée par notre propre dispositif d'acquisition des données, dans le cadre du projet ASPIB. L'objectif était de balayer un maximum de situations de production, c'est-à-dire d'explorer une large gamme de pratiques croisée à une large gamme de milieux. Pour compléter le jeu de données destiné à la validation du modèle, nous avons donc choisi de mettre en place un réseau régional d'observation de parcelles d'agriculteurs en Midi-Pyrénées et Languedoc-Roussillon, afin de réaliser des enquêtes sur les pratiques culturales et des diagnostics sur les bioagresseurs. Ces diagnostics se sont en général réalisés en synergie avec des réseaux locaux existants.

2.1.4. Évaluation du modèle

Après avoir regroupé et sélectionné les données brutes, un travail de conversion de ces données a été réalisé pour les faire correspondre aux échelles qualitatives retenues pour les attributs de base de modèles IPSIM. En effet, les données fournies peuvent être de natures très différentes et elles doivent pouvoir être prises en compte dans cette diversité. Par exemple pour le blé d'hiver, une densité de semis peut être enregistrée en nombre de grains par hectare, en kilogramme de semence par hectare ou en valeur ordinale, de type dense, élevée, ou faible. Les échelles retenues pour quelques attributs de base sont synthétisées sur le **Tableau 1**. Certaines échelles utilisent le terme « favorable », il doit alors être compris comme favorable au bioagresseur, et inversement pour « défavorable ».

Ainsi, soit les données recueillies sont des valeurs qualitatives, ordinales ou nominales. Dans ce cas, les valeurs quantitatives ont déjà été appréciées qualitativement par les expérimentateurs en fonction du contexte régional et on admet alors que leur expertise fait foi.

Soit les données recueillies sont quantitatives et dans ce cas, nous avons appliqué des règles de décision, définies pour les régions représentées dans notre jeu de données et reposant sur la littérature grise et l'expertise. Ces règles de décision sont regroupées via une interface, non directement visible pour l'utilisateur mais tout à fait transparent.

Ces données ont été utilisées par la suite pour évaluer la qualité prédictive du sous-modèle construit en comparant les intensités simulées par le modèle avec les intensités réelles. Plusieurs indicateurs statistiques ont été utilisés comme critères d'évaluation. La qualité prédictive des modèles développés avec la plateforme IPSIM est satisfaisante, même si elle est perfectible, surtout en tenant compte du fait qu'aucune procédure d'ajustement n'a été mise en œuvre (Robin et al, 2013 ; Robin, 2014).

Attribut de base	Natures possibles de l'attribut fourni	Échelles de l'attribut du modèle	Règle ou description
Niveau de résistance de la variété	Nom de la variété, note de résistance	Assez résistant à résistant/ Moyennement sensible / Très sensible à sensible	Échelle basée sur les notations de résistance établie par le CTPS (Comité Technique Permanent de la Sélection des Plantes Cultivées) lors de l'inscription de la variété.
Travail du sol	Labour, travail simplifié, semis direct, …	Travail du sol avec inversion / Travail du sol sans inversion	Travail du sol utilisé avant l'implantation du blé et conduisant à une inversion des horizons ou non.
Précédent cultural	Toutes les cultures possibles, prairies, voire jachère, friche, …	Hôte/Non hôte	La classification des différents précédents en variable qualitative nominale est basée sur des données issues de la synthèse bibliographique.
Date de semis	Jour calendaire, précocité appréciée (précoce, ...)	Précoce/Normale/Tardive	La classification des dates de semis en variable qualitative ordinale est basée sur des données issues de la littérature technique et de l'expertise régionale.
Climat du printemps	Aucune indication hormis la position géographique, données météo diverses, …	Favorable/Moyennement favorable/Défavorable	Le climat est caractérisé en se basant sur des modèles existants, des typologies issues de données historiques, …

Tableau 1 : Exemples de conversion de variables quantitatives ou nominales en variables qualitatives (ordinales ou nominales) pour quelques attributs d'entrée.

3. Conclusion

Le programme ASPIB a permis des avancées significatives pour la protection intégrée du blé. Une base de données à l'échelle nationale a été constituée à partir d'une enquête aussi exhaustive que possible (Cholez et al, 2011) et d'observations supplémentaires sur des réseaux de parcelles agricoles du sud-ouest de la France. Cette base de données sera une source de connaissances précieuses pour de futures recherches sur la maîtrise des stress biotiques du blé. En interaction avec le programme ANR Mic-Mac design (http://www6.inra.fr/micmac-design) et le projet européen PURE (http://www.pure-ipm.eu/), il a permis la réalisation de la thèse de Marie-Hélène Robin (http://ethesis.inp-toulouse.fr/archive/00002650/). Au delà des modèles spécifiques au blé, la principale sortie du programme ASPIB est la mise au point conceptuelle et technique de la plateforme IPSIM via le logiciel DEXi (Bohanec, 2003). Outre le développement de plusieurs modules sur blé, différentes adaptations à d'autres cultures sont d'ores et déjà en cours ou sont prévues, en collaboration avec différentes équipes de recherche, ainsi que des développements méthodologiques complémentaires (pour la multi-simulation, l'analyse de sensibilité, et l'optimisation des tables d'agrégation). Le logiciel DEXi étant désormais populaire au sein de différentes communautés d'agronomes via les outils MASC (Sadok et al.,

2009) ou DEXiPM (Pelzer et al., 2012), pour l'agrégation d'indicateurs permettant l'évaluation multicritères, la plateforme IPSIM montre qu'il est possible d'utiliser le logiciel pour créer de véritables modèles de simulation qualitatifs dans le champ de l'agroécologie. La démarche suivie pourra ainsi donner lieu à d'autres applications que la Protection Intégrée des Cultures. La simplicité de mise en œuvre du modèle, le choix de disposer de variables d'entrée facilement renseignables, et la transparence des modèles IPSIM devraient permettre une appropriation aisée des outils par différentes communautés de chercheurs, de conseillers ou d'ingénieurs agricoles. Par ailleurs, la plateforme IPSIM est déjà utilisée comme support pédagogique pour l'enseignement supérieur agricole. Au travers du programme ASPIB, nous espérons ainsi avoir contribué au renouvellement méthodologique nécessaire aux évolutions attendues des systèmes de culture de demain, qui devront être moins dépendants de l'utilisation des pesticides.

REORIENTATIONS PAR RAPPORT AU PROJET INITIAL

Comme tout projet de recherche innovant, le projet ASPIB a connu des réorientations substantielles. Le projet initial proposé figure en annexe et permet de comparer les actions prévues initialement et celles effectivement réalisées.

Il convient tout d'abord de souligner que l'objectif initial visait à proposer des avancées quant à la conception de stratégie de protection intégrée contre un ensemble de bioagresseurs. Même si le projet n'a pas encore débouché sur la mise en œuvre concrète, sur le terrain, de systèmes de culture à base de blé limitant les stress biotiques, le développement de la plateforme de modélisation IPSIM (Aubertot et Robin, 2013) constitue une réelle avancée méthodologique pour la protection des cultures. Cette avancée est spécifique puisqu'elle constituera, à notre connaissance, le premier outil permettant de concevoir des stratégies de gestion intégrée de l'ensemble des principales pressions biotiques d'une culture. De plus, cette avancée est générique puisque, *a priori*, toute culture et tout bioagresseur peuvent être modélisés selon la méthode proposée.

En ce qui concerne l'application au blé, ce ne sont pas moins de 8 modèles qui ont été développés au cours de la thèse de MH Bonnemé (http://ethesis.inp-toulouse.fr/archive/00002650/01/Robin.pdf). Un est achevé, sa qualité prédictive estimée et publié (IPSIM-Wheat-Eyespost ; Robin et al, 2013). Un est achevé, sa qualité prédictive estimée et sur le point d'être soumis pour publication à la revue Phytopathology (IPSIM-Wheat-Brown Rust). Deux autres ont fait l'objet de Mémoires de Fin d'Etudes (IPSIM-Wheat-Septoria tritici ; Carrière, 2014 ; IPSIM-Wheat-Fusarium et IPSIM-Wheat-DON ; Thomas, 2013), ont été achevés et leurs qualités prédictives évaluées. Un a été achevé et sa qualité prédictive n'a pas encore été évaluée (IPSIM-Wheat-Sharp Eyespot ; Robin, 2014). Trois sont en cours de développement (IPSIM-Wheat-Powdery Mildew, Garcia, 2012 ; Sedira, 2014 ; IPSIM-Wheat-Aphids ; Dalbard, 2013 ; IPSIM-Wheat-Weeds ; Marti, 2013). Il sera nécessaire de travailler plusieurs années avant de pouvoir disposer du modèle complet pour le blé, mais les différents modules déjà développés et évalués peuvent d'ores et déjà être utilisés individuellement lors de phase de conception de systèmes de culture à base de blé limitant les stress biotiques.

Du point de vue conceptuel, le projet visait initialement à mobiliser le concept de traits de réponse des populations de bioagresseurs aux pratiques agricoles, ainsi que des traits de nuisibilité. Si les traits de nuisibilité ont pu effectivement être mobilisés pour représenter l'impact des bioagressions sur le fonctionnement d'un peuplement cultivé dans le cadre du développement d'un modèle simple de nuisilité (Willocquet et al, 2008), le concept de trait de réponse aux pratiques agricoles n'a pas pu être mis en œuvre pour plusieurs raisons. Tout d'abord, il existe des dizaines d'actes techniques susceptibles d'influencer le développement des populations de bioagresseurs (e.g. la succession des cultures, le travail du sol, la date de semis, la densité de semis, la date de récolte, la fertilisation azotée, l'irrigation). Chaque taxon considéré pourra répondre différemment à chacune des techniques mise en œuvre, et ce, même s'il sera possible de proposer une typologie de réponse pour chaque technique (e.g. la fertilisation azotée favorise le développement de l'organisme considéré, est neutre ou bien défavorise son développement). Ainsi, chaque bioagresseur considéré pourra être caractérisé par un « vecteur de traits de réponse aux pratiques agricoles », mais ne pourra être associé à un ensemble d'autres bioagresseurs ayant des caractéristiques identiques (i.e. ayant un « vecteur de traits de réponse » commun). Il est donc apparu nécessaire de bâtir les relations entre pratiques agricoles (ainsi que le pédoclimat et l'environnement de la parcelle) et le développement de la population (ou des dégâts associés) espèce par espèce. En outre, en agronomie, on sait bien que l'effet d'une pratique agricole n'est pas univoque et qu'elle dépend des états du milieu et d'interactions avec d'autres pratiques. C'est pour ces raisons que le concept de trait de réponse aux pratiques n'a pu être mobilisé dans l'approche qui a été mise en œuvre.

En revanche, nous avons proposé un trait, appelé « endocyclisme» pour caractériser la biologie de l'organisme concerné. Ce concept a permis de proposer une typologie des profils de dégâts que les modèles issus de la plateforme IPSIM pourront utiliser pour identifier le type de levier prioritaire à mobiliser pour gérer les stress biotiques rencontrés (adaptation du système de culture versus adaptation du paysage autour de la parcelle considérée). Cette typologie est générique puisqu'elle ne spécifie ni l'espèce de bioagresseur considérée, ni la culture considérée. De plus, le concept d'endocyclisme a également été mobilisé lors du développement d'IPSIM-Wheat-Weeds afin de réaliser une typologie des plantes adventices du blé (Marti, 2013).

Le diagnostic en parcelles agricoles qui était prévu initialement a bien été conduit et a permis de mieux caractériser les relations entre les pratiques des agriculteurs, les conditions de milieu et les communautés de bioagresseurs du blé. Il a porté sur les 4 réseaux suivants en Midi-Pyrénées : MAESTRIA, TTSI, Ecophyto et BIO. Des enquêtes avaient été envisagées pour caractériser les freins et les leviers à l'adoption de pratiques économes en produits phytosanitaires, mais elles n'ont pu être effectuées faute de temps et de moyens. Les analyses des teneurs en mycotoxines des parcelles agricoles suivies dans la région Midi-Pyrénées ont bien été conduites, et ce pour 3 années (2012 ; 2013 ; analyses pour les échantillons 2014 en cours). Elles ont servies à l'évaluation du modèle IPSIM-Wheat-DON (Thomas, 2013). Elles serviront certainement également à étayer la modélisation d'un projet de recherche européen, en cours de montage, sur la gestion de la production des mycotoxines sur céréales.

Une expérimentation sur les fonctions de nuisibilité (relations dégâts-dommages) était prévue initialement pour tester la qualité de prédiction de certaines relations du modèle WHEATPEST (Willocquet et al, 2008). Elle a été mise en place au cours de la saison 2010/2011 (Figure 4), en ayant pris le soin d'apporter soigneusement les inocula nécessaires au développement des maladies qui devaient être étudiées.

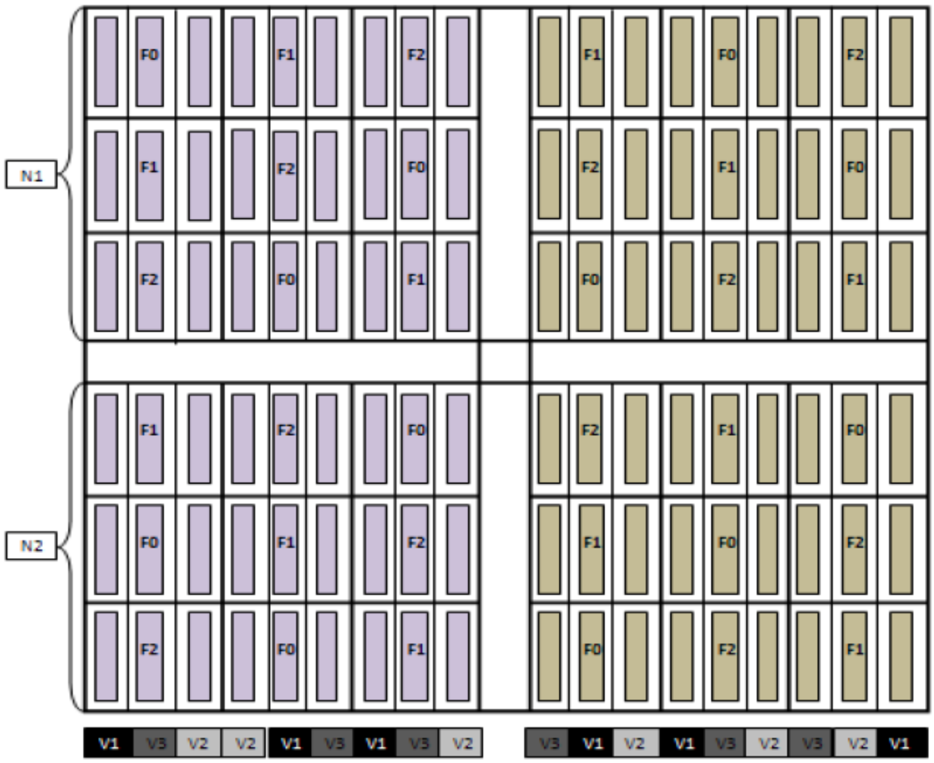


Figure 4. Dispositif expérimental mis en place sur la saison 2010/2011 pour analyser la nuisibilité de différentes maladies du blé sur le domaine expérimental de Lamothe (Ecole d'Ingénieurs de Purpan). L'essai croisait les facteurs suivants : 3 variétés x 2 densités x 2 fertilisations N x 3 protections fongicides x 3 répétitions. Il comportait 108 parcelles élémentaires.

Malheureusement, les conditions climatiques de l'année en Midi-Pyrénées n'ont pas permis le développement des agents pathogènes (Figure 5). Aucune maladie racinaire, du feuillage, de la tige, ou des épis (hormis quelques très rares symptômes de septoriose) n'a été observée aux différents stades de développement de la culture.

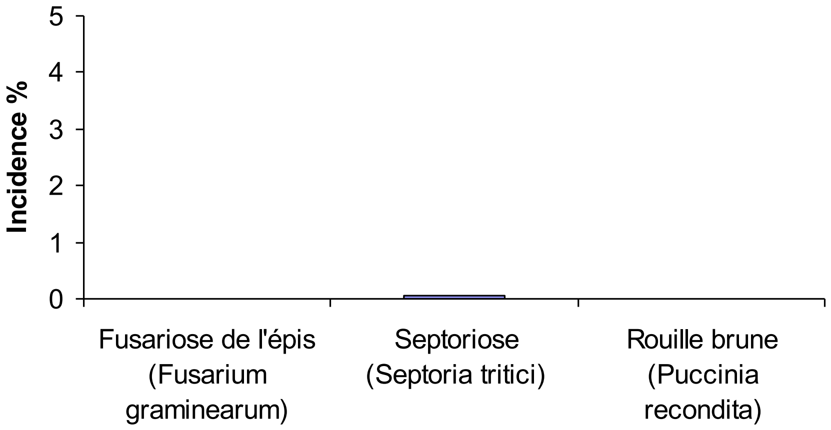


Figure 5. Mesure de l'incidence moyenne de 3 maladies sur l'ensemble de l'essai mis en place et présenté sur la figure 4.

Le comité de pilotage de Marie-Hélène Robin du 24 juin 2011 (Centre INRA de Toulouse, Auzeville) a recommandé de ne pas remettre en place l'essai pour une nouvelle année, jugeant qu'il ne pourrait pas être valorisé dans le cadre de la thèse et qu'il était jugé dès lors comme moins prioritaire par rapport aux autres enjeux de la thèse (développement des modèles IPSIM-Wheat et évaluation de leurs qualités prédictives).

Le projet initial prévoyait la rédaction de 3 articles potentiels. Deux articles ont été publiés jusqu'à présent, un est sur le point d'être soumis au moment de la rédaction de ce rapport, mais de nombreux autres articles devraient être soumis prochainement (*a minima* un par modèle développé).

Enfin, le projet initial prévoyait une intervention au colloque de restitution du projet CASDAR TTSI (28.09.2012). Celle-ci n'a pu être réalisée car les organisateurs n'ont pu consacré qu'un seul exposé à la gestion des stress biotiques et ont choisi d'aborder la question de la gestion des plantes adventices. Pour des raisons d'organisation (i.e. de temps), ils n'ont donc pu inclure une intervention sur la modélisation des maladies du blé (http://www.mp.chambagri.fr/Colloque-de-restitution-du-projet.html). En revanche, des retours individuels aux agriculteurs impliqués dans les réseaux ont été effectués, notamment en ce qui concerne les teneurs mesurées en mycotoxines.

Ainsi, le programme ASPIB a-t-il subi différentes réorientations au cours de son déroulement. Ceci résulte certainement du caractère très ambitieux (modélisation d'un ensemble de bioagresseurs d'une culture) et innovant (la méthode de modélisation à mobiliser n'était pas identifiée au début du programme) du projet. Malgré ces réorientations, il apparaît que le programme a généré des retombées inattendues et non mentionnées dans le projet initial. On peut citer notamment l'utilisation de la plateforme de modélisation IPSIM pour l'enseignement (TD/projets de groupes d'étudiants sur une ou plusieurs semaines dans le cadre de formations initiales dispensées à l'EI Purpan et à l'ENSAT ; Ecole-Chercheur internationale sur la modélisation pour la gestion durable de la santé des cultures ; http://www6.inra.fr/reseau-pic/Seminaires/Ecole-chercheur-internationale-sur-la-modelisation). Par ailleurs, on peut citer pas moins de 7 nouveaux programmes de recherche qui ont déjà commencé à mobiliser la plateforme IPSIM, ou qui envisage de le faire moyennement l'obtention de financements idoines. Parmi ces projets, deux sont des travaux de thèse visant à modéliser un cortège de bioagresseurs sur des cultures pérennes. Ceci est certainement un marqueur de la généricité forte du travail qui n'avait pas été identifié aussi clairement au début du programme.

ANNEXE 1: TEXTES DES PUBLICATIONS

PUBLICATIONS SCIENTIFIQUES PARUES

Injury Profile SIMulator, a Qualitative Aggregative Modelling Framework to Predict Crop Injury Profile as a Function of Cropping Practices, and the Abiotic and Biotic Environment. I. Conceptual Bases

Jean-Noël Aubertot[1,2]*, **Marie-Hélène Robin**[1,3]

1 Institut National de la Recherche Agronomique, Unité Mixte de Recherche 1248 Agrosystèmes et Agricultures, Gestion des Ressources, Innovations et Ruralités, Castanet-Tolosan, France, **2** Université Toulouse, Institut National Polytechnique de Toulouse, Unité Mixte de Recherche 1248 Agrosystèmes et Agricultures, Gestion des Ressources, Innovations et Ruralités, Castanet-Tolosan, France, **3** Université de Toulouse, Institut National Polytechnique de Toulouse, Ecole d'Ingénieurs de Purpan, Toulouse, France

Abstract

The limitation of damage caused by pests (plant pathogens, weeds, and animal pests) in any agricultural crop requires integrated management strategies. Although significant efforts have been made to i) develop, and to a lesser extent ii) combine genetic, biological, cultural, physical and chemical control methods in Integrated Pest Management (IPM) strategies (vertical integration), there is a need for tools to help manage Injury Profiles (horizontal integration). Farmers design cropping systems according to their goals, knowledge, cognition and perception of socio-economic and technological drivers as well as their physical, biological, and chemical environment. In return, a given cropping system, in a given production situation will exhibit a unique injury profile, defined as a dynamic vector of the main injuries affecting the crop. This simple description of agroecosystems has been used to develop IPSIM (Injury Profile SIMulator), a modelling framework to predict injury profiles as a function of cropping practices, abiotic and biotic environment. Due to the tremendous complexity of agroecosystems, a simple holistic aggregative approach was chosen instead of attempting to couple detailed models. This paper describes the conceptual bases of IPSIM, an aggregative hierarchical framework and a method to help specify IPSIM for a given crop. A companion paper presents a proof of concept of the proposed approach for a single disease of a major crop (eyespot on wheat). In the future, IPSIM could be used as a tool to help design *ex-ante* IPM strategies at the field scale if coupled with a damage sub-model, and a multicriteria sub-model that assesses the social, environmental, and economic performances of simulated agroecosystems. In addition, IPSIM could also be used to help make diagnoses on commercial fields. It is important to point out that the presented concepts are not crop- or pest-specific and that IPSIM can be used on any crop.

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* E-mail: Jean-Noel.Aubertot@toulouse.inra.fr

Introduction

Third millennium agriculture must reconcile environmental protection and productivity. The world population is projected to reach 8.7–10 billion by 2050 and annual production will need to increase by 200 million tons by then to meet the projected 470 million ton demand [1]. Several authors attribute the spectacular increase of agricultural production in the second half of the twentieth century to the massive use of products resulting from chemical synthesis [2]; but this intensive production model is nowadays questioned because of public health, agronomic, environmental, and sometimes socio-economic issues. Concepts in crop protection in intensive agricultural production systems changed from destruction of pests (by which we mean, plant pathogens and animal pests in this paper) by the use of pesticides to pest management with techniques based on the improved knowledge of pest dynamics and their natural enemies and the interaction between pests and crops under the influence of Cropping Practices [3]. It is therefore necessary to combine cultural, genetic, biological, physical and chemical control methods to manage pests through Integrated Pest Management (IPM) strategies in order to maintain the pest population levels below those causing economic losses [4].

True IPM is quite different from the practices recommended up to now [5] and is still faced with agronomic and technical difficulties which can curb its development. Its impact on pests is difficult to estimate because of their multiplicity and of their many interactions within agroecosystems. Studies on the effects of alternative control methods mostly concern a major pest (monospecific approach) while farmers have to manage an injury profile in a given field, i.e. a combination of injury levels caused by multiple pests (multi-specific approach) [6]. Similarly, the research has focused on the effect of one (or a few) control method(s), but farmers usually combine several operations (which may have only partial effects) to limit pest development. Each technical operation is likely to modify the sanitary status of a crop [7]. In addition, not only do cultural practices interact with each other, but also, one technique can be detrimental to some pests and favourable to others. Pest populations are characterised by a very high level of diversity and complexity because of multiple interactions within and between populations and with biological, physical, and chemical environments. This complexity is one of the constraints to the implementation of IPM, in addition to others [8]. In order to reduce the reliance of cropping systems on pesticides, it is therefore necessary to develop tools to help the "vertical integration" (combination of several control methods) and the "horizontal integration" (simultaneous management of several pests) of IPM strategies. Dynamics of pest populations can lead to combinations of injuries on a crop which can in turn lead to quantitative or qualitative damage, which usually results in economic losses for farmers and more generally for society as a whole. However, these relationships are not linear and depend on the production situation as shown by several authors [6,9,10]. In this paper, we will assume that the production situation is defined by the physical, chemical and biological components, except for the crop, of a given field (or agroecosystem) and its environment, as well as socio-economic drivers that affect farmer's decisions (adapted from [11]). In this definition, the term "environment" refers to the climate and the territory (i.e. landscape and the associated actors) that can directly or indirectly influence the considered field. In a given production situation, a farmer can design several cropping systems according to his goals, his perception of the socio-economic context and his environment, farm organisation, knowledge and his cognition. However, a given cropping system in a given production situation will be assumed to lead to a unique injury profile.

In order to help design cropping systems, modelling is a key tool [12]. However, because of the complexity of agroecosystems, models usually only address a limited part of agroecosystems. Crop models have been developed for decades but do not take into account interactions with pests (e.g. [13,14]). Epidemiological models *sensu lato* have been developed to represent pest dynamics, often to help decision making for pesticide treatments. However, these models usually take into account rather poorly the critical effects of cropping practices [15] due to their multiple consequences on the crop-pest-environment dynamics [16]. In addition, the majority of these models address single pests (except for models such as EPIPRE [17,18]). So far, the only models that consider injury profiles are damage models [19,20]. However these models do not predict injury profiles but the quantitative damage that they cause. There is thus a strong need to develop an innovative approach to predict injury profiles as a function of production situations and cropping practices. Because of the complexity of the considered systems [21], and the lack of representation of the effects of cropping practices and their interactions, the linkage of available crop models to epidemiological models seems unlikely to happen when considering multiple pests [3]. Even if a crop model was available, together with epidemiological models for diseases, weeds and animal pests, taking into account the crop status and the effects of cropping practices, attempting to link them would certainly lead to a dead end because of the propagation error phenomenon as well as the large number of parameters and input variables needed. Alternatively, one could consider statistical approaches to cope with the impossibility of addressing these issues when using mechanistic models. However, datasets with observed injury profiles, cropping systems and production situation are scarce and statistical approaches are thus even more unlikely to succeed than mechanistic modelling approaches. As an alternative, a generic modelling framework, called IPSIM for Injury Profile SIMulator is proposed. It is deliberately simple in the way mechanisms are represented because the system being described, i.e. the agroecosystem, is far too complex for a truly mechanistic representation. It is based on a simple qualitative hierarchical aggregative approach to represent the effects of various factors affecting injury profiles. This paper presents the basic principles of IPSIM, describing its implementation in a software program and providing an example of its specification for a given crop. A companion paper [22] provides a proof of concept of this innovative modelling approach in the field of crop protection for an important disease of wheat.

Materials and Methods

Basic Principles of IPSIM

Figure 1 is a schematic representation of an agroecosystem. This figure is the conceptual basis of IPSIM, although its scope is broader than the system directly addressed by IPSIM. According to the farmer's goals, his farm features, his perception of the environment and of the socio-economic context, as well as his knowledge and cognition, he designs cropping systems that will achieve social, economic and environmental performances, as a function of the production situation. These performances will be highly dependent on the injury profile encountered. The term "cropping system" refers here to "a set of management procedures applied to a given, uniformly treated area, which may be a field, part of a field or a group of fields" [23]. This covers many technical operations, for instance, the choice of the crop sequence, cover cropping, cultivar, tillage practices, date and density of sowing, rate of fertilisation and chemical pest control. The term "system" is used here because these technical choices are interdependent [24].

IPSIM is embedded in Figure 1, where its output variable is the injury profile. Input variables of IPSIM are embedded within the three following components: cropping practices, field environment, and physical, chemical and biological components of the field (crop, pests, beneficial and harmless living organisms). An injury profile can thus be seen as the result of hierarchical interactions among the cropping practices and the production situation. Qualitative aggregative hierarchical approaches have been used in several fields to help assess the performances of various options when managing a system: industry (e.g. [25,26]), soil science (e.g. [27]), tourism (e.g. [28,29]). In the field of agronomy, qualitative aggregative hierarchical models have been used for the assessment of the sustainability of cropping systems *ex-ante* or *ex-post* [30–32], the assessment of organic systems [33], the management of Genetically Modified crops (e.g. [34]), the assessment of less-favoured areas for agricultural production (e.g. [35]), the evaluation of energy crops for biogas production (e.g. [36]), the assessment of varieties or cultivars (e.g. [37,38]) and the assessment of the effects of market-gardening cropping systems on soil borne pathogens and animal pests using expert knowledge of advisors [39]. We used this approach to summarise available knowledge in the literature for a given crop and to develop a generic modelling framework for IPM.

Implementation of IPSIM with a Software Program

IPSIM was developed using the DEX method, and is implemented with the DEXi software ([40], http://www-ai.ijs.si/

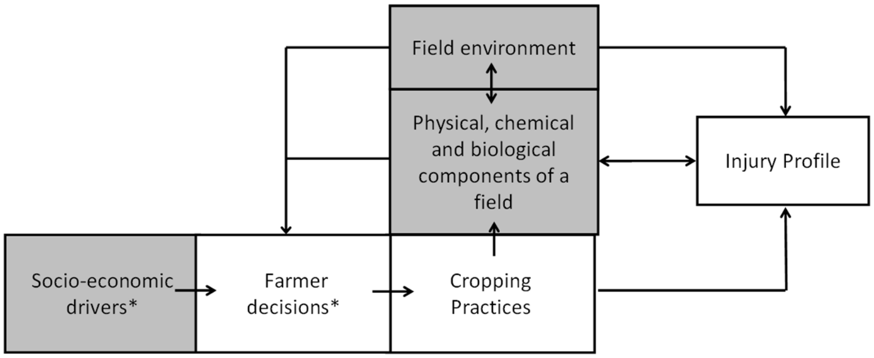

Figure 1. Schematic representation of an agroecosystem and its drivers. In green: components defining the Production Situation (except for the crop). The injury profile is the output variable of IPSIM, whereas its input variables are included within the three following components: cropping practices, field environment, and physical, chemical and biological (crop, pests, beneficials and harmless living organisms) components of the field. *Not taken into account in IPSIM.
doi:10.1371/journal.pone.0073202.g001

MarkoBohanec/dexi.html). DEX is a method for qualitative hierarchical multi-attribute decision modelling and support based on a breakdown of a complex decision problem into smaller and less complex sub-problems. This tool is generally used to evaluate and analyse decision problems [27,29,41]. In this study, it is used for the first time to develop a simulation model that represents the behaviour of an agroecosystem and which quality of prediction can be assessed. The modelling framework has the following features [40]. The sub-problems are hierarchically structured into a tree of attributes that represents the "skeleton" of the model. Terminal nodes of the tree, i.e. leaves or basic attributes, represent input variables of the model (and must be specified by the user). The root node represents the main output: an overall assessment of the evaluated scenarios (an injury profile which is defined by cropping practices and elements of the production situation in this case). The internal nodes of the model are called aggregated attributes. All the attributes in the model are qualitative (ordinal and nominal) rather than quantitative (interval) variables. They take only discrete symbolic values usually represented by words. In the DEX method, the aggregation of values up the tree is defined by "utility functions" based on a set of "if-then" aggregation rules. In our approach, we renamed these functions "aggregating tables" since they are not related to the concept of "utility" in decision theory.

IPSIM Structure

The process of building a DEXi model usually involves the following four steps [40]: (1) identifying the attributes, (2) structuring the attributes, (3) defining attribute scales, and (4) defining the aggregating tables. These steps should be followed for the development of IPSIM using the diagram presented Figure 1. However, only the first three steps can be carried out in a generic way. Only the generic aggregating tables will be described here since most of them are crop-specific.

Structure of the attributes used to predict injury profiles. The structure of attributes that predict injury profiles is presented in Figure 2. Each injury can take a limited number of severity levels. For instance, 5 classes (very low, low, medium, high, very high) or 7 classes (nil, very low, low, medium, high, very high and maximum) can be considered in IPSIM. Even if only 10 pests and 5 severity levels are considered for a given crop, a theoretical number of $5^{10} = 9.765625 \times 10^{6}$ possible injury profiles could thus be simulated with IPSIM. This number is only theoretical since some of these injury profiles are impossible due to interactions among pests. In order to take into account these interactions, IPSIM first calculates the severity for single pests independently, as if one pest only was present (Figure 2). Then, interactions between pests are taken into account according the level of each pest and a simple typology of interaction between two pests: high facilitation, low facilitation, no interaction, low reduction, high reduction (Table 1). Table 1 is used to calculate the overall effect of all other pests on the considered pest. Then, the number of pests with high facilitation, low facilitation, no effect, low reduction, high reduction is calculated (Figure 2) and the overall interactions are calculated according to the aggregating tables presented Table 2. Ultimately, the severity of each pest is calculated using the generic aggregating table presented in Table 3 as a function of the severity that would occur without any other pest, and the overall interactions calculated with the aggregating table presented in Table 2.

Structure of the attributes used to predict the severity of a single pest. The input attributes of IPSIM describe cropping

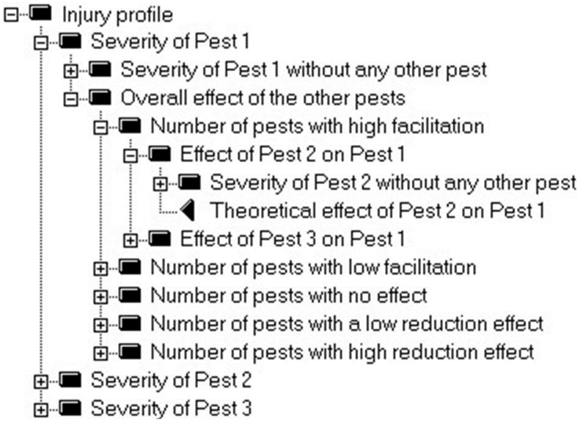
- Injury profile
  - Severity of Pest 1
    - Severity of Pest 1 without any other pest
    - Overall effect of the other pests
      - Number of pests with high facilitation
        - Effect of Pest 2 on Pest 1
          - Severity of Pest 2 without any other pest
          - Theoretical effect of Pest 2 on Pest 1
        - Effect of Pest 3 on Pest 1
      - Number of pests with low facilitation
      - Number of pests with no effect
      - Number of pests with a low reduction effect
      - Number of pests with high reduction effect
  - Severity of Pest 2
  - Severity of Pest 3

Figure 2. Overall output attributes of IPSIM: description of an injury profile (screenshot of the DEXi software). For the sake of simplicity, only 3 pests are represented in this figure. The severity of a given pest is first calculated independently by IPSIM as if no other pest was present. The aggregated severity of a given pest is then calculated by taking into account the combined effects of all other pests. This is done by considering the theoretical effect of one pest on another according to five levels: high facilitation, low facilitation, no effect, low reduction, high reduction.
doi:10.1371/journal.pone.0073202.g002

Table 1. Generic aggregating table used to represent the effect of one pest on another in IPSIM.

Severity of Pest 2 without any other pest	Theoretical effect of Pest 2 on Pest 1	Actual effect of Pest 2 on Pest 1
Maximum, very high or high	High facilitation	High facilitation
Maximum, very high or high	Low facilitation	Low facilitation
Maximum, very high or high	No effect	No effect
Maximum, very high or high	Low reduction	Low reduction
Maximum, very high or high	High reduction	High reduction
Medium	High and low facilitation	Low facilitation
Medium	No effect	No effect
Medium	High and low reduction	Low reduction
Low or very low	High facilitation	Low facilitation
Low or very low	Low facilitation, no effect, low reduction	No effect
Low or very low	High reduction	Low reduction
Nil	Any	No effect

doi:10.1371/journal.pone.0073202.t001

practices, soil and climate (physical and chemical components of the field which partly define the considered production situation), and biological interactions at the territory level (Figure 1). Figure 3 represents the sub-tree used in IPSIM to calculate the severity of a single pest without any interaction with other pests for a given crop. In this sub-tree, cropping practices are composed of cultural, genetic, biological, physical and chemical control actions. Inocula *sensu lato* are supposed to be non limiting in order to keep basic attributes as simple as possible. The most detailed level is cultural control. It is composed of actions for the management of primary inoculum (through the interaction between crop sequence and tillage for arable crops and prophylactic measures for perennial crops); escape strategies through the choice of the sowing date (some crops are less susceptible to some pests after or before some phenological stages) and mitigation through crop status (as a function of the sowing rate, fertilisation, irrigation, pruning for perennial crops, and application of crop growth regulators). The genetic control represents the level of resistance of the cultivar (or the cultivar mixture) to the considered pest. For some pests, biological control can be applied using living organisms released at the field or greenhouse scale. Physical control consists of using any mechanical, thermal, or electromagnetic actions to limit the pest population. Finally, the attribute "Chemical control" describes the efficacy of pesticide treatments and/or use of non-lethal chemicals such as pheromones or repellents. The effect of soil and climate are described independently and later aggregated in a "Soil and climate" attribute. Finally, the effects of elements (e.g. other fields, hedges, forests) at the territory level are taken into account by describing sources of primary inoculum and beneficials at the territory level, as well as the presence of physical barriers that might limit these interactions between the considered field and its surrounding environment. Harmless living organisms (i.e. neither pests nor beneficials) are not specifically represented in the model.

The scales and the aggregating tables used for the attributes presented in Figure 3 cannot be determined in a generic way. They have to be defined according to experimental results, literature, models, or expert knowledge and are specific to the considered crop and pests.

Typology of simulated injury profiles. So far, IPSIM was presented as a simulator of the severity levels for single pests interacting in an injury profile (Figure 2). This detailed information is valuable to researchers, advisers and even farmers to characterise the agronomic performance of cropping practices in a given production situation with regard to potential losses that various pests may cause. However, IPSIM can provide other information, less precise for the injury profile description, but more pertinent for the diagnosis of the overall effects of cropping practices and the biological environment of the considered field on injury dynamics. We chose to categorise pests according to a simple characteristic that describes their level of dependency to the cropping system: their level of endocyclism (high and low). The term "endocyclic" refers to an organism whose development is mostly restricted to a field and highly depends on the field endo-inoculum. The level of endocyclism of a given pest is therefore directly defined by the level of persistence of primary endo-inoculum *sensu lato* in a given field and its dispersal ability. Pests with a high level of persistence and low dispersal ability are highly endocyclic. Pests with a low level of persistence are slightly endocyclic, regardless their dispersal ability. Pests with a high level of persistence and a high dispersal ability are moderately endocyclic. The inoculum produced by an endocyclic pest in one season can be carried over to the next, thus building up a cumulative inoculum reservoir over the years. Endocyclic organisms are thus highly dependent on field history. The categorisation of pests into two groups (high/medium and low levels of endocyclism) can help identify the main level to address to control them: the field or territory level.

For example, root-knot nematodes (*Meloidogyne* spp.) on horticultural crops, wireworms on potato (*Agriotes* spp.), wheat common bunt (*Tilletia* spp.), take-all on wheat (*Gaeumannomyces graminis* var. *tritici*), dicotyledonous weeds such as *Chenopodium album* and *Fallopia convolvulus* are highly endocyclic pests. However, highly endocyclic pests can sometimes be spread to other fields by anthropic activities (e.g. via agricultural machinery, pruning tools, clothes and boots of greenhouse technicians). This dispersal mechanism will not be taken into account in the model. Aphids on several crops (e.g. *Brevicoryne brassicae*), powdery mildew on grapevine (*Erysiphe necator*), rusts on cereals (e.g. *Puccinia recondita*), codling moth on apple tree (*Cydia pomonella*), and weeds such as some *Asteraceae* (e.g. *Taraxacum dens leonis*) or grassy weeds (e.g. *Bromus sterilis*) are slightly endocyclic pests.

Two aggregating tables were designed to summarise the distribution of final injury levels of single pests using two aggregated variables: the overall final severity of i) highly/

Table 2. Generic aggregating table used to calculate the overall effect on a given pest caused by all the other pests in an injury profile.

Number of pests with high facilitation	Number of pests with low facilitation	Number of pests with no effect	Number of pests with low reduction	Number of pests with high reduction	Overall effects of all other pests
0	0	0	0	0	No effect
0	0	0	0	≥1	High reduction
0	0	0	≥1	0	Low reduction
0	0	0	≥1	≥1	High reduction
0	0	≥1	0	0	No effect
0	0	≥1	0	≥1	High reduction
0	0	≥1	≥1	0	Low reduction
0	0	≥1	≥1	≥1	High reduction
0	≥1	0	0	0	Low facilitation
0	≥1	0	0	≥1	High reduction
0	≥1	0	≥1	0	Low reduction
0	≥1	0	≥1	≥1	Low reduction
0	≥1	≥1	0	0	Low facilitation
0	≥1	≥1	0	≥1	High reduction
0	≥1	≥1	≥1	0	Low reduction
0	≥1	≥1	≥1	≥1	High reduction
≥1	0	0	0	0	High facilitation
≥1	0	0	0	≥1	Low reduction
≥1	0	0	≥1	0	No effect
≥1	0	0	≥1	≥1	Low reduction
≥1	0	≥1	0	0	High facilitation
≥1	0	≥1	0	≥1	Low reduction
≥1	0	≥1	≥1	0	Low reduction
≥1	0	≥1	≥1	≥1	Low reduction
≥1	≥1	0	0	0	High facilitation
≥1	≥1	0	0	≥1	Low reduction
≥1	≥1	0	≥1	0	Low reduction
≥1	≥1	0	≥1	≥1	High reduction
≥1	≥1	≥1	0	0	High facilitation
≥1	≥1	≥1	0	≥1	Low reduction
≥1	≥1	≥1	≥1	0	No effect
≥1	≥1	≥1	≥1	≥1	Low reduction

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moderately and ii) slightly endocyclic pests (Table 4). Considering three levels of final injury (low, medium, high) for each of the two endocyclism groups, a range of nine possible generic injury profiles was proposed (Figure 4) for any agricultural productions worldwide (i.e. major crops; vegetables; vineyard; orchards; horticulture; industrial crops, aromatic and medicinal plants; grassland; in field or in Controlled Environment Agriculture). For production situations where injury profile haves high final injury levels of highly endocyclic pests (IP7, IP8; IP9; Table 5), a better management of primary inoculum production at the field level should be undertaken (e.g. interaction between by crop sequence and tillage; stubble management, volunteer management, stale seedbeds and sanitation measures for perennial crops). For production situations with injury profiles with high levels of slightly endocyclic pests (IP3, IP6; IP9; Table 5), special attention should be paid to i) the management of inoculum production at the territory level (e.g. spatial distribution of cropping systems, management of primary inoculum production in the neighbouring fields or waste piles, management of interstitial spaces to promote beneficials); ii) escape strategies (sowing date adaptation); iii) mitigation through the crop status (e.g. cultivar choice, sowing rate, nitrogen fertilisation, irrigation).

Results

Implementation of IPSIM Generic Framework into a Simulation Model, an Example

This article aims to present the whole modelling process: i) development of a conceptual framework; ii) implementation of this conceptual scheme into a simulation model for a simple case; iii) simulation to exemplify potential uses of IPSIM models. The specification of IPSIM will be performed for a simple injury profile on wheat: two highly endocyclic diseases (eyespot and sharp eyespot) and a slightly endocyclic disease (brown rust). Eyespot,

Table 3. Generic aggregating table used to calculate the severity of one pest in interaction with the other pests of an injury profile.

Severity of the considered pest without any other pests	Overall effect of the other pests	Severity of the considered pest under the influence of other pests
Maximum	High facilitation	Maximum
Maximum	Low facilitation	Maximum
Maximum	No effect	Maximum
Maximum	Low reduction	Very high
Maximum	High reduction	High
Very high	High facilitation	Maximum
Very high	Low facilitation	Maximum
Very high	No effect	Very high
Very high	Low reduction	High
Very high	High reduction	Medium
High	High facilitation	Maximum
High	Low facilitation	Very high
High	No effect	High
High	Low reduction	Medium
High	High reduction	Low
Medium	High facilitation	Very high
Medium	Low facilitation	High
Medium	No effect	Medium
Medium	Low reduction	Low
Medium	High reduction	Very low
Low	High facilitation	High
Low	Low facilitation	Medium
Low	No effect	Low
Low	Low reduction	Very low
Low	High reduction	Very low
Very low	High facilitation	Medium
Very low	Low facilitation	Low
Very low	No effect	Very low
Very low	Low reduction	Very low
Very low	High reduction	Very low
Nil	High facilitation	Nil
Nil	Low facilitation	Nil
Nil	No effect	Nil
Nil	Low reduction	Nil
Nil	High reduction	Nil

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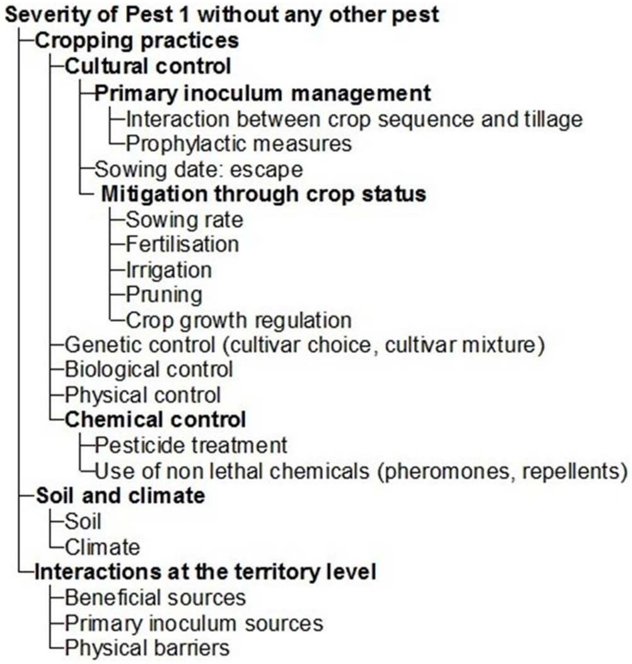
caused by the necrotrophic and soil-borne fungi *Oculimacula yallundae* and *O. acuformis*, anamorph *Pseudocercosporella herpotrichoides* is considered to be the most important stem-base disease of cereals in temperate countries. In France, sharp eyespot, another soil-borne fungus caused *by Rhizoctonia cerealis,* is one of the minor diseases of the foot disease complex of winter wheat, but is thought to interact strongly with eyespot. The two pathogens show distinct antagonistic behaviour within the infected stem base, which translates into a negative correlation between sharp eyespot and eyespot incidence [42–44]. Finally, brown rust, caused by *Puccinia triticina*, is the most common rust disease of wheat and is now recognised as an important pathogen in wheat production worldwide, causing significant yield losses over large geographical areas [45]. As opposed to the first two soil-borne diseases which are disseminated over short distances, brown rust is an obligate, airborne disease with conidia which are wind-dispersed over hundreds of kilometres, resulting in rust epidemics on a continental scale [46].

The design of IPSIM-Wheat-Eyespot and the evaluation of its predictive quality is described in a companion paper [22]. For the sake of simplicity and readability, the other two models will not be presented in detail, but their development was similar to the one presented in [22]. The two models for eyespot and sharp eyespot are similar in terms of structure (tree) and aggregating tables because the impact of cropping practices on sharp eyespot is similar to that on eyespot [42]. However, since brown rust is an



Severity of Pest 1 without any other pest
- **Cropping practices**
  - **Cultural control**
    - **Primary inoculum management**
      - Interaction between crop sequence and tillage
      - Prophylactic measures
    - Sowing date: escape
    - **Mitigation through crop status**
      - Sowing rate
      - Fertilisation
      - Irrigation
      - Pruning
      - Crop growth regulation
  - Genetic control (cultivar choice, cultivar mixture)
  - Biological control
  - Physical control
  - **Chemical control**
    - Pesticide treatment
    - Use of non lethal chemicals (pheromones, repellents)
- **Soil and climate**
  - Soil
  - Climate
- **Interactions at the territory level**
  - Beneficial sources
  - Primary inoculum sources
  - Physical barriers

Figure 3. Hierarchical sub-tree to predict the severity of a single pest without any interaction with other pests (screenshot of the DEXi software).
doi:10.1371/journal.pone.0073202.g003

airborne disease, the effects of primary inoculum management at the field scale are less important than for the two soil-borne diseases. For this airborne disease, the main control methods are: i) mitigation through crop status (using a resistant cultivar for instance) and; ii) the management of primary inoculum sources at the territory level. For this schematic injury profile, we will assume that no direct interactions occur between the two soil-borne, stem-base diseases and this airborne, foliar disease.

Simulation Scenarios

The use of the model presented in the first sub-section of the "results" section is exemplified for three contrasting cropping practices in a given production situation (Figure 5). The three cropping practices considered were: intensive, integrated and organic systems. The intensive system is a wheat monoculture with a high level of inputs and a high-yielding cultivar susceptible to diseases, aiming at a high yield level. The integrated system is characterised by a limited use of inputs, with a lower-yielding cultivar than the former system, but less susceptible to diseases, a short wheat rotation, and a satisfactory yield level. The organic system is characterised by low inputs, with a disease-resistant cultivar with a limited yield, associated with a long wheat rotation and appropriate crop management. The three systems were tested in the same production situation, with a weather scenario favourable to the development of the considered diseases.

Simulation Results

The DEXi software computed the aggregated attribute values of the model presented in the first sub-section of the "results". In the same production situation, the three cropping practices led to contrasting injury profiles. In the absence of estimates of potential yield losses caused by these injury profiles, it is difficult to provide direct recommendations for cropping practices adaptations. However, these simulations enable a diagnosis in terms of pest development for the three simulated systems. The intensive system led to IP4, i.e. a medium final injury level for highly endocyclic pests associated with a low final injury level for slightly endocyclic pests (Figure 5). For this system, the model suggests that a better management of primary inoculum of the pathogen responsible for eyespot injury should be considered. The integrated system led to IP2, i.e. a low final injury level for highly endocyclic pests associated with a medium final injury level for slightly endocyclic pests (Figure 5). For this system, the model suggests that a better control of brown rust through the use of a more resistant cultivar or the use of a low-dose fungicide, provided that it would be economically sound. The organic system led to IP1, i.e. a low final injury level for highly endocyclic pests associated with a low final injury level for slightly endocyclic pests (Figure 5). This is consistent with the associated cropping practices which aims at minimising pest development by combining prophylactic measures with partial effects. It is important to underline that this diagnosis did not address yield losses, but focused only on injury.

Discussion

Potential Uses of IPSIM Models

These simulations illustrate how IPSIM can be used to assess *ex-ante* the performance of various cropping systems with regard to the control of pest injury on a given crop. This information is useful when designing innovative cropping systems, either by prototyping, e.g. [47], simulation, e.g. [48], or expert knowledge, e.g. [12]. Since climate significantly affects injury profiles, weather frequency analyses are needed, using a set of input variables describing a wide range of climatic scenarios so that the information provided by IPSIM is robust in the face of weather variability. However, IPSIM cannot be seen as a model to design innovative cropping systems *in silico* for two major reasons. First, crop damage is not simulated by IPSIM, which makes it difficult to rank pests with respect to the crop losses they cause. Second, the social, economic and environmental performance of the simulated cropping systems are not calculated. To tackle this problem, IPSIM could be coupled to a damage model (such as RICEPEST [6,19,20] or WHEATPEST [20]) that would predict yield losses as a function of the injury profiles encountered and other relevant variables. Alternatively, a crop model (e.g. STICS [14]) could be used, with a set of single damage functions (such as the ones used in WHEATPEST [20]), and coupled with IPSIM. Then, once the damage caused by a given injury profile in a given production situation has been predicted, a more general framework, such as MASC, [30] or DEXiPM, [49], could be used to predict the social, economic and environmental performance of the tested systems in a given production situation. This approach will help design innovative cropping systems less vulnerable to pests. Using that modelling framework, IPSIM would be the missing link to fill the gap between crop models that can help predict performance of pest-free cropping systems and epidemiological models that generally do not represent the effects of crop status under the influence of cropping practices. In addition, models developed with IPSIM could be used to create typologies of injury profiles at a regional, national, continental or even worldwide scale, using a schematic description of soil and climate, together with a description of the diversity of cropping practices. This should reveal the main injury profiles encountered and help design strategies to control them with better vertical and horizontal integration of IPM. If the corresponding damage models were available, the typology produced could help prioritise objectively research efforts on the main harmful pests.

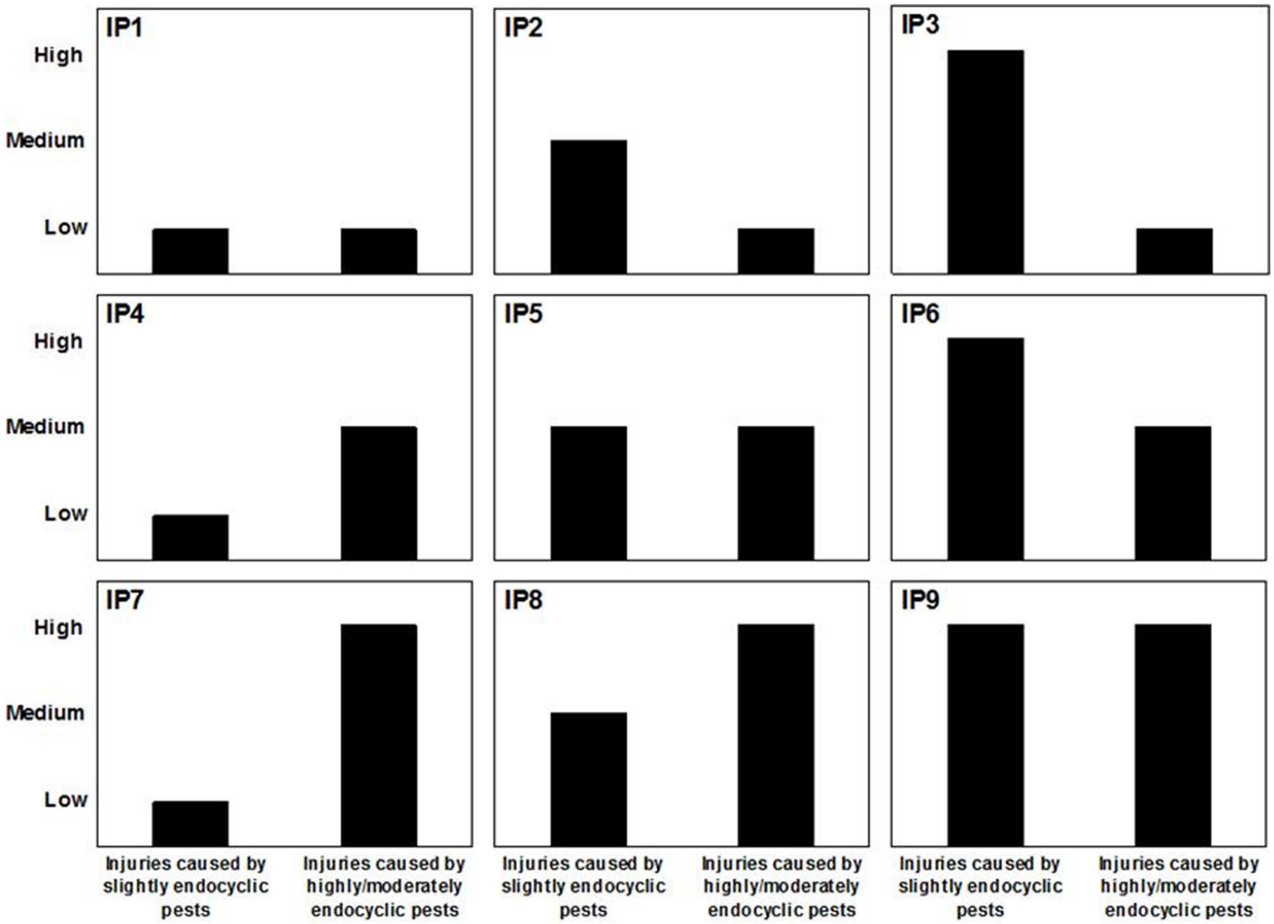


Figure 4. Typology of injuries caused by multiple pests on a crop for given Cropping Practices in a given Production Situation using nine generic Injury Profiles (IP1–IP9). These Injury Profiles are determined by the final levels of the injuries caused by slightly and highly/moderately endocyclic pests (plant pathogens, weeds and animal pests). They can be used to perform cross-cutting analyses for a wide range of agricultural productions.
doi:10.1371/journal.pone.0073202.g004

IPSIM could also be used in an *ex-post* analysis to understand the behaviour of commercial field or experimental plots. Finally, it can be viewed as a communication tool for groups, as well as to teach practitioners and students. Knowledge of several scientific fields involved in crop protection, as well as several types of expertise (of scientists, extension engineers, or farmers) can be built into IPSIM, offering a framework for these various communities to interact and combine their knowledge.

Table 4. Generic aggregating table used to define the level of severity of slightly endocyclic pests in an Injury Profile as a function of the final injury level of single pests.

Number of slightly endocyclic pests with a very high or maximum final injury level	Number of slightly endocyclic pests with a low, medium or high final injury level	Number of slightly endocyclic pests with a null or very low final injury level	Overall severity of slightly endocyclic pests in the Injury Profile
>1	>1	>1	High
>1	>1	0	High
>1	0	>1	High
>1	0	0	High
0	>1	>1	Medium
0	>1	0	Medium
0	0	>1	Low
0	0	0	Low

The same aggregating table is used to define the level of severity of highly/moderately endocyclic pests.
doi:10.1371/journal.pone.0073202.t004

Table 5. Equivalence between features of qualitative models developed within the IPSIM framework and quantitative simulation models.

Feature	Qualitative simulation models such as the ones developed with the IPSIM framework	Quantitative simulation models
Type of input variables	Nominal, ordinal, or interval	Interval
Type of state variables	Ordinal	Interval
Type of output variables	Ordinal (can be transformed into static interval or even dynamic interval)	Interval
Model structure	Aggregation tree	Equations
Specification of the model structure	Aggregating tables	Parameters
Analysis of model's behaviour	Table of local and global weights for each input and aggregated attributes	Sensitivity analyses to input variables and parameters
Measures of agreement (non exhaustive)	Proportion of correctly predicted ordinal classes; non parametric Wilcoxon signed rank test to analyse if the distribution of errors is significantly biased or not; matched marginal distribution analysis or joint distribution analysis in a square contingency table	Bias; Mean Absolute Error; Root Mean Squared Error; Efficiency

doi:10.1371/journal.pone.0073202.t005

Limitations of the Approach

Like any other model, the predictive quality of IPSIM should be assessed prior to its use. This highlights the urgent need to collect data in commercial fields describing the input and output variables of IPSIM (*i.e.* cropping practices, soil and climate, field environment, injury profiles), along with the social, economic and environmental performances of the monitored agroecosystems. It is important to also add measurements of state variables characterising the crop status (e.g. biomass per area unit, Leaf Area Index) in order to better describe important state variables of the agroecosystem for other possible future analyses of the created datasets. However, due to the lack of datasets containing a description of injury profiles, the confidence that users may have in IPSIM models could also be enhanced by comparing simulation outputs with their own expertise to identify any mismatches. All the information contained within IPSIM models is held in the hierarchical trees and the associated aggregating tables. One of the consequences of this specificity of models developed with the IPSIM framework is that, once developed, the predictive quality of the models can be enhanced easily using experimental datasets by modifying aggregating tables, and, if need be, the structure of the model.

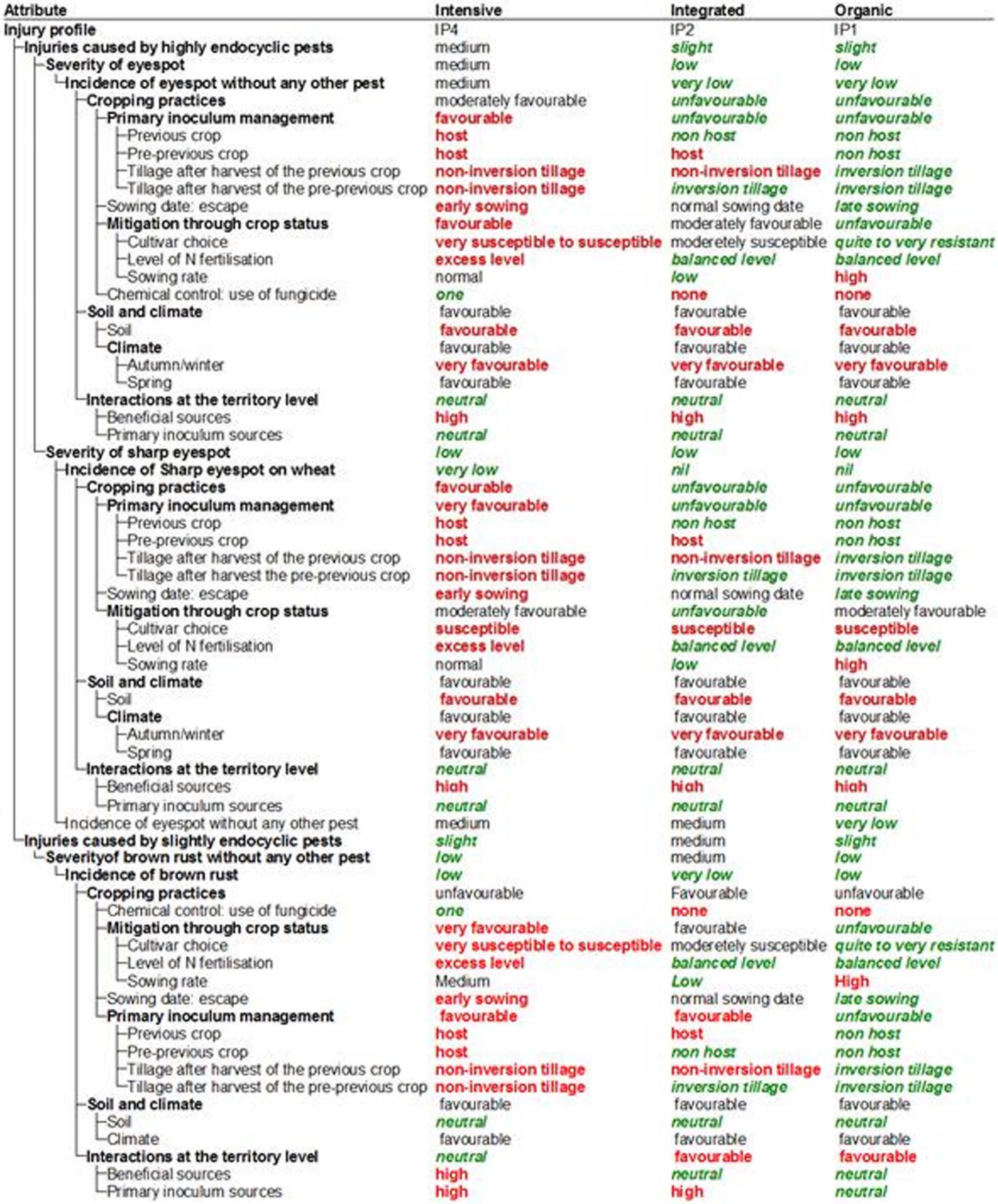
The possible injury profiles that IPSIM models can simulate are numerous. However, observations tend to show that the diversity of injury profiles encountered in commercial fields is much less than the structure of IPSIM models can generate. This results from two mechanisms. First, pests can interact directly (through facilitation, predation, competition for the same ecological niche) or indirectly (though modification of the biotope). This implies that not all potential theoretical injury levels could occur simultaneously. This is a limitation of IPSIM which does not account for the impact of injuries on crop growth. Secondly, the soil, climate, cropping practices and landscape occurring in a given territory might not be diverse enough to lead to all theoretical injury levels (for instance, the theoretical injury profile with all the forms of injury at their maximum level does not exist in reality). Another limitation of IPSIM is the way that interactions between pests are represented. If n pests are considered, n (n-1) interactions are to be described. This is similar to the three-body (or n-body) problem in physics, which has a global analytical solution in the form of convergent power series [50], but that has to be approximated in practice because they converge too slowly. IPSIM models approximate interactions among injuries by arbitrarily calculating the global interaction that would occur between a given injury and the rest of the injury profile defined as the sum of single injuries simulated without taking into account interactions among pests. However, this approximation certainly appears negligible as compared to other necessary simplification hypotheses.

From the conceptual viewpoint, it could be asked why the crop which is entered in the field biological component (Figure 1) does not appear at the first level of the IPSIM tree. After all, pests only experience physical, chemical and biological interactions within agroecosystems and a description of i) the crop status, ii) soil and climate, and iii) the neighbouring environment of the field are indeed the true drivers of pest dynamics. This option was tried when developing IPSIM structure, but led to too complicated a structure, the effect of single cultural operations being overlooked among the numerous levels of the tree. In addition, datasets with a description of cropping practices and injury profiles are extremely scarce. The requirement of additional variables describing the crop status (e.g. in terms of phenology, architecture, biomass, Leaf Area Index) would also lead to greater difficulties in developing IPSIM models and in evaluating its predictive quality.

We recommend to develop models with no more than 7 final injury levels for a single pest. The lack of precision of IPSIM models could be seen as a drawback as compared to quantitative epidemiological models. Firstly this is because these latter models address a much simpler system: a single pest, rather than an injury profile. Secondly, when developing models of complex systems, accuracy should be sought rather than precision. Searching for better precision would certainly lead to an increase in the model's complexity and possibly to a dead end. We believe that the proposed precision of the models that will be developed with the IPSIM framework is more than enough for the main ultimate purpose of the model: helping the design of innovative cropping systems less vulnerable to pests.

Points for Reflection

The presented structure of IPSIM is not exhaustive in terms of control methods that can be undertaken. However, developers of models within the IPSIM framework can always easily modify its structure in order to take into account the effects of control



Attribute	Intensive	Integrated	Organic
Injury profile	IP4	IP2	IP1
Injuries caused by highly endocyclic pests	medium	*slight*	*slight*
Severity of eyespot	medium	*low*	*low*
Incidence of eyespot without any other pest	medium	*very low*	*very low*
Cropping practices	moderately favourable	*unfavourable*	*unfavourable*
Primary inoculum management	**favourable**	*unfavourable*	*unfavourable*
Previous crop	**host**	*non host*	*non host*
Pre-previous crop	**host**	**host**	*non host*
Tillage after harvest of the previous crop	**non-inversion tillage**	**non-inversion tillage**	*inversion tillage*
Tillage after harvest of the pre-previous crop	**non-inversion tillage**	*inversion tillage*	*inversion tillage*
Sowing date: escape	**early sowing**	normal sowing date	*late sowing*
Mitigation through crop status	**favourable**	moderately favourable	*unfavourable*
Cultivar choice	**very susceptible to susceptible**	moderetely susceptible	*quite to very resistant*
Level of N fertilisation	**excess level**	*balanced level*	*balanced level*
Sowing rate	normal	*low*	**high**
Chemical control: use of fungicide	*one*	**none**	**none**
Soil and climate	favourable	favourable	favourable
Soil	**favourable**	**favourable**	**favourable**
Climate	favourable	favourable	favourable
Autumn/winter	**very favourable**	**very favourable**	**very favourable**
Spring	favourable	favourable	favourable
Interactions at the territory level	*neutral*	*neutral*	*neutral*
Beneficial sources	**high**	**high**	**high**
Primary inoculum sources	*neutral*	*neutral*	*neutral*
Severity of sharp eyespot	*low*	*low*	*low*
Incidence of Sharp eyespot on wheat	*very low*	*nil*	*nil*
Cropping practices	**favourable**	*unfavourable*	*unfavourable*
Primary inoculum management	**very favourable**	*unfavourable*	*unfavourable*
Previous crop	**host**	*non host*	*non host*
Pre-previous crop	**host**	**host**	*non host*
Tillage after harvest of the previous crop	**non-inversion tillage**	**non-inversion tillage**	*inversion tillage*
Tillage after harvest the pre-previous crop	**non-inversion tillage**	*inversion tillage*	*inversion tillage*
Sowing date: escape	**early sowing**	normal sowing date	*late sowing*
Mitigation through crop status	moderately favourable	*unfavourable*	moderately favourable
Cultivar choice	**susceptible**	**susceptible**	**susceptible**
Level of N fertilisation	**excess level**	*balanced level*	*balanced level*
Sowing rate	normal	*low*	**high**
Soil and climate	favourable	favourable	favourable
Soil	**favourable**	**favourable**	**favourable**
Climate	favourable	favourable	favourable
Autumn/winter	**very favourable**	**very favourable**	**very favourable**
Spring	favourable	favourable	favourable
Interactions at the territory level	*neutral*	*neutral*	*neutral*
Beneficial sources	**high**	**high**	**high**
Primary inoculum sources	*neutral*	*neutral*	*neutral*
Incidence of eyespot without any other pest	medium	medium	*very low*
Injuries caused by slightly endocyclic pests	*slight*	medium	*slight*
Severityof brown rust without any other pest	*low*	medium	*low*
Incidence of brown rust	*low*	*very low*	*low*
Cropping practices	unfavourable	Favourable	unfavourable
Chemical control: use of fungicide	*one*	**none**	**none**
Mitigation through crop status	**very favourable**	favourable	*unfavourable*
Cultivar choice	**very susceptible to susceptible**	moderetely susceptible	*quite to very resistant*
Level of N fertilisation	**excess level**	*balanced level*	*balanced level*
Sowing rate	Medium	*Low*	**High**
Sowing date: escape	**early sowing**	normal sowing date	*late sowing*
Primary inoculum management	**favourable**	**favourable**	*unfavourable*
Previous crop	**host**	**host**	*non host*
Pre-previous crop	**host**	*non host*	*non host*
Tillage after harvest of the previous crop	**non-inversion tillage**	**non-inversion tillage**	*inversion tillage*
Tillage after harvest of the pre-previous crop	**non-inversion tillage**	*inversion tillage*	*inversion tillage*
Soil and climate	favourable	favourable	favourable
Soil	*neutral*	*neutral*	*neutral*
Climate	favourable	favourable	favourable
Interactions at the territory level	*neutral*	**favourable**	**favourable**
Beneficial sources	**high**	*neutral*	*neutral*
Primary inoculum sources	**high**	**high**	*neutral*

Figure 5. Example of simulation outputs for wheat obtained for three cropping systems (intensive, integrated and organic) in a given production situation (screenshot of the DEXi software). Three pests in interaction were taken into account in these simulations: eyespot, sharp eyespot and brown rust.

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measures not present in Figure 3. For instance, the effect of cultivar mixtures or intercrops could be implemented, provided that the required knowledge is available.

The main breakthrough of IPSIM is to be able to handle complexity in a simple way. Input variables of the IPSIM models should be simple to provide. Most of these input variables will be static variables, except for weather variables that will be dynamic. The price to pay to handle the level of ecological complexity (such as defined by Li [51]) addressed by IPSIM is that IPSIM models are static. This is certainly not a problem to predict the consequences of technical options in a given production situation, but could hamper the linkage with dynamic models as suggested earlier. This limitation could easily be overcome by associating the level of final injury predicted by IPSIM models with generic dynamics. In order to do so, exponential, monomolecular, logistic, Gompertz, or Richards models [52] could be used with generic parameters chosen to represent the qualitative ordinal different injury levels predicted by IPSIM models.

The choice of qualitative variables to describe agroecosystems is relevant for several reasons. Firstly, farmers generally rely on a qualitative perception of their environment to make decisions. This suits the formalism of IPSIM. Secondly, because of the complexity of the system, few datasets are available to describe its components, i.e. the production situation, cropping practices and the injury profile. Using qualitative variables enables one to gather and use various existing datasets that were not acquired for the development of IPSIM models. For instance, datasets from diagnoses of commercial fields or even from experiments may not have used the same severity scale for a given disease. The use of qualitative classes allows data from different origins and/or with different precision to be combined. It is possible to associate interval classes with qualitative attributes. For instance, the 7 levels "nil"; "very low"; "low"; "medium"; "high"; "very high"; and "maximum" can be transformed into [0]; [0–20]; [20–40]; [40–60]; [60–80]; [80–100]; [100] intervals of percentage of diseased foliage respectively, if one wants to compare these outputs with observed severities of a disease for instance. Thus, data acquired on various scales can still be combined to strengthen the dataset used to estimate the predictive quality of the model or to improve the aggregating tables.

Table 5 presents the equivalence between features of models developed within the IPSIM framework and more common quantitative simulation models. Input attributes of IPSIM models can be nominal, ordinal or interval variables, unlike quantitative simulation models, which require only interval input variables. The state variables (aggregated attributes) of IPSIM models, including output variables, are ordinal. However, if need be, output variables of IPSIM models can be transformed into interval variables. This transformation can be performed by associating each possible ordinal value with a quantitative value (e.g. static final value of an injury level, or quantitative intervals) or with an injury dynamic. The relationship between variables is described by a tree in aggregative qualitative models, whereas quantitative models use equations. The DEXi software [40] provides a table with the respective weights of input and aggregated attributes on the value of the root node (main output). This table can be seen as an equivalent to a simple sensitivity analysis to input variables for quantitative models, prior to more detailed ones [53]. It is notable that IPSIM models have no parameters. The equivalents of parameters that specify relationships among variables in quantitative models are the aggregating tables. The proportion of situations correctly simulated is a criterion that can be used to characterise the agreement between values simulated with an IPSIM model and observations. In addition, a non-parametric Wilcoxon signed rank test can be used to analyse whether the distribution of errors is significantly biased or not. These criteria can be seen as equivalent to common statistical criteria for quantitative models (Bias, Mean Absolute Error; Root Mean Square Error; Efficiency [54]). At last, methods specific to matched-pairs data with ordered categories can be used. In order to do so, various models comparing matched marginal distributions or analysing the joint distribution in a square contingency table can be applied [55].

The qualitative attributes of IPSIM models can lead to threshold effects. In order to cope with this limitation, a tool, named proDEX was developed to model uncertain expert knowledge [56]. This software offers the definition of probabilistic aggregating tables, where each combination of descendants' values maps to a probability distribution of the aggregated attributes, rather than a single value. In this approach, input values must be categorised prior to their use in the model. Since this process is time-consuming, proDEX allows categorisations to be part of the model definition and the inputs to be entered as interval variables. In combination with probabilistic aggregating tables, categorisations can be made to transform numerical values into probabilistic distributions, eliminating the problem of crisp interval boundaries. Eventually, the proDEX method could permit a useful extension of the modelling approach presented in this paper.

Finally, a website giving online access to all the functionalities of IPSIM is planned. This website will enable researchers, advisors, farmers and students to develop their own models for a wide range of crops.

Conclusion

We believe that IPSIM is a useful innovative modelling framework to help vertical and horizontal integrations for IPM. Its output attributes include nine generic injury profiles that are based on a two-level categorisation of the degree of endocyclism of harmful organisms. These nine injury profiles can be seen as a tool to perform cross-cutting typologies of agroecosytems for various types of crop (arable crops, vegetables, orchards, vineyards, Controlled Environment Agriculture), with regard to the main pests that have to be managed. IPSIM will generate new knowledge by combining various sources of information from experiments, diagnoses of commercial field, models, and expert panels in a simple way, despite the high ecological complexity of the system addressed. The associated companion paper provides a proof of concept of the proposed method for a single pest.

Author Contributions

Analyzed the data: JNA MHR. Contributed reagents/materials/analysis tools: JNA MHR. Wrote the paper: JNA MHR.

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Injury Profile SIMulator, a Qualitative Aggregative Modelling Framework to Predict Injury Profile as a Function of Cropping Practices, and Abiotic and Biotic Environment. II. Proof of Concept: Design of IPSIM-Wheat-Eyespot

Marie-Hélène Robin[1,2], Nathalie Colbach[3], Philippe Lucas[4], Françoise Montfort[4], Célia Cholez[1,2], Philippe Debaeke[1,5], Jean-Noël Aubertot[1,5]*

1 Institut National de la Recherche Agronomique, Unité Mixte de Recherche 1248 Agrosystèmes et agricultures, Gestion des ressources, Innovations et Ruralités, Castanet-Tolosan, France, **2** Université de Toulouse, Institut National Polytechnique de Toulouse, Ecole d'Ingénieurs de Purpan, Toulouse, France, **3** Institut National de la Recherche Agronomique, Unité Mixte de Recherche 1347 Agroécologie, Dijon, France, **4** Institut National de la Recherche Agronomique, Unité Mixte de Recherche 1099 Biologie des Organismes et des Populations appliquée à la Protection des Plantes. Le Rheu, France, **5** Université Toulouse, Institut National Polytechnique de Toulouse, Unité Mixte de Recherche 1248 Agrosystèmes et agricultures, Gestion des Ressources, Innovations et Ruralités, Castanet-Tolosan, France

Abstract

IPSIM (Injury Profile SIMulator) is a generic modelling framework presented in a companion paper. It aims at predicting a crop injury profile as a function of cropping practices and abiotic and biotic environment. IPSIM's modelling approach consists of designing a model with an aggregative hierarchical tree of attributes. In order to provide a proof of concept, a model, named IPSIM-Wheat-Eyespot, has been developed with the software DEXi according to the conceptual framework of IPSIM to represent final incidence of eyespot on wheat. This paper briefly presents the pathosystem, the method used to develop IPSIM-Wheat-Eyespot using IPSIM's modelling framework, simulation examples, an evaluation of the predictive quality of the model with a large dataset (526 observed site-years) and a discussion on the benefits and limitations of the approach. IPSIM-Wheat-Eyespot proved to successfully represent the annual variability of the disease, as well as the effects of cropping practices (Efficiency = 0.51, Root Mean Square Error of Prediction = 24%; bias = 5.0%). IPSIM-Wheat-Eyespot does not aim to precisely predict the incidence of eyespot on wheat. It rather aims to rank cropping systems with regard to the risk of eyespot on wheat in a given production situation through *ex ante* evaluations. IPSIM-Wheat-Eyespot can also help perform diagnoses of commercial fields. Its structure is simple and permits to combine available knowledge in the scientific literature (data, models) and expertise. IPSIM-Wheat-Eyespot is now available to help design cropping systems with a low risk of eyespot on wheat in a wide range of production situations, and can help perform diagnoses of commercial fields. In addition, it provides a proof of concept with regard to the modelling approach of IPSIM. IPSIM-Wheat-Eyespot will be a sub-model of IPSIM-Wheat, a model that will predict injury profile on wheat as a function of cropping practices and the production situation.

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* E-mail: Jean-Noel.Aubertot@toulouse.inra.fr

Introduction

Stem base diseases on cereals and grasses are widespread in many eco-regions of the world and cause important production and economic losses. The most detrimental foot and root pathogens on cereals in temperate areas are *Pseudocercosporella herpotrichoides*; *Fusarium* spp, *Rhizoctonia cerealis* and *Gaeumannomyces graminis* [1]. Eyespot caused by the necrotrophic and soil-borne fungi *Oculimacula yallundae* and *O. acuformis*, anamorph *Pseudocercosporella herpotrichoides* [2–4] is considered to be the most important stem base disease of cereals in temperate countries [5]. Under cool and wet conditions in autumn and spring, both species sporulate and infect the stem bases of their hosts. Without any host crops (cereals, ryegrass), the pathogen survives on previously infected stubble, on which splash-dispersed conidia and air-dispersed ascospores are produced [6]. Injuries interfere with the circulation of nutrients and water through the base of the stem [7] leading to a weakening and possibly to a breakage of the stem base, causing lodging before harvest [5,8]. Relative yield losses of up to 50%

have been reported for the most severe attacks on winter wheat with lodging [2,7,9–11].

In the past, the control of eyespot has relied largely on chemical protection [12]. However, due to the development of resistance to the main available fungicides in *O. yallundae* and *O. acuformis* populations, adaptation of the entire cropping system to control eyespot on wheat is a sound alternative [13,14]. Furthermore, growing concerns about the impact of pesticides on the environment and human health has led to attempts to limit pesticide use [15,16]. Most governments of developed countries have launched national action plans to reduce pesticide use. For instance, the French government has set as a goal to reduce pesticide use by 50% by 2018 if possible [17]. The European Union has proposed to encourage the use of low-pesticide farming as one of its priorities by the Sustainable Use Directive (SUD) (http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri = OJ:L:2009:309:0071:0086:FR:PDF, accessed November 2012).

In addition, the USA decided to support and develop Integrated Pest Management (IPM) nationwide in order to reduce pesticide use [18]. It appears necessary therefore to combine various methods (cultural, genetic and chemical) in IPM strategies [19] to control eyespot on wheat. The main cultural practices that can partly control eyespot through a specific adaptation are: a low host frequency in the crop sequence, infected stubble management through adapted tillage, a late sowing date and low sowing rate [10,20,29] The genetic control of eyespot consists of using resistant cultivars. There are several known sources of resistance to eyespot, but only three resistance genes have been described so far [21–23].

IPM strategies, based on these control methods, have to be developed, adapted and applied to a wide range of physical, chemical, biological and socio-economic contexts. However, it is extremely difficult to describe the entirety of the cropping practices*environment*crop*pest system because of the tremendous number of interactions [24]. Modelling is certainly the best way to handle such a level of complexity and to help design sustainable innovative cropping systems less reliant on pesticides.

However, crop models do not deal with injuries caused by pests [25] and few pest models integrate the effects of cultural practices because of the difficulty of describing their numerous consequences on the agroecosystem [26] Thus, different models have been developed to represent eyespot injuries on wheat [27–29] or the associated damage [30] Among these, only one model takes into account the effect of the cropping system (crop succession, tillage, sowing date, sowing rate, total nitrogen fertiliser and its form) on injuries caused by eyespot [29]. However, this model does not take into account soil and climate, along with some cultural practices that can greatly influence the disease development (e.g. cultivar choice). There is therefore a need for a model that predicts as exhaustively as possible the effect of cropping practices on eyespot on wheat in a given production situation.

In this article, we will define the production situation as the physical, chemical and biological components, except for the crop, of a given field (or agroecosystem), its environment, as well as socio-economic drivers that affect farmers' decisions (adapted from [31,32], [33]). In this definition, "environment" refers to climate and the fraction of the territory that can influence pest dynamics through dispersal of harmful or beneficial organisms. In a given production situation, a farmer can design several cropping systems according to his goals, his perception of the socio-economic context and his environment, farm features, his knowledge and cognition. However, it is assumed that a given cropping system in a given production situation, such as defined above, should lead to a unique injury profile. In IPSIM, production situations are partly described by three components: soil, climate, and the biological environment of the field [33]. In the approach used here, the farmer's decision-making process and socio-economic drivers are not taken into account.

The conceptual bases of IPSIM have been described in detail by Aubertot and Robin [33]. The generic hierarchical aggregative modelling framework of IPSIM aims at predicting an injury profile as a function of cropping practices, soil, and climate and the biological field environment for any mono-specific crop production (arable crop, perennial or protected crops). In order to test whether this modelling approach could be successfully applied to represent injuries caused by a single pest, a model, named IPSIM-Wheat-Eyespot, has been developed according to the conceptual framework of IPSIM. It aims at predicting the final incidence of eyespot on wheat as a function of the production situation and cropping practices. IPSIM-Wheat-Eyespot gathers available knowledge in the scientific literature (models, experimental results) and expertise and will help design cropping systems with low risk of eyespot on wheat and perform diagnoses of commercial wheat fields. IPSIM-Wheat-Eyespot will be used as a sub-model for IPSIM-Wheat, a model that will predict the injury profile on winter wheat (i.e. the distribution of injuries caused by the most important detrimental pests on wheat [34]). This paper presents the method used to develop IPSIM-Wheat-Eyespot using the conceptual modelling framework of IPSIM [33], an evaluation of its predictive quality and a discussion on the limitations and benefits of the model.

Materials and Methods

Design of IPSIM-Wheat-Eyespot

1. General Approach. IPSIM-Wheat-Eyespot is based on the DEX method, and is implemented with the software DEXi [35]. DEX is a method for qualitative hierarchical multi-attribute decision modelling and support, based on a breakdown of a complex decision problem into smaller and less complex sub-problems, characterised by indicators (or attributes) that are organised hierarchically into a decision tree. These attributes are characterised by their name, a description and a scale. DEXi is generally used to evaluate and analyse decision problems, e.g. [36]. However, the DEX method has been used here in an original way to model complex agroecosystems. IPSIM-Wheat-Eyespot is therefore a hierarchical and qualitative multi-criteria model, allowing the prediction of eyespot injury according to various factors with sometimes opposite effects. IPSIM-Wheat-Eyespot has the following features (derived from [37]):

i) Processes are hierarchically organised into a tree of attributes that constitutes the structure of the model;

ii) Terminal attributes of the tree (i.e. leaves or *basic attributes*) are input variables of the model and must be specified by users; the "trunk" of the tree (i.e. the final aggregated attribute) is the main model output variable (final eyespot incidence on wheat); internal nodes are called *aggregated attributes*;

iii) All model attributes are qualitative variables (nominal or ordinal) rather than quantitative variables. They take only discrete symbolic values, usually represented by words rather than numbers: e.g. "ploughing, stubble disking, rotary harrowing" for nominal variables, "low, medium, high" for ordinal variables;

iv) The aggregation of values up the tree is defined by aggregating tables for each aggregated attribute based on "if-then" decision rules. These aggregating tables can be seen as equivalents of parameters for quantitative numerical models, whereas the tree of attributes can be viewed as the equivalent of their mathematical structure.

IPSIM-Wheat-Eyespot was designed in 3 steps [37]: (1) identification and organisation of the attributes, (2) definition of attribute scales, and (3) definition of aggregating tables.

2. Identification and Organisation of Attributes. IPSIM-Wheat-Eyespot aims at predicting the incidence of eyespot on wheat in a given field according to a set of input variables. The spatial scale addressed is the field and the temporal scale is the wheat growing season, although some input variables encompass the crop sequence (up to the pre-preceding crop). IPSIM-Wheat-Eyespot is a static deterministic model.

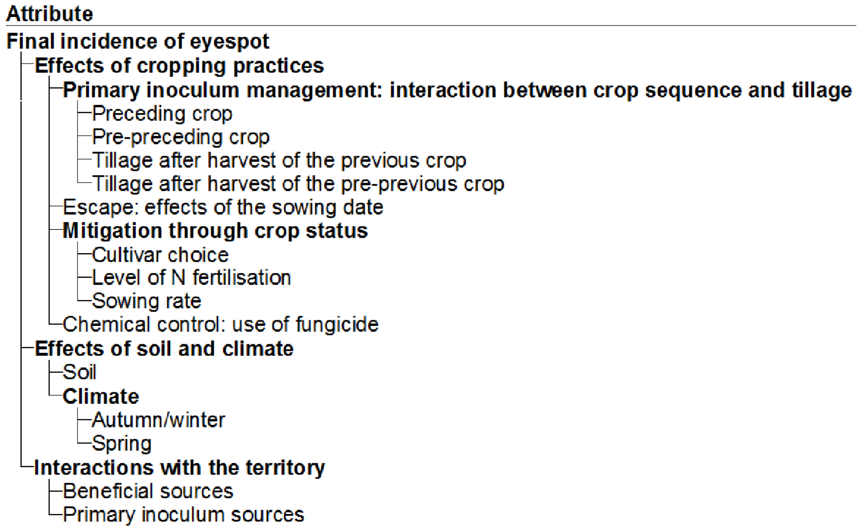
The hierarchical structure presented in Figure 1 represents the breakdown of factors affecting eyespot final incidence into specific explanatory variables, represented by lower-level attributes. This figure represents the adaptation to eyespot of the model structure presented in Figure 2 by Aubertot and Robin [33].

In all, IPSIM-Wheat-Eyespot has 21 attributes, of which 14 are basic (i.e. input variables) and 7 aggregated. The 14 basic attributes are presented as the terminal leaves of the tree and their levels are aggregated into higher levels according to aggregating tables. They represent input variables of the model. Some of them (e.g. those representing the interactions at the territory level) could be omitted since they do not influence the final output. However, they were kept because these basic attributes will be necessary for the modelling of the whole injury profile on wheat. The aggregated attributes are internal nodes. They represent state variables or the output variable of IPSIM-Wheat-Eyespot. They are determined by lower-level basic attributes [38]. The output of IPSIM-Wheat-Eyespot is represented by the attribute "Final eyespot incidence" (eyespot incidence at the "milky grain", stage 7: development of fruit on BBCH scale [39]) which is determined by three main factors: cropping practices, soil and climate and the biological environment of the considered field. This is reflected by the hierarchical structure of the model, which consists of three sub-trees of attributes (Figure 1) split into one main part and two smaller ones. The main sub-tree, "Effect of cropping practices", illustrates the complexity of the effects of cropping practices and the need to consider a combination of practices in order to evaluate the final eyespot incidence. It uses indicators based on tactical (with a short time-frame) or strategic decisions (with a longer time-frame [40]). These decisions can affect the agroecosystem at several stages.

i) Eyespot is considered as a highly endocyclic disease (as defined in [33]). Upstream, some cropping practices affect the quantity of the endo-inoculum (initial pathogen population present in the field). Crop sequence and tillage determine the vertical distribution of infected stubble and have proven to be of major importance for eyespot control [41–45]. Nevertheless, the effects of tillage on the disease are controversial in the literature. According to several authors [1,41,46–50], minimum tillage is highly favourable to eyespot development in the presence of preceding host-crop residues in the top layer, whereas ploughing significantly reduces its incidence by burying host-crop residues. These results conflict with those that show that eyespot was more severe after soil inversion than after non-inversion under moist, cool conditions [44–47,51–55]. The possible explanation of this apparent contradiction is that non-inversion is more favourable to antagonistic micro-organisms than ploughing (the microbiological activity is higher at the soil surface than in the top 20 cm soil layer and the weather in some experiments, such as those in Italy, was probably too dry for antagonistic biota to flourish on crop debris and thus to control eyespot [1].

ii) Action by escape consists of shifting periods of highest crop susceptibility away from the main periods of pathogen contamination. This is achieved by altering the wheat sowing date. In the case of eyespot, "escape strategies" cannot really be considered. However, early sowing increases the probability of autumn contamination through primary infection, due to the longer time available for eyespot to develop and to affect stems [42].

iii) During the crop cycle, some cropping practices can mitigate infection through crop status by increasing crop competitiveness and/or by creating less favourable conditions for pest development. Low plant density can limit pathogen development through several mechanisms, such



Attribute

- **Final incidence of eyespot**
  - **Effects of cropping practices**
    - **Primary inoculum management: interaction between crop sequence and tillage**
      - Preceding crop
      - Pre-preceding crop
      - Tillage after harvest of the previous crop
      - Tillage after harvest of the pre-previous crop
    - Escape: effects of the sowing date
    - **Mitigation through crop status**
      - Cultivar choice
      - Level of N fertilisation
      - Sowing rate
    - Chemical control: use of fungicide
  - **Effects of soil and climate**
    - Soil
    - **Climate**
      - Autumn/winter
      - Spring
  - **Interactions with the territory**
    - Beneficial sources
    - Primary inoculum sources

Figure 1. Hierarchical structure of IPSIM-Wheat-Eyespot (screenshot of the DEXi software). Bolded and non-bold terms represent aggregated and basic attributes, respectively.
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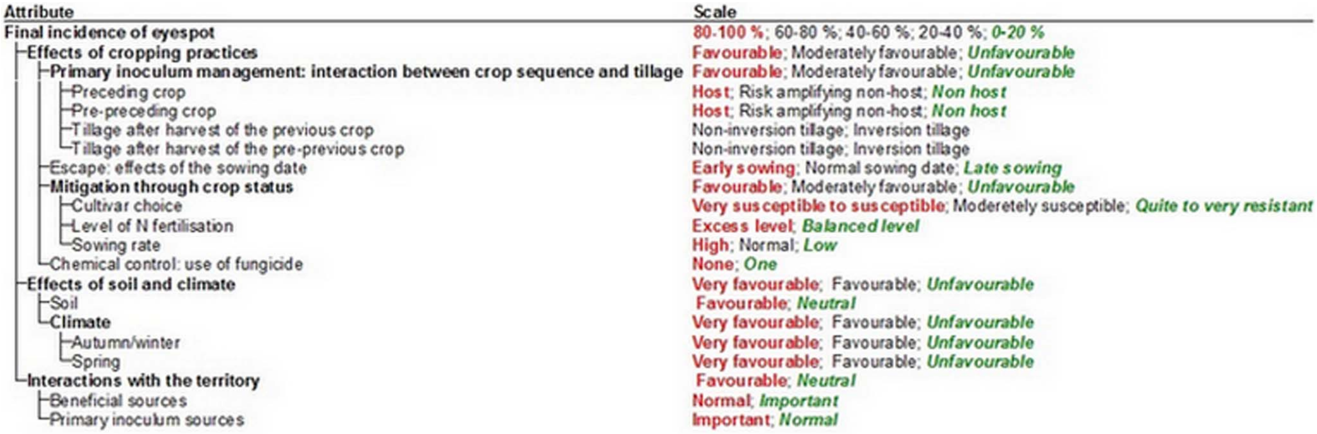

Attribute	Scale
Final incidence of eyespot	80-100 %; 60-80 %; 40-60 %; 20-40 %; *0-20 %*
├**Effects of cropping practices**	Favourable; Moderately favourable; *Unfavourable*
│├**Primary inoculum management: interaction between crop sequence and tillage**	Favourable; Moderately favourable; *Unfavourable*
││├Preceding crop	Host; Risk amplifying non-host; *Non host*
││├Pre-preceding crop	Host; Risk amplifying non-host; *Non host*
││├Tillage after harvest of the previous crop	Non-inversion tillage; Inversion tillage
││└Tillage after harvest of the pre-previous crop	Non-inversion tillage; Inversion tillage
│├Escape: effects of the sowing date	Early sowing; Normal sowing date; *Late sowing*
│├**Mitigation through crop status**	Favourable; Moderately favourable; *Unfavourable*
││├Cultivar choice	Very susceptible to susceptible; Moderetely susceptible; *Quite to very resistant*
││├Level of N fertilisation	Excess level; *Balanced level*
││└Sowing rate	High; Normal; *Low*
│└Chemical control: use of fungicide	None; *One*
├**Effects of soil and climate**	Very favourable; Favourable; *Unfavourable*
│├Soil	Favourable; *Neutral*
│└**Climate**	Very favourable; Favourable; *Unfavourable*
│ ├Autumn/winter	Very favourable; Favourable; *Unfavourable*
│ └Spring	Very favourable; Favourable; *Unfavourable*
└**Interactions with the territory**	Favourable; *Neutral*
├Beneficial sources	Normal; *Important*
└Primary inoculum sources	Important; *Normal*

Figure 2. Attribute scales of IPSIM-Wheat-Eyespot (screenshot of the DEXi software). All the scales are ordered from values detrimental to the crop (i.e. favourable to eyespot) on the left-hand side to values beneficial to the crop on the right-hand side (i.e. unfavourable to eyespot). In the DEXi software, this difference is clearly visible because, by convention, values beneficial to the user are coloured in green, detrimental in red, and neutral in black.

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as restricting the contact between plant organs and infectious propagules and lowering the humidity within the canopy. This results in a control of soil-borne diseases like eyespot by low plant density and/or a high shoot number per plant [20]. In addition, low densities increase distances between plants, which limits secondary pathogen cycles, and leads to a drier microclimate. Excessive use of nitrogen fertilisers produces lush crops and favours eyespot through direct and indirect effects [56,57]. However, in the case of eyespot, nitrogen availability in the soil seems to be a minor factor for the development of the disease [10,20,29].

Use of disease-resistant cultivars provides an economic, environmentally friendly and effective strategy to control disease. However, not all resistant cultivars have been assessed in integrated cropping systems [58] and cultivars do not share the same susceptibilities to different diseases [59]. Eyespot resistance is generally not complete and its expression depends widely on environmental factors [22].

iv) Lastly, a fall-back solution (use of fungicide) can be used when alternative practices are not sufficient. However, several studies have provided evidence for reduced susceptibility to fungicides in populations of *O. yallundae* and *O. acuformis* [60]. For the sake of simplicity, resistance to fungicide in pathogen populations was not taken into account in IPSIM-Wheat-Eyespot.

The two other sub-trees describe the biological environment of the considered field, as well as soil and climate. These sub-trees are not affected by cropping practices. Among these factors, climate is the main factor affecting eyespot development [9,43].

3. Definition of the Attribute Scales. The second step in the design of a DEXi model is the choice of ordinal or nominal scales for basic and aggregated indicators. Sets of discrete values were defined for all attributes of the model and described by symbolic value scales defined by words. These values were defined according to the knowledge available in the international literature and some expertise when needed. IPSIM-Wheat-Eyespot uses at most a three-grade value scale (i.e. "Unfavourable", "Favourable", "Very favourable") for the aggregated and basic attributes. This scale refers to the disease. The value "Favourable" means that the attribute is favourable to the development of the disease and therefore potentially detrimental to the crop.

Some values for basic indicators can be specified using quantitative values that are then translated into qualitative values. For instance, the translation into qualitative values of the sowing date, sowing density or N rate is performed using experimental references or expertise. This translation takes into account the regional context. For example, a sowing date classified as "Early" in the south of France might be classified as "Normal" in northern France. This classification actually depends on the sowing date distribution in the considered region.

Other attributes are directly qualitatively estimated. For instance, the indicators "inversion tillage or non-inversion tillage" or "preceding and pre-preceding crop" are nominal variables and directly monitored as such in experiments [61,62]. The level of cultivar resistance has been described using the official list provided by the French National Seed Station (Groupe d'Etude et de contrôle des Variétés et des Semences; http://cat.geves.info/Page/ListeNationale; accessed November 2012) and published by Arvalis-Institut du végétal (http://www.arvalisinfos.fr/_plugins/WMS_BO_Gallery/page/getElementStream.html?id = 13504&prop = file; accessed November 2012). In this list, cultivars are rated for their susceptibility to eyespot on a 0–9 scale, from very susceptible to resistant.

For the climate attribute, a three-value scale ("Unfavourable"; "Favourable"; "Very favourable") was defined using climatic models [27,43] and data from the INRA Climatik database.

All the scales in Figure 2 are ordered from values detrimental to the crop (i.e. favourable to the disease) on the left-hand side to values beneficial to the crop on the right-hand side (i.e. unfavourable to the disease). In the DEXi software, this difference is clearly visible because, by convention, values beneficial to the user are coloured in green, detrimental in red, and neutral in black. The scales for the "tillage after preceding crop" and "tillage after pre-preceding crop" attributes appear in black since their effects on the disease cannot be defined independently from the crop sequence.

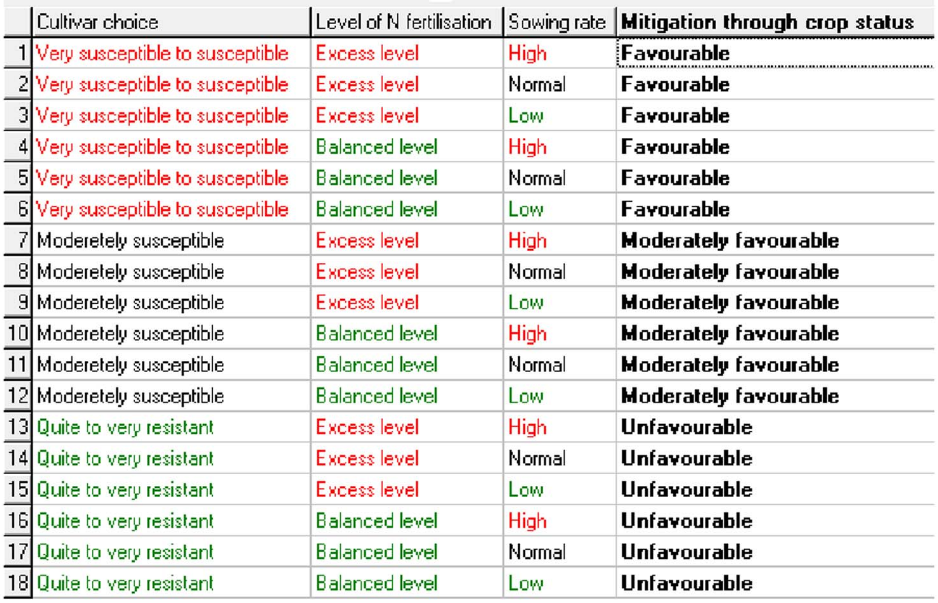
Initial input attribute values (either quantitative or qualitative) are translated into qualitative appreciation, according to two to three scales defined on the basis of available information in the literature, models or expertise. Sometimes, a two-value scale is enough to represent the value of an indicator (e.g. chemical control was applied or not; or the soil has either been ploughed or not after the preceding harvest). However, other attributes usually need a three-value scale to describe the diversity of cropping practices or environment (e.g. the sowing rate attribute requires three grades to describe farmers' practices: the sowing rate can be low, normal or high).

4. Definition of Aggregating Tables. The third step in the design of a DEXi model is the choice of aggregating tables determining the aggregation of attributes in the tree and their interactions. For each aggregated attribute in the model, a set of "*if-then*" rules define the value of the considered attribute as a function of the values of its immediate descendants in the model. The rules that correspond to a single aggregated attribute are gathered together and conveniently represented in tabular form. In this way, each table defines a mapping of all value combinations of lower-level attributes into the values of the aggregate attribute. Figure 3 shows decision rules that correspond to the "mitigation through crop status" aggregated attribute and define the value of this attribute for the 18 possible combinations of the three cultivar choices, the 2 levels of fertilisation and the 3 sowing densities. For example, if the cultivar is quite resistant, the level of N fertilisation balanced and the sowing rate low, then the "mitigation through crop status" attribute will be unfavourable to eyespot (the final incidence will decrease). However, even if the sowing rate and the N application rate are both high, the "mitigation through crop status" attribute during wheat growth will control eyespot significantly because the "cultivar choice" attribute is much more influential than the two other attributes (Figure 3).

The aggregating tables of IPSIM-Wheat-Eyespot have been established using knowledge available in the international literature and summarised in Table 1, and expert knowledge when needed. All aggregating tables of the model are presented in figures S1, S2, S3, S4, S5, S6.

5. Attribute Weights. The influence of each basic and aggregated attribute on the value of the output variable can be characterised with weights. The higher the weight, the more important the attribute. Table 2 summarises the weights of each of the 19 attributes of the model, providing an overview of the model's structure. IPSIM-Wheat Eyespot has 3 levels of aggregation (Figure 1), the third one being the leaves (i.e. the model input basic attributes). The "local" and "global" weights are normalised in two different ways. "Local" weights are given to each aggregated attribute separately so that the sum of weights of its immediate descendants in the hierarchy equals 100%. The "global" weights are calculated at a given level of aggregation and express the influence of each attribute at that aggregation level. They are obtained by multiplying the local weight of a given attribute at a given level of aggregation, by local weighting of its ascendants. For instance, the value of the "soil and climate" attribute is completely defined by the "Climate" attribute (100%, local weight), but this attribute only contributes 53% to the definition of the value of "Eyespot incidence" (global weight at the second level of aggregation). Local and global weights are identical at the first level of aggregation, since in this case there is only one level of aggregation. Global weights of basic attributes are shown in bold in Table 2 in order to ease their identification, since they are distributed among the second and third levels of aggregation of IPSIM-Wheat-Eyespot. The sum of global weights at the third level is only 76%. This is because some basic attributes are directly embedded in the model at the second level of aggregation. The sum of global basic attribute weights is logically equal to 100%. Table 2 can be seen as an equivalent of a sensitivity analysis that would aim at identifying the most influential input (and state) variables of a quantitative model.

6. Simulations with DEXi. The qualitative final attribute value (final incidence of eyespot) is calculated by DEXi. The



	Cultivar choice	Level of N fertilisation	Sowing rate	Mitigation through crop status
1	Very susceptible to susceptible	Excess level	High	**Favourable**
2	Very susceptible to susceptible	Excess level	Normal	**Favourable**
3	Very susceptible to susceptible	Excess level	Low	**Favourable**
4	Very susceptible to susceptible	Balanced level	High	**Favourable**
5	Very susceptible to susceptible	Balanced level	Normal	**Favourable**
6	Very susceptible to susceptible	Balanced level	Low	**Favourable**
7	Moderetely susceptible	Excess level	High	**Moderately favourable**
8	Moderetely susceptible	Excess level	Normal	**Moderately favourable**
9	Moderetely susceptible	Excess level	Low	**Moderately favourable**
10	Moderetely susceptible	Balanced level	High	**Moderately favourable**
11	Moderetely susceptible	Balanced level	Normal	**Moderately favourable**
12	Moderetely susceptible	Balanced level	Low	**Moderately favourable**
13	Quite to very resistant	Excess level	High	**Unfavourable**
14	Quite to very resistant	Excess level	Normal	**Unfavourable**
15	Quite to very resistant	Excess level	Low	**Unfavourable**
16	Quite to very resistant	Balanced level	High	**Unfavourable**
17	Quite to very resistant	Balanced level	Normal	**Unfavourable**
18	Quite to very resistant	Balanced level	Low	**Unfavourable**

Figure 3. Aggregating table for the "Mitigation through crop status" aggregated attribute (screenshot of the DEXi software). Aggregation rules for the 18 possible combinations of the 3 cultivar choices, the 2 levels of fertilisation and the 3 sowing rates.
doi:10.1371/journal.pone.0075829.g003

Table 1. Available knowledge in the scientific literature describing the effects of cropping practices and the production situation on the incidence of eyespot on wheat.

Factor	Direction of the effect	Intensity of the effect	Impact on eyespot development	References
Tillage	+/−	++	Contradictory results. For some authors, reduced soil tillage decreased eyespot infection. For others, eyespot was often more severe after ploughing than after non-inversion tillage.	[1,11,41,42,44–55]
Preceding and pre-preceding crop	+	++	Preceding and pre-preceding host crops are known to favour eyespot. However, the interaction between tillage and the crop sequence has to be taken into account.	[9,10,29,41–42,55,61,62]
Sowing date	+	++	Eyespot has always been reported to be more severe in early sown crops.	[10,20,27,29,42,55]
N fertilisation rate	+	+	High nitrogen availability generally favoured the disease. However these results were questioned.	[9,10,20,29,56,57]
Sowing rate	+	+	Prevalence was increased by high plant density and/or low shoot number per plant.	[20,29]
Cultivar choice	+	+++	The use of varieties with resistance could obviate the need for fungicide.	[10,21,22,42,58,59]
Cultivar mixture	0	0	No significant difference was found between the disease level in mixtures and the mean of disease level of the mixture components in pure stands.	[70–72]
Climate	+	++	Eyespot strongly depends on climate. Infections require periods of at least 15 h with T° between 4°C and 13°C and HR>80% (from October to April).	[9,27,28,29,43]

Cropping practices and climate can be favourable (+), unfavourable (−) or neutral (0) to the development of eyespot. The intensity of the considered factor is summarised with 4 classes: 0, no effect; +, slight; ++, significant; +++, crucial.

doi:10.1371/journal.pone.0075829.t001

calculation consists in computing all aggregated attribute values according to: (i) the structure of the tree; (ii) a set of input variables (basic attribute values) defining a simulation unit; and (iii) the aggregating tables for the aggregation of attributes. An example of output results obtained for two simulation units is provided in Figure 4 (input basic attributes and calculated aggregated attribute values for the simulation of two systems: an organic and a high-input one).

Table 2. Respective weights of the attributes of IPSIM-Wheat-eyespot.

Attributes defining the final incidence of eyespot	Local level 1	Local level 2	Local level 3	Global level 1	Global level 2	Global level 3
1 Effects of cropping practices	47			47		
1.1 Primary inoculum management		21			10	
1.1.1 Preceding crop			40			4
1.1.2 Pre-preceding crop			12			1
1.1.3 Tillage after the preceding crop			40			4
1.1.4 Tillage after pre-preceding crop			8			1
1.2 Escape: effects of sowing date		9			4	
1.3 Mitigation through crop status		26			12	
1.3.1 Cultivar choice			100			12
1.3.2 Level of N fertilisation			0			0
1.3.3 Sowing rate			0			0
1.4 Chemical control		44			21	
2 Effects of soil and climate	53			53		
2.1 Soil		0			0	
2.2 Climate		100			53	
2.2.1 Autumn/winter			29			15
2.2.2 Spring			71			38
3 Interactions with the rest of the territory	0			0		

The "local" and "global" weights are calculated for each aggregated attribute separately and are distributed in 3 levels of aggregation. Bold and non-bold terms represent basic attributes and aggregated terms, respectively.

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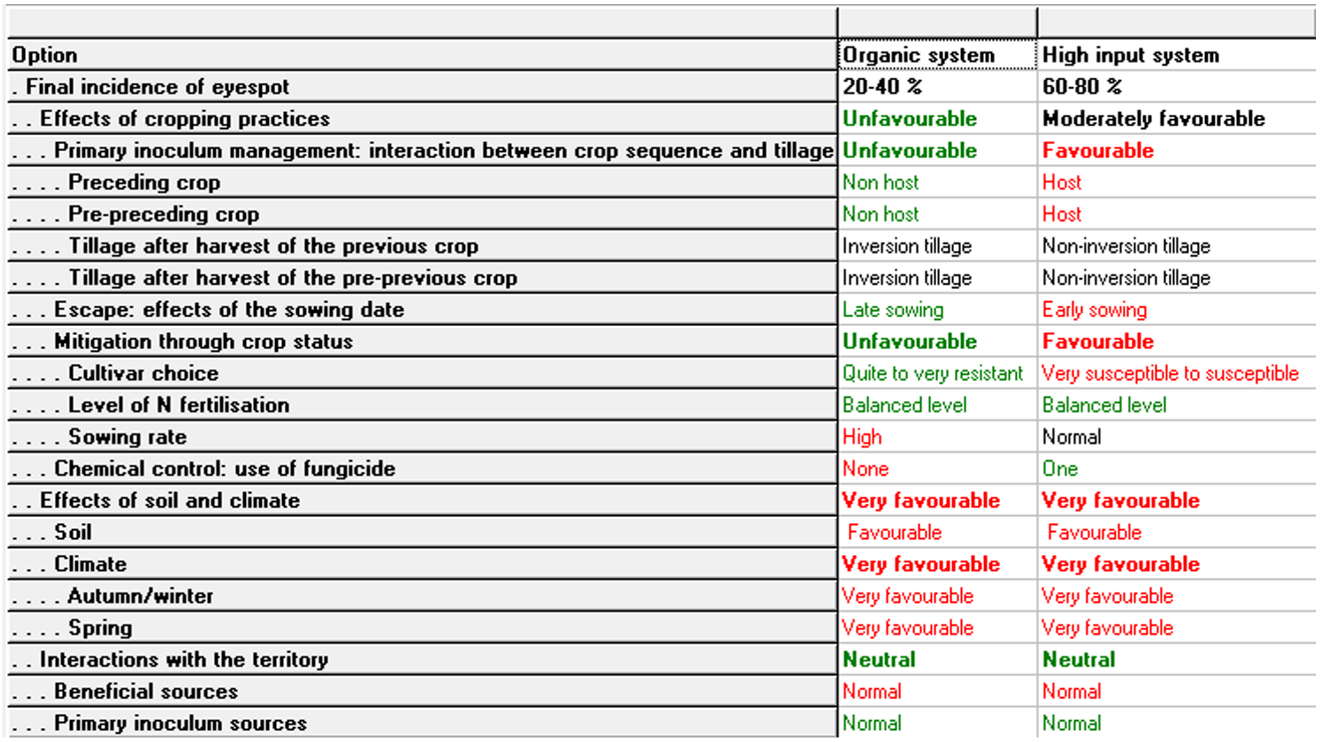

Option	Organic system	High input system
. Final incidence of eyespot	20-40 %	60-80 %
. . Effects of cropping practices	Unfavourable	Moderately favourable
. . . Primary inoculum management: interaction between crop sequence and tillage	Unfavourable	Favourable
. . . . Preceding crop	Non host	Host
. . . . Pre-preceding crop	Non host	Host
. . . . Tillage after harvest of the previous crop	Inversion tillage	Non-inversion tillage
. . . . Tillage after harvest of the pre-previous crop	Inversion tillage	Non-inversion tillage
. . . Escape: effects of the sowing date	Late sowing	Early sowing
. . . Mitigation through crop status	Unfavourable	Favourable
. . . . Cultivar choice	Quite to very resistant	Very susceptible to susceptible
. . . . Level of N fertilisation	Balanced level	Balanced level
. . . . Sowing rate	High	Normal
. . . Chemical control: use of fungicide	None	One
. . Effects of soil and climate	Very favourable	Very favourable
. . . Soil	Favourable	Favourable
. . . Climate	Very favourable	Very favourable
. . . . Autumn/winter	Very favourable	Very favourable
. . . . Spring	Very favourable	Very favourable
. . Interactions with the territory	Neutral	Neutral
. . . Beneficial sources	Normal	Normal
. . . Primary inoculum sources	Normal	Normal

Figure 4. Example of 2 simulations carried out with IPSIM-Wheat-Eyespot (screenshot of the DEXi software).
doi:10.1371/journal.pone.0075829.g004

Evaluation of the Predictive Quality of IPSIM-Wheat-Eyespot

1. Description of the Dataset Used. Data representative of a wide range of climate patterns, soils and cropping practices are needed to assess the predictive quality of the model. A large dataset was therefore developed to assess the predictive quality of IPSIM-Wheat-Eyespot. A national survey was conducted to identify relevant data from various research and development institutes. The required datasets had to provide information for input attributes of IPSIM-Wheat-Eyespot (description of cropping practices, soil and climate) and its output (eyespot incidence at the "milky grain", stage 7: development of fruit on BBCH scale [39]). The dataset obtained is summarised in Table 3. It comprises results from multifactorial trials from 1980 to 1994 in 7 contrasting regions in France, which were set up to analyse the effects of various cropping practices on foot and root winter wheat diseases on different soils and with differing climate patterns. Various cultivars were combined with different crop sequences, conventional and reduced tillage, low or high plant densities, early or late sowing dates, low or high N fertilisation, in various areas of production where eyespot epidemics are observed. Most of these trials were specific studies on foot diseases [20,41,61,62], so the experimental conditions were suited to ensure the presence of eyespot (i.e. infected wheat present in the crop sequence and only susceptible cultivars). Other data originated from a regional agronomic diagnosis [63] performed in cereal fields from 1987 to 1994 in 19 French regions to analyse the effects of cultural practices on the incidence and severity of foot and root disease complexes [64]. In this survey, data were collected on 894 cereal fields in a wide range of production situations.

For some situations, the pre-preceding crop (3 possible types of crop in the model: "host", "non-host" and "risk amplifying") and the associated tillage after the harvest of this crop (2 possible values in the model) were not observed. Instead of ignoring these precious data, simulations were performed for the 3*2 possibilities and only cases for which the 6 simulations led to similar output values were kept for evaluating the model. In all, 526 site-years were used for the evaluation of the model and they represented a large number of combinations of cropping practices and production situations (19 French regions over 9 years).

The data presented in Table 3 were transformed into qualitative values and used as input basic attributes to feed IPSIM-Wheat-Eyespot.

2. Evaluation of the Predictive Quality of IPSIM-Wheat-Eyespot. The evaluation consisted in comparing simulated and observed values. Since the model predicts classes of incidence, observed incidences at wheat stage 7 were transformed into observed incidence classes using the same discretisation as the model (i.e. 0–20%, 20–40%, 40–60%, 60–80%, 80–100%). However, one might want to predict incidences rather than classes of incidence. In order to test the predictive quality of IPSIM-Wheat-Eyespot for incidences, its output main variable was transformed into a numerical value by replacing the predicted incidence class by the centre of the class. The model was therefore evaluated in two ways: first, on its ability to predict incidence classes, and second on its ability to predict eyespot incidences.

For incidence classes, the deviation of the model was characterised by calculating the number of classes of difference between observed and simulated classes. The distribution of simulated classes was displayed according to observed incidence classes. This information was summarised by a multinomial distribution in 9 difference classes (from −4 to +4) since the model has 5 incidence classes. The proportion of situations for which the model correctly predicted the observed incidence class was taken as an indicator of the quality of prediction of the model. In addition, a non-parametric Wilcoxon test was performed to test

Table 3. Main features of the datasets used for the evaluation of IPSIM-Wheat-Eyespot's predictive quality.

Cropping practice	Design	Year	Location	Number of site-years	References
Crop sequence	Multifactorial field trials	1981–1982	Toulouse (Midi-Pyrénées)	11	[61]
Crop sequence including various durations of continuous cereal cropping	Multifactorial field trials	1980–1994	Grignon (Ile-de-France)	29	[62]
Tillage (soil structure)	Multifactorial field trials	1992–1993	Péronne (Picardie)	8	[73]
Tillage (crop residue vertical distribution)	Multifactorial field trials	1992–1993	Chartres (Centre), Grignon (Ile-de-France)	12	[41]
Sowing date, sowing rate, N fertilisation	Multifactorial field trials	1992–1994	Chartres, La Verrière (Ile-de-France), Le Rheu (Bretagne), Nancy (Lorraine), Dijon (Bourgogne)	95	[20]
Tillage, previous crop, fertilisation, sowing rate, sowing date, cultivar choice and use of fungicide	Diagnoses in cereal fields	1987–1994	19 French regions	370	[64]
Crop sequence	Multifactorial field trials	1981–1982	Toulouse (Midi-Pyrénées)	11	[61]
Crop sequence including various durations of continuous cereal cropping	Multifactorial field trials	1980–1994	Grignon (Ile-de-France)	29	[62]
Tillage (soil structure)	Multifactorial field trials	1992–1993	Péronne (Picardie)	8	[73]
Tillage (crop residue vertical distribution)	Multifactorial field trials	1992–1993	Chartres (Centre), Grignon (Ile-de-France)	12	[41]
Sowing date, sowing rate, N fertilisation	Multifactorial field trials	1992–1994	Chartres, La Verrière (Ile-de-France), Le Rheu (Bretagne), Nancy (Lorraine), Dijon (Bourgogne)	95	[20]
Tillage, previous crop, fertilisation, sowing rate, sowing date, cultivar choice and use of fungicide	Diagnoses in cereal fields	1987–1994	19 French regions	370	[64]

doi:10.1371/journal.pone.0075829.t003

whether the distribution of errors was zero-centred (in that case, the model can be considered unbiased).

For incidences, the predictive quality of IPSIM-Wheat-Eyespot was characterised using three common statistical criteria [65]: bias (Equation 1), Root Mean Square Error of Prediction (RMSEP, Equation 2), and efficiency (Equation 3).

$$Bias = \frac{1}{n}\sum_{i=1}^{i=n}\left(Y_i^{obs} - Y_i^{sim}\right) \tag{1}$$

where n is the total number of considered situations, Y_i^{obs} the observed value for situation i, and Y_i^{sim} is the corresponding value simulated by the model. The bias measures the average difference between observed and simulated values. If the model underestimates the considered variable, the bias is positive. Conversely, if the model overestimates the variable, the bias is negative.

$$RMSEP = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n}\left(Y_i^{obs} - Y_i^{sim}\right)^2} \tag{2}$$

RMSEP quantifies the prediction error when the model parameters have not been estimated using the observations Y_i^{obs} used in the calculation of this criterion.

$$EF = 1 - \frac{\sum_{i=1}^{i=n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{i=n}\left(Y_i^{obs} - \bar{Y}\right)^2} \tag{3}$$

Where $\bar{Y}$ is the mean of observed data. Nash and Sutcliffe [66] defined the efficiency as a normalised statistic that determines the relative magnitude of the residual variance ("noise") compared with the measured data variance ("information"). The efficiency defines the ability of a model to predict the value of a variable. The efficiency can range from –∞ to 1. If the model perfectly predicts the observations, the efficiency is maximum and is equal to 1. Efficiency values lower than 0 indicate that the mean observed value is a better predictor than the simulated values, which indicate a poor predictive quality of the model. Values between 0 and 1 are generally viewed as acceptable levels of performance. The closer the model efficiency is to 1, the better is the fit between observed and simulated data [65].

Results

Evaluation of the Quality of Prediction for Final Incidence Classes

The high number of observed site-years in the dataset (526) permitted a reliable evaluation of the predictive quality of IPSIM-Wheat-Eyespot. Residuals were distributed around 0 (Figure 5), indicating that the predicted values were close to observations. Nearly half (47.1%) of the simulated classes encompassed the observed values and 80.4% had at most a difference of one class only. In addition, there are nearly as many negative as positive differences of exactly one class. The Wilcoxon test performed over the 9 class differences (from −4 to +4) proved that the model was significantly biased (simulated final incidence classes lower than observations, $p<1.0\ 10^{-10}$). Figure 6 illustrates the distribution of class differences between observed and predicted final eyespot incidences. The overall predictive quality of IPSIM-Wheat-Eyespot was judged fair, even if slightly biased. The predictive

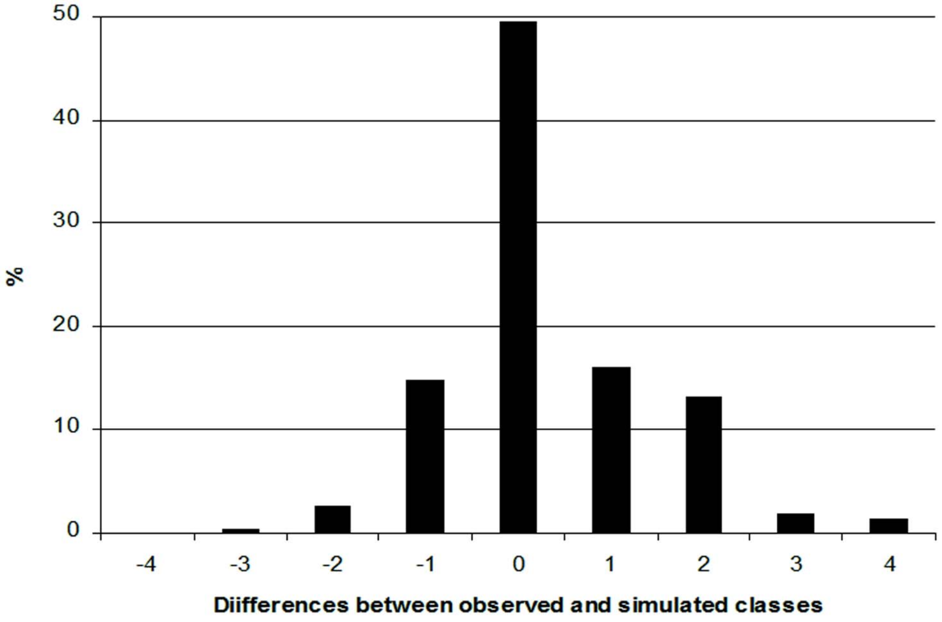

Figure 5. Evaluation of the predictive quality of IPSIM-Wheat-Eyespot. Residuals distribution: number of classes of difference between observed and simulated final eyespot classes (0–20%, 20–40%, 40–60%, 60–80%, 80–100%; 526 fields, over 9 years and 19 French regions).
doi:10.1371/journal.pone.0075829.g005

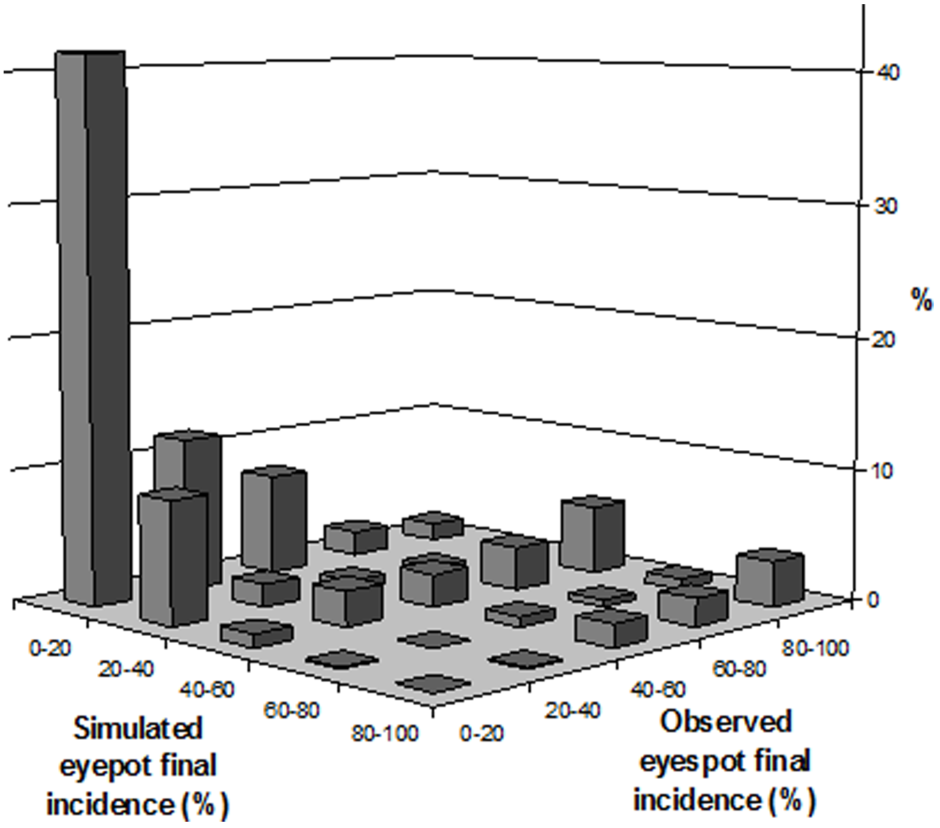

Figure 6. Evaluation of the predictive quality of IPSIM-Wheat-Eyespot Distribution of class differences between observed and predicted final eyespot incidences. (526 fields, over 9 years and 19 French regions).
doi:10.1371/journal.pone.0075829.g006

quality was good for the lowest class (52% of all the observations in the dataset): 80% of the observed values between 0 and 20% were correctly simulated. The model underestimated final incidences for observations higher than 20%.

Evaluation of the Quality of Prediction for Final Incidence Values

For these 526 output values, the overall predictive quality of the model was correct. The model's predictive quality was good as its efficiency value was correct: 0.51. The Root Mean Square Error of Prediction error was quite high, 24%. The bias was positive (5.0%), so the model slightly underestimated final eyespot incidences.

Discussion

Interests and Limitations of IPSIM-Wheat-Eyespot

Several studies have been conducted to analyse the effects of cropping practices on the development of eyespot on wheat [10,29]. However, only one statistical model had been developed in order to predict the incidence of eyespot as a function of few cropping practices [29]. IPSIM-Wheat-Eyespot offers new possibilities for the design of innovative cropping systems since it is the first functional model to encompass simultaneously the effects of soil, climate and the cropping system and to represent the effects of interactions among these many factors.

The development of IPSIM-Wheat-Eyespot was made possible using (1) a schematic representation of the relationships between cropping practices, the production situation and injuries, (2) the translation of this conceptual scheme into a simulation model, and (3) a combination of data from a wide range of production situations (many regions and years) to test its predictive quality.

1. Conceptual Bases of IPSIM-Wheat-Eyespot. The conceptual scheme of IPSIM-Wheat-Eyespot is innovative because i) it encompasses a temporal scale longer than the cropping season (effect of the crop sequence in interaction with tillage over two years); ii) the main cropping practices that can affect the disease are represented; iii) interactions between practices as well as interactions between practices and climate are taken into account. As compared to the conceptual scheme of IPSIM [33], the spatial scale considered was limited to the field because of the lack of interactions at larger scales. In addition, the conceptual scheme of IPSIM-Wheat-Eyespot does not take into account socio-economic drivers, farmer's goals and cognition since it does not aim at simulating decisions. However, this original conceptual model can help design innovative cropping systems less susceptible to eyespot. The information provided by IPSIM-Wheat-Eyespot should be combined with other sources of information (references, other models, or expertise) in order to design new cropping systems, especially since damage (*i.e.* crop loss) caused by the disease are not represented.

2. Hierarchical Tree of Attributes and Aggregating Tables. The qualitative nature of the DEX method is well suited to the modelling of complex systems for which no high level of precision is required. The DEXi software tool [36] offered a suitable environment for the organisation of available knowledge and a rapid development of IPSIM-Wheat-Eyespot. The main breakthrough of the IPSIM platform is to allow the handling of complexity in a simple way [33]. The work presented in this paper provides a proof of concept for this innovative modelling approach in the field of crop protection for a single disease. A major innovation of this modelling approach is to be able to aggregate attributes of different natures (e.g. cultivar choice, a nominal variable and fertilisation rate, a quantitative variable) to describe the impact of various components of cropping systems and their interactions on eyespot incidence. IPSIM-Wheat-Eyespot is actually the first model which can overcome the lack of data on the relationships between cropping practices and a single pest in a given production situation to help design strategies to control the disease. The qualitative DEXi approach may lead to a loss of precision and sensitivity in the developed model [67]. Increasing the number of attribute scales at the top of the decision tree could be a way to improve the sensitivity [68]. However, it results in more complicated aggregating tables which are consequently more difficult to define. Due to the tremendous complexity of interactions between cropping practices and the production situation, a smaller number of indicator states have been chosen to keep the representation of the complex underlying mechanisms as simple as possible. A correct definition of aggregating tables is of primary importance in DEXi models [68]. The choice of the nature and the number of qualitative scales is also crucial and will partly determine the quality of prediction. The choices of both aggregating tables and qualitative scales of attributes have to be explicit and traceable. Indeed, the scales and the aggregating tables used for the attributes of IPSIM-Wheat-Eyespot could not be determined in a generic way but have been specifically defined according to experimental results, models available in the literature and expert knowledge if need be. Unfortunately, literature to analyse some attributes may not exist, lack certain features, or controversial. For instance, the impact of soil type on eyespot incidence is very poorly described in the international literature and the relationships between tillage and eyespot are subject to much controversy [43]. For these cases, expert knowledge had to be used to complete some aggregating tables. In addition, the model runs using simple "if–then" rules, which are "shallow" in the sense that they only define direct relationships between conditions and consequences, but do not represent any "deeper" (or mechanistic) biological, physical, chemical processes [69]. Since the early stages of development of IPSIM-Wheat-Eyespot, it has been clear that precision was not an objective of the model. It appears more important to focus on accuracy rather than precision when modelling such a complex system.

Table 2 reveals the overall behaviour of IPSIM-Wheat-Eyespot. This is also an additional value of the IPSIM approach: the model is transparent and can be easily discussed. For instance, it is clear that the overall effect of fungicide on the disease is low (21%). This is because fungicide does not always control the disease efficiently [59]. The main factor influencing the disease is the spring weather (38%). This is consistent with Matusinsky et al. [43] who showed that the disease was very dependent on the climatic conditions during spring.

3. Predictive Quality of IPSIM-Wheat-Eyespot. The quality of the analysis of the IPSIM-Wheat-Eyespot predictive quality not only depends on the model itself (hierarchical structure of attributes and aggregating tables) but also on the diversity of the data used, which must reflect a wide range of production situations. These data should represent a variety of soil, climate and cropping practices, but also of final incidences. The dataset used in this study satisfied the three former conditions, but did not fully satisfy the latter. The observed final eyespot incidences were generally quite low, so the predictive quality of IPSIM-Wheat-Eyespot could not be extensively evaluated for high levels of incidence.

The main difference with other models is that IPSIM-Wheat-Eyespot is based on qualitative variables and not quantitative ones. The use of qualitative data requires greater attention to the description of the adopted hypotheses, because qualitative data are more difficult to interpret objectively [68]. This is particularly the case for the transformation of quantitative variables that have to be translated into qualitative input of IPSIM-Wheat-Eyespot (e.g. sowing density expressed in kg/ha or number of seeds m^{-2} and translated into "low", "normal" or "high"). Thus, IPSIM-Wheat-Eyespot can be used in 2 ways. On the one hand, some users can provide directly qualitative basic attributes (i.e. input variables of the model) if they want to test the performance of some technical options in given production situation. On the other hand, other users might want to run the model for real or putative situations where both the production situation and cropping practices are characterised with quantitative, qualitative or nominative data. In this case, an algorithm should be developed in order to rigorously translate these data into appropriate basic attributes based on national or international official references (e.g. a given cultivar will be classified as "very susceptible to susceptible"; "moderately susceptible"; or "resistant" according to official national or international seed classification); regional references (e.g. a given sowing date will be classified as "early"; "normal"; "late" as a function of regional references established by extension services); knowledge available in the literature (e.g. a given crop will be classified as "host", "non-host", or "risk-amplifying crop" according to published scientific articles); references produced by models (e.g. a given weather scenario can be classified as "very favourable"; "favourable"; or "unfavourable" according to a published model).

IPSIM-Wheat-Eyespot proved to fairly represent the variability of the 526 "site-years" used to test its predictive quality. This indicates that the model is already operational and can represent the effects of a wide range of production situations*cropping practices combinations for eyespot epidemics to help design cropping systems less susceptible to the disease. This is remarkable since, unlike most models, no fitting procedure was used.

Prospects

1. Improvements to the Model. Further refinements could be added in the future. They should keep the balance between: i) modelling of the effects of cropping practices and the production situation on eyespot epidemics as accurately as possible, and ii) keeping the model as simple as possible. In addition to the design of a model, the approach presented in this article allowed us to structure the available knowledge in the literature about the effects of cropping practices and the production situation on eyespot epidemics (Table 1). Aggregating tables derived from Table 1 could be easily adapted according to future advances in the knowledge of underlying mechanisms responsible for the disease. In the same way, the model structure could easily be modified to integrate new knowledge. For instance, the model does not yet take into account the effects of cultivar mixtures, whereas some authors have described a reduction of eyespot by cultivar mixtures [70–72]. However, this cropping practices is not currently widespread, data are sparse and there is no consensus in the literature on this matter.

IPSIM-Wheat-Eyespot requires the provision of qualitative basic attributes. This is a benefit for the *ex-ante* design of innovative cropping systems. However, this requires translating nominative or quantitative variables used to describe cropping practices and the production situation into *ad hoc* qualitative variables. In order to avoid subjectivity when translating these variables, some reference values have to be used. Such values were gathered for several French regions (data not shown) in order to design an algorithm that translates nominative or quantitative variables describing cropping practices and the production situation into relevant basic attributes of the model. This algorithm can be easily adapted to any location where wheat is grown and eyespot is present, provided that relevant reference values are available. At last, aggregating tables could be adjusted to improve IPSIM-Wheat-Eyespot's predictive quality using statistical procedures, as done for parameter estimation for quantitative models.

2. Future Use of the Model. The main breakthrough of the IPSIM framework, with a simple hierarchical aggregative structure, is to allow the handling of complexity in a simple way. The input variables of models developed with IPSIM, such as IPSIM-Wheat-Eyespot, are easily obtained [33]. IPSIM-Wheat-Eyespot will help design cropping systems with a lower risk of eyespot on wheat. In order to do so, simulation plans will be defined to assess the performance of cropping practices in a given production situation with regard to the control of the disease. It is obvious that this simulation work will have to be combined with other sources of information such as other models, expert knowledge, diagnoses in commercial fields or experiments to propose innovative sustainable cropping systems.

The model, along with the interface that translates nominative and quantitative variables into relevant qualitative input variables for IPSIM-Wheat-Eyespot (Microsoft® Office Excel 2003), is now available upon request. This model can now be used as a communication, organisation, training and teaching tool for researchers, extension engineers, advisers, teachers or even farmers. Appropriation and adaptation of the model by technicians, advisers or farmers could be useful to exchange knowledge and experience (building up from their technical know-how).

The model presented in this paper only takes into account one pest among the biocenosis of a wheat field. Nevertheless, it is necessary to consider the entirety of the major pests when designing cropping systems because farmers have to manage combinations of pest populations, leading to injury profiles, which can in turn lead to quantitative or qualitative damage and ultimately economic losses. In addition to being a model specific to a given disease, IPSIM-Wheat-Eyespot can also be seen as the first sub-model of IPSIM-Wheat, a model that will predict injury profiles on wheat as a function of cropping practices and the production situation.

Supporting Information

Figure S1 Aggregating table used for the calculation of the value of the aggregative attribute "Final incidence of Eyespot" (screenshot of the DEXi software).
(TIF)

Figure S2 Aggregating table used for the calculation of the value of the aggregative attribute "Effects of cropping practices" (screenshot of the DEXi software).
(TIF)

Figure S3 Aggregating table used for the calculation of the value of the aggregative attribute "Effects of soil and climate" (screenshot of the DEXi software).
(TIF)

Figure S4 Aggregating table used for the calculation of the value of the aggregative attribute "Primary inoculum management: interaction between crop sequence and tillage" (screenshot of the DEXi software).
(TIF)

Figure S5 Aggregating table used for the calculation of the value of the aggregative attribute "Mitigation through crop status" (screenshot of the DEXi software).
(TIF)

Figure S6 Aggregating table used for the calculation of the value of the aggregative attribute "Climate" (screenshot of the DEXi software).
(TIF)

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Author Contributions

Conceived and designed the experiments: NC PL FM. Performed the experiments: NC PL FM. Analyzed the data: JNA MHR CC. Contributed reagents/materials/analysis tools: JNA MHR. Wrote the paper: JNA MHR PD NC.

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Design and evaluation of IPSIM-Wheat-Brown Rust, a model that predicts Brown Rust injuries on winter Wheat as a function of cropping practices, soil, weather, and field environment.

Marie-Hélène Robin[1, 2], Adèle Magnard[2], Irène Felix[3], Bernard Rolland[4], Axel Olivier[5], Marie-Odile Bancal[6], Yvan Sache[7], Marc Délos[8], Jean-Noël Aubertot[2, 9]

[1] Université Toulouse, INPT EI Purpan, F-31076 Toulouse, France

[2] INRA, UMR 1248 AGIR, F-31320 Castanet-Tolosan, France

[3] ARVALIS Institut du végétal, Service Agronomie Economie Environnement

F-18570 Le Subdray, France

[4] INRA, UMRUMR APBV, F- 35653 Le Rheu, France

[5]InVivo AgroSolutions Pool Technique Santé Végétale et Agronomie - Grandes Cultures, France

[6] UMR EGC, 78850 Thiverval-Grignon, France

[7] INRA, unité BIOGERCCP, 78850 Thiverval-Grignon, France

[8] DRAAF- SRAl, 31074 TOULOUSE cedex, France

[9] Université Toulouse, INPT, UMR AGIR, F-31029 Toulouse, France

Abstract

IPSIM (Injury Profile SIMulator) is a generic modelling framework. It aims at predicting a crop injury profile as a function of cropping practices, soil, weather and field environment. The IPSIM modelling approach consists of designing a model with an aggregative hierarchical tree of attributes. This method was used successfully to develop IPSIM-Wheat-Brown Rust, a model that predicts Brown Rust severity, an important foliar disease caused by *Puccinia triticina*, as a function of cropping practices, soil, climate, and field environment. This paper briefly presents the pathogen life cycle, the method used to develop IPSIM-Wheat-Brown Rust using the IPSIM modelling framework, simulation examples, an evaluation of the predictive quality of the model with a large dataset (1045 observed site-years) and a discussion on the limitations and the benefits of the approach. The model proved to have a good predictive quality: 88% of the simulated classes encompassed the observed values and 95% had at most a difference of one class only). It can now be used to help design strategies to control Brown Rust on Wheat. It will be used as a sub-model for IPSIM-Wheat, as model that will predict injury profile on Wheat as a function of cropping practices and some components of the production situation.

Key words: Cropping practices, production situation, Integrated Pest Management, foliar diseases, *Triticum aestivum*, *Puccinia triticina.*

PUBLICATIONS SCIENTIFIQUES PREVUES

- Design and evaluation of IPSIM-Wheat-Septoria tritici, a model that predicts Septoria tritici injuries on winter Wheat as a function of cropping practices, soil, weather, and field environment.
- Design and evaluation of IPSIM-Wheat-Fusarium, a model that predicts Fusarium graminearum injuries on winter Wheat as a function of cropping practices, soil, weather, and field environment.

ANNEXE 2 : PROJET INITIAL

Programme « Evaluation et réduction des risques liés à l'utilisation des pesticides »

Appel à propositions 2009

« Approche Systémique pour appréhender les communautés de bioagresseurs : application à la Protection Intégrée du Blé – ASPIB »

- Descriptif du projet -

Responsable scientifique : Jean-Noël AUBERTOT, chargé de recherche, INRA UMR AGIR.

Période de réalisation : 2010-2013 (durée : 36 mois)

1. Justifications du projet de recherche

1.1.Situation actuelle du projet

Ce projet se situe dans la dynamique de réduction des pesticides dont les modalités ont été analysées lors de l'expertise scientifique collective pesticides (Aubertot et al., 2006) et dont la nécessité a été répétée lors du Grenelle de l'Environnement. Des décisions politiques et réglementaires ont suivi cette expertise : plan Ecophyto 2018 de réduction de 50% des usages de pesticides dans la mesure du possible (sur la base des IFT, Indices de Fréquence de Traitement) et sous réserve de la mise en œuvre par la recherche de solutions alternatives non chimiques. Ainsi, pour de nombreux bioagresseurs, des méthodes à effet partiel ont été identifiées : contrôle cultural (adaptation des pratiques en vue de défavoriser le développement des populations de bioagresseurs), contrôle génétique (choix de variétés présentant des caractéristiques de résistance ou de tolérance), la lutte biologique (utilisation d'agents biologiques vivants pour limiter ou réduire les ennemis des cultures), et la lutte physique (telle que la lutte mécanique contre les mauvaises herbes) qui se combinent dans le cadre de la protection intégrée des Cultures (PIC, Meynard et al. 2003).

Néanmoins, à ce jour, la mise en œuvre de la PIC en grandes cultures est confrontée à des difficultés techniques et agronomiques qui freinent son développement : la prise en compte de l'impact sur les bioagresseurs de la combinaison des différentes pratiques culturales et de leurs interactions au sein d'un itinéraire technique ou d'un système de culture est difficile non seulement à cause de la multiplicité des bioagresseurs à considérer, mais également à cause de la multiplicité des interactions à considérer entre système de culture, communautés de bioagresseurs, milieu et peuplement (Aubertot et al., soumis). De plus, le peu d'études réalisées sur les effets du contrôle cultural ne concerne, en général, qu'un seul bioagresseur majeur (approche mono-spécifique). Ceci n'est pas complètement satisfaisant car les agriculteurs doivent gérer des profils de dégâts (approches pluri-spécifiques : maladies cryptogamiques, plantes adventices et ravageurs). Or, la mise en œuvre de tout acte technique peut affecter l'ensemble de la biocénose et donc l'ensemble du profil de dégâts de la culture (Zadoks, 1993).

De plus, les communautés d'ennemis des cultures se caractérisent par une grande diversité et un niveau de complexité élevé à cause d'un nombre élevé d'interactions entre leurs populations et entre ces populations et le peuplement cultivé. Par ailleurs, les techniques culturales interagissent entre elles et avec les conditions climatiques et édaphiques. Par exemple, c'est l'interaction entre le travail du sol et la succession des cultures qui détermine la quantité d'inoculum primaire à la surface du sol pour un certain nombre de maladies telluriques ou pseudo-telluriques (e.g. Schneider et al., 2006). Il est donc extrêmement difficile de décrire l'ensemble du système 'pratiques culturales/peuplement/communauté de bioagresseurs/milieu'. Il existe peu de travaux de modélisation prenant en compte plusieurs bioagresseurs et rares sont ceux où les effets des pratiques agricoles sur le développement des ennemis des cultures sont pris en compte. Notamment, les modèles épidémiologiques développés pour les maladies du blé ne prennent en compte au mieux qu'un seul élément de l'itinéraire technique et le plus souvent aucun (Aubertot et al., 2005).

Il apparait donc prioritaire de pouvoir appréhender la diversité et la complexité du profil de bioagresseur au sein d'un agrosystème afin de concevoir des stratégies de gestion intégrée. En effet, une technique peu favoriser la maîtrise d'une population et en favoriser une autre. Sans représentation, même simplifiée, du comportement des communautés nuisibles sous l'effet des pratiques agricoles, il semble difficile de concevoir des stratégies réellement intégrées pour protéger les cultures. Pour ce faire, nous proposons de mobiliser le concept de trait fonctionnel issu de l'écologie. De plus, l'objectif ultime de la protection des cultures *étant la limitation des dommages, il est nécessaire de hiérarchiser les pertes engendrées par les différentes populations de bioagresseurs (Savary et al. 2006). Nous proposons de développer une approche combinant diagnostic en parcelles agricoles, enquêtes chez les agriculteurs, expérimentations au champ, et modélisation afin de contribuer à la conception et à l'évaluation de stratégies de gestion de communautés de bioagresseurs (mauvaises herbes, agents pathogènes et ravageurs).*

1.2.Etude bibliographique

La notion de trait de vie a été largement utilisée dans les domaines de l'écologie et de la génétique évolutive à la suite des travaux de Darwin (1859). Depuis les trois dernières décades, le concept a évolué. Il est désormais utilisé dans des études à différents niveaux d'organisation biotique, de l'individu à l'écosystème (Violle et al. 2007). Le concept de trait fonctionnel propose que les espèces soient regroupées selon des réponses communes à l'environnement ou selon des effets communs sur différents paramètres de l'écosystème (Lavorel et Garnier, 2002). Cette approche a, jusqu'à ce jour, surtout été le fait de l'écologie et a encore peu servi l'agronomie. Par exemple, les travaux de V. Maire ont permis de comprendre comment les traits de 13 espèces de graminées pouvaient conditionner le fonctionnement d'un écosystème prairial (Maire, 2009). Les références dans la littérature sont rares où la notion de trait de vie permet de démêler les relations, interactions entre individus au sein d'agrosystèmes. Dans leurs travaux, Gardarin et al. (2007) ont mis en évidence la corrélation entre les traits de vie et la faculté de germination pour différentes espèces de mauvaises herbes en Europe du nord-ouest. Le concept de trait fonctionnel, issu de l'écologie, sera intégré pour la première fois dans l'analyse des interactions entre les pratiques et un profil de dégâts (maladies, mauvaises herbes, ravageurs) et entre le profil de dégâts et les dommages engendrés. Cette démarche permettra par la suite de corréler ces traits de vie, communs à des espèces d'ennemis différentes et parfois très éloignées, à des pratiques agricoles diversifiées au sein d'une région. L'approche permettra alors d'analyser comment des pratiques favorisent ou défavorisent certaines populations de bioagresseurs regroupées sous des traits et engendrant ainsi une plus ou moins forte dépendance à l'usage des pesticides. Ce travail innovant fera écho aux préconisations généralement formulées quant au rapprochement des disciplines reliées à la protection des cultures et l'écologie (McRoberts et al. 2003).

Nous avons choisi de travailler sur la culture du blé car il s'agit certainement de la grande culture la mieux documentée, tant du point de vue de son écophysiologie que de ses bioagresseurs. Le blé est une culture moyennement consommatrice de pesticides (l'IFT moyen tous produits confondus est de 4 (INRA, 2009)) mais représente en surface la première culture française (43% de la part cultivée en grande culture). Elle contribue donc très largement à l'utilisation des pesticides. Ainsi, en grande culture, 66% de l'utilisation des produits phytosanitaires est le fait des céréales à paille, et 44% le fait du blé. En France, 52% de la part de l'équivalent dose pleine des fongicides sont appliqués sur la culture du blé (INRA, 2009).

1.3.Articulation avec les programmes régionaux, nationaux, européens

Ce travail s'articulera avec un projet SYSTERRA nommé 'Micmac design' et qui débutera le 1er janvier 2010. Ce projet, d'une portée plus grande que celle du projet soumis au présent appel d'offres porte sur la conception et l'évaluation de systèmes de culture à bas niveaux d'intrants. De plus, il s'appuiera également sur un projet Casdar « Techniques très simplifiées d'implantation des cultures » (Midi-Pyrénées) qui met en place le suivi d'un réseau d'exploitations en semis direct sur céréales et évalue l'impact de ces pratiques culturales sur la qualité des grains (mesures des mycotoxines). Enfin, le modèle WHEATPEST, développé dans le cadre du réseau d'Excellence européen ENDURE sera mobilisé. Des retombées pour l'estimation des paramètres de ce modèle et l'évaluation de sa qualité prédictive sont attendues.

2. Plan de recherche détaillé

2.1. Objectif général, résultats attendus et aspects innovants

Objectif

L'objectif appliqué du projet est l'analyse des relations entre le système de culture, l'ensemble des communautés de bioagresseurs, et le peuplement cultivé afin de contribuer à la conception et à l'évaluation de stratégies de protection/production intégrée. Cet objectif ambitieux nécessite de ne pas vouloir embrasser l'ensemble de la complexité des agro-écosystèmes abordés afin de pouvoir être réalisé dans le cadre d'un projet de trois ans, avec les moyens alloués. Tout d'abord, l'échelle d'espace considérée sera celle de la parcelle, même si certaines dynamiques biotiques ont lieu à des échelles supérieures. Si le travail sera conduit à cette échelle, les effets des niveaux supra-parcellaires pourront néanmoins être intégrés au travers de variables synthétiques simples décrivant les effets des espaces interstitiels et du paysage. De même, l'échelle temporelle abordée sera celle de l'itinéraire technique, même si l'effet du précédent devra être pris en compte pour les organismes polyétiques.

Nous avons choisi de travailler sur la culture du blé du fait de sa contribution forte à l'utilisation des pesticides au niveau national (44 % des pesticides utilisés en grandes cultures, dont 52 % de la part de l'équivalent dose pleine des fongicides (INRA, 2009)), mais aussi parce que les connaissances scientifiques qui sont nécessaires au projet apparaissent suffisantes (notamment en termes de références pour la conduite du blé, et de modélisation de son écophysiologie, et de ses bioagresseurs). Au-delà des avancées sur la protection intégrée du blé, les enjeux tant conceptuels que méthodologiques portés par le projet constituent les objectifs de généricité du projet.

Résultats attendus

D'un point de vue méthodologique, le projet présenté devra proposer des avancées quant à la conception de stratégie de protection intégrée contre un ensemble de bioagresseurs (dimension horizontale de la protection intégrée).

D'un point de vue conceptuel, une des principales attentes du projet est de proposer des traits de réponse des populations de bioagresseurs aux pratiques agricoles, ainsi que des traits de nuisibilité. La mobilisation, selon ces deux axes, du concept de trait fonctionnel utilisé en écologie devrait donc permettre de dépasser la description spécifique des communautés de bioagresseurs du champ cultivé.

Le diagnostic conduit en parcelles agricoles permettra d'identifier les liens entre les pratiques des agriculteurs, les conditions de milieu (édaphiques et climatiques) et les communautés de bioagresseurs du blé rencontrées. Ce diagnostic permettra de proposer une *typologie d'itinéraires techniques (décrits par des corpus de règles de décision et inscrits dans des systèmes de culture) plus ou moins à risque vis-à-vis des pressions biotiques. L'objectif ultime de la protection des cultures étant la réduction des dommages, une hiérarchisation des pressions biotiques sera réalisée (en utilisant l'outil de simulation WHEATPEST) afin de contribuer à la hiérarchisation des priorités de protection prophylactiques.*

Ce diagnostic en parcelles agricoles sera complété par une enquête auprès des agriculteurs concernés afin d'identifier les freins et les leviers à l'adoption de pratiques économes en produits phytosanitaires.

Enfin, des expérimentations permettront de développer et/ou d'évaluer la qualité prédictive de fonctions individuelles de dommage (relation dégâts-dommages) des principaux bioagresseurs du blé.

L'ensemble du travail conduit devrait donc produire des références, des méthodes et des outils pour la conception de conduite intégrée du blé économe en produits phytosanitaires.

Aspects innovants

Les dimensions horizontale (gestion de plusieurs populations de bioagresseurs) et verticale (combinaison de méthodes à effets partiels) de la protection intégrée ne sont que trop peu étudiées par la recherche agronomique. Du fait de la spécialisation disciplinaire, les travaux systémiques pour la protection/production intégrée sont trop rares. La principale originalité du projet repose sur la mobilisation du concept de trait fonctionnel utilisé en écologie. En effet, ce concept n'est que très rarement mobilisé en agronomie et en protection des cultures. Il permettra ici d'appréhender la complexité spécifique des bioagresseurs du blé.

La mise en œuvre de la protection intégrée des cultures (PIC) en grandes cultures se heurte encore à de nombreuses difficultés : au niveau agronomique, les effets d'un ensemble de méthodes culturales sur le contrôle des bioagresseurs n'ont été que peu étudiés. Outre les études analytiques décrivant les cycles biologiques des populations de bioagresseurs, les travaux publiés sur la manière de contrôler ces populations portent généralement sur l'effet d'une méthode de contrôle (e.g. un pesticide, un élément de l'itinéraire technique, une résistance variétale). Or, les pratiques culturales (y compris le choix variétal) agissent le plus souvent en interrelation pour limiter (ou favoriser) le développement des ennemis des cultures et une seule pratique peut suffire à affecter l'ensemble de la biocénose de l'agro-écosystème piloté. Le projet proposé vise donc à améliorer non seulement la prise en compte de la dimension horizontale, mais aussi de la dimension verticale de la protection intégrée. L'analyse des relations dégâts-dommages des différents bioagresseurs du blé n'est encore que partielle et le lien avec la conduite de la culture est rarement pris en compte.

Enfin, l'évaluation des propositions de systèmes de protection alternatifs sera réalisée auprès d'agriculteurs en s'attachant aux dimensions sociologiques et économiques de leur acceptabilité, dimensions rarement prises en considération à ce jour.

2.2.<u>Sites et cas retenus</u>

Le travail portera à la fois sur un réseau d'exploitations agricoles afin de renseigner les relations entre pratiques culturales, communautés de bioagresseurs et peuplement, et sur un dispositif expérimental visant à tester des stratégies alternatives à bas niveaux de produits phytosanitaires sur la culture du blé.

Le réseau de parcelles utilisé pour ce travail s'appuiera sur plusieurs réseaux déjà existants en France et pour lesquels des données sont d'ores et déjà disponibles. Tout d'abord, le *réseau « biovigilance », coordonné par la Protection des Végétaux qui, depuis 8 années caractérise le lien entre les pratiques agricoles et la flore adventice sur un peu moins d'un millier de parcelles par an à l'échelle nationale. Même si ce réseau ne sera pas reconduit officiellement pour l'année 2009/2010, l'intérêt d'inscrire notre étude dans la poursuite de ce réseau est de disposer de contacts et d'un historique détaillé des pratiques et de valoriser des dynamiques régionales qui subsistent quant à la caractérisation des pressions biotiques observées dans les champs. Une réorientation des protocoles de recueil des données permettra de caractériser non seulement les plantes adventices présentes, mais également les maladies et les ravageurs rencontrés. Le second réseau mobilisé sera le réseau « exploitations en techniques très simplifiées d'implantation ». Ce réseau est composé de 20 exploitations situées principalement en Midi-Pyrénées et en Languedoc-Roussillon. 80 parcelles sont suivies sur des volets agronomiques (notamment développement phénologique des cultures, état sanitaire de la culture* sensu lato*, composantes du rendement, rendement final, qualité des productions, mycotoxines) et socio-économiques (e.g. temps de travail, coûts de production, marges). Près de 75% des surfaces en céréales sont aujourd'hui implantées sans labour, ce qui génère une augmentation de l'usage des pesticides pour le contrôle des adventices et des populations pathogènes maintenues dans les résidus de culture (Labreuche et al., 2007; Agreste, 2008). Le suivi réalisé par les partenaires de ce réseau (Chambres d'agriculture, instituts techniques, groupements d'agriculteurs) apportera une base d'informations importante afin de caractériser les relations entre pratiques culturales et bioagresseurs.*

Le dispositif expérimental mobilisé pour ce projet est situé sur le domaine expérimental de l'école d'ingénieurs de Purpan (à proximité de Toulouse). Sur ce dispositif, des systèmes de culture à bas niveaux de protection phytosanitaire vont être mis en œuvre et évalués sur des critères agronomiques, économiques et environnementaux. L'ensemble des informations collectées permettra la mise en relation entre les dégâts observés sur le blé et les dommages qui en découlent. Il est prévu de réaliser des mini-parcelles avec des niveaux de protection non complets afin de préciser et/ou d'évaluer la qualité prédictive de certaines fonctions de nuisibilité individuelles.

2.3. Programme de travail : hypothèses, méthodes, outils et protocoles, calendrier prévisionnel

Hypothèses

L'hypothèse principale du projet est que le concept de trait fonctionnel est adapté pour représenter les différents bioagresseurs du blé (choix des traits de vie permettant de créer des « groupes d'ennemis » selon leur sensibilité aux interactions pratiques agricoles/états du milieu et leur nuisibilité).

Méthodes, outils et protocoles

(1) Expérimentation

Une expérimentation permettra de spécifier et/ou de valider des relations dégâts-dommages pour les principaux bioagresseurs du blé. Les pressions biotiques seront quantifiées selon les recommandations données par la plateforme européenne QUANTIPEST, développée au sein du réseau d'excellence européen ENDURE. Des mini-parcelles expérimentales permettront de quantifier le rendement accessible du blé (en protection complète) de différentes situations de production, et les pertes de rendement en créant de manière artificielle des pressions biotiques individuelles. L'évaluation des performances agronomique, socio-économique et environnementale *de conduites à bas niveaux d'intrants permettra de constituer des références précieuses et de données utilisables pour l'estimation de paramètres et/ou l'évaluation de la qualité prédictive de différents modèles (modèles de culture et modèles épidémiologiques* sensu lato*). Un diagnostic au laboratoire sera effectué pour identifier les différentes races de fusarioses, la présence de mycotoxines, et la présence de nématodes.*

(2) Diagnostic/enquêtes

Le diagnostic conduit en parcelles agricoles reposera sur une exploration d'une large gamme de pratiques croisée à une large gamme d'états du milieu (Doré et al., 1997). Une attention particulière sera portée à la caractérisation des pressions biotiques, qui sera standardisée, et aussi exhaustive et juste que possible, à défaut d'être précise pour des raisons de faisabilité. Ce diagnostic sera associé à des enquêtes permettant d'identifier les pratiques les plus à risque et d'analyser les freins à l'adoption des solutions alternatives à l'usage des pesticides et de recenser les innovations agricoles portant sur la protection des cultures.

(3) Modélisation

Le projet proposé ne vise pas à développer de nouveaux modèles, mais utilisera des modèles déjà existant, soit pour le diagnostic, soit pour l'analyse des pertes de rendement (e.g. WHEATPEST, Willocquet et al., 2008). Les références établies pourront être utilisées pour développer de nouvelles fonctions de dommage ou bien proposer de nouveaux jeux de paramètres le cas échéant.

Calendrier prévisionnel

	2010		*2011*				*2012*				*2013*	
Synthèse bibliographique sur l'utilisation des traits fonctionnels pour caractériser les relations pratiques/bioagresseurs/peuplement	*X*	*X*										
Diagnostic en parcelles agricoles, enquêtes	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*			
Expérimentation sur le domaine de Purpan	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*			
Modélisation Wheatpest					*X*				*X*	*X*		
Typologie des systèmes de culture économes en pesticides										*X*	*X*	
Rédaction de la thèse										*X*	*X*	*X*

2.4. Composition et responsabilité de chaque partenaire

Le travail proposé sera conduit dans le cadre de la thèse de Marie-Hélène Bonnemé (enseignante à l'Ecole d'Ingénieurs de Purpan). Le laboratoire d'accueil de la thèse est l'UMR AGIR 1248 INRA/INP-ENSAT Toulouse, sous l'encadrement de Jean-Noël Aubertot (HDR à soutenir en 2010). L'UMR AGIR s'assurera du bon déroulement du travail de thèse et fournira un appui méthodologique quant au diagnostic et à la modélisation (équipe VASCO), à l'écologie (Pablo Cruz, équipe ORPHEE), et à l'évaluation socio-économique des stratégies considérées (M'hand Fares, équipe IODA).

L'école Ingénieur de Purpan sera responsable de la mise en place et de la conduite d'un essai systémique sur son domaine expérimental visant à analyser les performances de systèmes de culture à bas niveaux de produits phytosanitaires.

La protection des végétaux appuiera la démarche par son expertise de la caractérisation des pressions biotiques et en coordonnant les contacts avec les différents partenaires du réseau biovigilance.

Enfin, la Chambre d'Agriculture de la Haute-Garonne, la Chambre Régionale d'Agriculture Midi-Pyrénées, Arvalis - Institut du végétal apporteront leurs expertises et, le cas échéant, des données pour étayer le programme proposé.

2.5. Expérience des équipes dans le domaine considéré (publications, réalisations)

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3. ***Insertion du projet***

3.1. *Position par rapport aux termes de l'appel à propositions*

Le projet proposé s'inscrit clairement dans le volet 2 de l'appel à propositions : réduction de l'utilisation des pesticides. Approches systémiques et analyse socio-économique. La principale contribution du projet porte sur une approche systémique, mais il comporte également une partie plus réduite concernant l'analyse socio-économique des freins à l'adoption de stratégies innovantes et l'évaluation des performances socio-économiques de systèmes innovants. L'approche proposée rentre, de facto*, dans l'axe 2.1 : stratégies innovantes : protection et production intégrées, en proposant d'acquérir des références et de développer des méthodes pour la conception d'itinéraires techniques intégrés pour le blé, même si certains aspects du projet peuvent contribuer aux axes 2.3 et 2.4.*

3.2. *Autres projets ou collaborations conduits par les partenaires du projet sur le même sujet*

L'UMR AGIR coordonne une activité de recherche au sein du réseau d'Excellence Européen ENDURE (www.endure-network.eu) portant sur le développement du modèle WHEATPEST, qui permet de représenter les pertes de rendement causées par un profil de dégâts dans une situation de production donnée. L'originalité du modèle développé réside dans la prise en compte d'un nombre élevé de bioagresseurs (mauvaises herbes, maladies des racines, du pied, des feuilles et des épis) et de leurs interactions quant à la nuisibilité, tout en gardant des formalismes volontairement simples. Les liens entre cette activité et le projet proposé seront forts.

En outre, cette même UMR coordonnera, à partir du 1^er^ janvier 2010, un projet ANR Systerra nommé 'Micmac design' (Modelling for Integrated Crop Management in low input farming, Assessment and Cropping system design) sur la conception et l'évaluation par expérimentation et modélisation de prototypes de systèmes de culture intégrés à bas niveaux d'intrants. Ce projet financera un demi-salaire pour le doctorant qui mènera ce travail (l'autre partie du salaire étant financée par l'Ecole d'Ingénieurs de Purpan). De plus, dans le cadre de l'UMT Tournesol présente sur le pôle Toulousain, une thèse sera engagée à partir du 1^er^ novembre 2009 sur la modélisation du complexe parasitaire du tournesol (doctorante : Mme Myriam Desanlis). Des échanges méthodologiques sont prévus entre les deux travaux de thèse.

Enfin, sur les questions relatives à la conception et à l'évaluation des systèmes de culture, la réflexion sera partagée avec d'autres structures, telles que le RMT Systèmes de culture innovants, le réseau Protection Intégrée des Cultures de l'INRA, ou encore le groupe de travail STEPHY (émanation du CORPEN) visant à développer un guide pour la conception de systèmes de culture limitant le recours aux produits phytosanitaires.

4. ***Valorisation envisagée***

Le travail présenté sera tout d'abord valorisé par la rédaction d'une thèse (soutenance début 2013). Trois articles scientifiques peuvent déjà être envisagés, sous *réserve, bien sûr, de la bonne marche du travail de recherche : 1) mobilisation du concept de trait fonctionnel pour appréhender les communautés de bioagresseurs ; 2) diagnostic et hiérarchisation des pressions biotiques du blé en parcelles agricoles ; 3) Evaluation expérimentale ex-post des performances agronomiques, socio-économiques et environnementales de conduites intégrées du blé.*

Outre ces trois articles scientifiques potentiels, les travaux seront communiqués a minima *dans une conférence internationale et seront diffusés à la profession au travers d'au moins une publication de vulgarisation à caractère technique. Des interventions sur la présentation des résultats obtenus seront également programmées dans le cadre du projet Casdar « techniques très simplifiées d'implantation » auprès des conseillers agricoles des chambres d'agriculture et des instituts techniques ainsi que des agriculteurs participant à ce réseau. Enfin, des journées techniques « au champ » réalisées sur le dispositif expérimental de Lamothe (Ecole d'ingénieurs de Purpan) seront une autre occasion de transfert des résultats aux acteurs du monde agricole.*

5. ***Bibliographie***

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