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Qualitative modelling of perennial weed management *Elytrigia repens*, *Cirsium arvense* and *Sonchus arvensis*

Octave Lacroix

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Modélisation qualitative de la gestion des adventices vivaces *Elytrigia repens*, *Cirsium arvense* et *Sonchus arvensis*

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Soutenu à Angers le 4 septembre 2020

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Résumé en Français

L'unité AGIR fait partie du projet AC/DC-weeds qui vise à modéliser trois grandes adventices vivaces. Les adventices vivaces sont souvent un problème énorme pour les agriculteurs, en particulier dans l'agriculture biologique. Leur comportement et leur cycle de reproduction sont si particuliers que leur gestion ne peut se faire que sur un contrôle à long terme. Les vivaces dépendent principalement de leur système racinaire ou de leurs rhizomes pour se propager.

Le chardon des champs (*Cirsium arvense* (L.) Scop.) est l'une des adventices vivaces les plus problématiques d'Europe. Il est originaire d'Europe du Sud-Est et de la Méditerranée orientale. Présent dans la plupart des pays tempérés du monde, il est soumis au contrôle obligatoire en France depuis 2000. Si les propriétaires individuels ou les agriculteurs ne contrôlent pas la prolifération des adventices, ils peuvent être punis d'une peine pouvant aller jusqu'à six mois d'emprisonnement et/ou d'une amende pouvant aller jusqu'à 30 000 euros (articles L. 251-20 et 21 du code rural). Cette weed est présente sur les listes A1 et sur les listes de ravageurs de quarantaine définies par l'EPPO en Argentine, au Brésil, au Mexique, en Israël, en Jordanie et aux États-Unis. L'enregistrement du chardon des champs comme ravageur de quarantaine aux États-Unis date de 1989. La nocivité du chardon des champs est fondée sur la perte de rendement, mais aussi sur les inconvénients à la récolte. La perte de rendement dans la production céréalière atteint 35 % à partir de 15 chardons par m² et peut dépasser 50 % lorsque 30 chardons par m² sont atteints (Favrelière, 2019 ; Hodgson, 1968). Rasmussen et Nielsen (2020) ont été en mesure d'établir une relation linéaire entre la couverture du champ par les chardons et la perte de rendement. La perte de rendement s'explique également par la récolte simultanée de graines de chardon, ce qui empêche la récolte de sécher correctement. Le GNIS (Groupement National Interprofessionnel des Semences et Plants) définit également les normes d'impureté des cultures qui pénalisent financièrement les récoltes de semences classées comme impures. Les graines de chardon sont difficiles à trier pour les cultures telles que la luzerne, le trèfle rouge et la carotte. Les périodes nocives pour le chardon des champs sont le printemps et l'été, ce qui correspond aux conditions météorologiques de l'émergence de la dormance. Cette herbe est la préoccupation la plus citée des agriculteurs biologiques, en particulier dans les exploitations sans prairies temporaires ou luzerne. Cette adventice se trouve dans toutes les cultures, des céréales aux légumes, mais cette adventice peut également être observée dans de nombreux pâturages. Pour un champ de luzerne infesté, la perte due à l'adventices peut atteindre 16,5 tonnes/ha en 4 ans (Schreiber, 1967). Dans une autre mesure, le chardon des champs peut être l'hôte d'insectes comme les pucerons des haricots ou l'agrite, qui s'attaquent aux cultures environnantes.

Le laiteron des champs (*Sonchus arvensis* (L.)) est très commun dans les cultures céréalières et oléagineux du Canada, des États-Unis et des pays européens. Le laiteron des champs est considéré comme un grave problème d'adventices (Holm et al., 1979) et est classé comme la 15^{ème} adventice la plus abondante dans les champs. Le laiteron est inscrit sur la liste des ravageurs de quarantaine et sur la liste A1 au Brésil, au Mexique, aux États-Unis et en Israël. Le premier enregistrement de cette adventice sur la liste des ravageurs de quarantaine remonte à 1989 aux États-Unis. Le laiteron des champs a été l'une des premières adventices à être ajoutée à la Loi sur le contrôle des adventices de 1990, qui édicte le contrôle des adventices en Ontario, au Canada. En France, le laiteron des champs est enregistré comme l'une des moins préoccupante sur la Liste rouge de l'UICN (Union internationale pour la conservation de la nature). Les pertes dues aux infestations du laiteron des champs sont principalement économiques et sont le résultat d'une baisse du rendement des cultures. Peschken et coll. (1983) a observé que le rendement des colzas a diminué de 12 % avec 5 pousses de laiteron/m², et de 18 % avec 10 pousses de laiteron/m² au Canada. Dans le blé de printemps, *Sonchus arvensis* a réduit le rendement de 4,5 à 27 % avec une densité de 3 à 15 *S. arvensis*/m² dans l'ouest de la Russie (Shashkov et al., 1977). La concurrence directe

du laiteron des champs dans le soja et les haricots comestibles secs est responsable de la réduction du poids des semences, du pourcentage de germination et du taux de croissance des semis de semences (Zollinger, Kells, 1993). Cependant, dans les prairies pâturées, le laiteron des champs est moins un problème que le chardon des champs. En effet, l'acceptation du bétail pour le laiteron des champs est plus grande et contribue à une herbe de haute qualité d'alimentation. En France, la nocivité de *S. arvensis* est faible et n'est pas considérée comme un problème, même par les agriculteurs biologiques. Cependant, le laiteron des champs est l'hôte de nombreux ravageurs et maladies. Henderson (1951) a observé par exemple le nématode de pourriture des tubercules de pommes de terre, *Ditylenchus destructor*, dans les racines de *S. arvensis*, ce qui pourrait aider à maintenir le ravageur dans le champ. Le laiteron des champs n'a pas d'effet allélopathique connu (Weill, 2005b).

Le chiendent (*Elytrigia repens* (L.) Gould) est un problème sérieux dans le monde entier dans une grande variété de cultures, de vergers et dans les zones d'établissement de semis forestiers (Westra, Wyse, 1981). Le chiendent se trouve dans toute l'Europe, la Méditerranée, la Macaronie, la mer Noire, le Caucase et l'Asie (sauf le sud). Le chiendent est enregistré sur les listes de peste de quarantaine, A1 et A2 aux États-Unis, en Israël, en Jordanie et plus récemment au Brésil (2018). *E. repens* peut affecter le rendement dans de nombreuses cultures. Dans les céréales par exemple, 25 à 85% de pertes de maïs, 19 à 55% dans le soja et jusqu'à 57% pour le blé (DRAAF, 2017). Dans les champs de légumes, les rhizomes peuvent faire des trous dans les légumes tuberculeux. Les pertes économiques peuvent provenir de la concurrence directe pour l'espace et les nutriments. La concurrence s'exprime également par des effets allélopathiques. En effet, les racines expriment une substance toxique qui inhibe la croissance des plantes adjacentes. Des pertes économiques sont également observées avec le ravageur qui sont hébergés par le chiendent, par exemple la maladie du piétin-échaudage (*Gaeumannomyces graminis* var. *tritidi*). Ce champignon est responsable de la nécrose des racines dans les céréales. Le chiendent peut également causer l'hébergement et entraîner des inconvénients à la récolte tels que l'humidité des graines. Les cultures de semences font également l'objet d'un contrôle de la pureté des cultures définies par le GNIS. Cette impureté est surtout problématique pour la culture des cultures de graines d'herbe à pature. En effet, les graines de chiendent et de raygrass sont similaires et difficiles à trier. Les graines de chiendent ne peuvent pas dépasser 1 % du poids total des graines d'herbe à rayons (GNIS). Avoir du chiendent dans une prairie de raygrass est un problème pour la quantité d'aliments pour le bétail. Le chiendent a une teneur en éléments nutritifs de qualité égale pour le bétail comme le raygrass mais la majeure partie de la biomasse est produite sous terre. Néanmoins, *A. repens* peut être utilisé pour entretenir les terres afin d'éviter l'érosion. Sa propagation végétative rapide est un avantage pour coloniser rapidement une terre menacée par l'érosion

Tableau 1: *C. arvense*, *S. arvensis* et *E. repens* principales caractéristiques

	<i>Cirsium arvense</i>	<i>Sonchus arvensis</i>	<i>Elytrigia repens</i>
Nocivité	<ul style="list-style-type: none"> • Diminution du rendement • Provoquer des inconvénients à la récolte • Sécheresse plus faible de la récolte • Impureté dans les cultures de semences • Hôte des ravageurs 	<ul style="list-style-type: none"> • Diminution du rendement • Hôte des ravageurs 	<ul style="list-style-type: none"> • Diminution du rendement • Impureté dans les cultures de semences • Hôte des ravageurs

Habitat	<ul style="list-style-type: none"> • Préférence du sol compacté • Large gamme de pH • Fortes précipitations 	<ul style="list-style-type: none"> • Sols légers • Large gamme de pH • Fortes précipitations 	<ul style="list-style-type: none"> • Sols argileux • Préférence pour les sols neutres et alcalins
Système racine	<ul style="list-style-type: none"> • Racine verticale profonde (6m de profondeur) • Racines basales (7-50cm de profondeur) 	<ul style="list-style-type: none"> • Racine verticale (2m) • Racines basales (5-20cm) 	<ul style="list-style-type: none"> • Rhizomes (0-20cm de profondeur)
Propagation végétative	<ul style="list-style-type: none"> • Majeure • Jusqu'à 6 millions par an 	<ul style="list-style-type: none"> • Majeure • 1 à 2 m par an 	<ul style="list-style-type: none"> • Majeure • 1,5 m
Propagation des semences	<ul style="list-style-type: none"> • Inexistant ou négligeable 	<ul style="list-style-type: none"> • Mineure 	<ul style="list-style-type: none"> • Mineure
Point de compensation	<ul style="list-style-type: none"> • Stade de 4 à 6 feuilles • Avant de fleurir 	<ul style="list-style-type: none"> • Stade de 4 à 6 feuilles • Avant de fleurir 	<ul style="list-style-type: none"> • Stade de 4 à 6 feuilles

Le contrôle des adventices vivaces doit durer plusieurs années pour montrer une bonne efficacité. Une seule méthode ne peut pas contrôler suffisamment les adventices. Les méthodes choisies doivent être adaptées au système afin de créer une synergie entre la rotation des cultures, le travail mécanique et l'utilisation d'herbicides. Le travail mécanique est considéré comme une alternative à la lutte chimique contre les adventices. Cependant, sur les adventices vivaces, la lutte mécanique doit être effectuée dans les bonnes conditions avec les outils appropriés pour éviter la propagation de l'infestation.

Le labour est une pratique courante qui consiste d'abord à couper, puis à retourner une bande de sol appelée le sillon. Le labour est réalisé pour préparer le sol à la prochaine récolte, pour enterrer la matière organique et l'engrais, améliorer la circulation de l'eau dans le sol et pour lutter contre les adventices (Cédra, 2009). Il est effectué grâce à la charrue en planche à moules ou à la charrue à disque. Dans la lutte contre les adventices vivaces, le labour est régi par trois composés : i) la profondeur d'enfouissement, (ii) le temps pendant le travail du sol d'inversion et (iii) la date.

Le déchaumage est un travail du sol peu profond ou profond, qui se produit après la récolte qui vise à enterrer les pailles, chaumes et autres restes de la récolte précédente. Ce travail du sol est effectué une ou plusieurs fois au cours de l'année. Le déchaumage est effectué pour contrôler les adventices comme une destruction des racines et des jeunes plantes telles que les vivaces émergées. Le déchaumage peut également homogénéiser la dispersion des résidus de culture et du fumier sur les 15 cm supérieurs du sol. Le mélange du sol et des résidus initialisera alors les processus d'humification. Ce travail du sol est effectué dans une moindre mesure pour améliorer la texture du sol et préparer le lit de semence (Cédra, 2009). L'efficacité du déchaumage est régie par i) la date d'intervention, ii) les outils utilisés, (iii) le nombre de travail du sol et (iv) le temps pendant et après le travail du sol.

Le binage inter-rang est un travail du sol peu profond effectué pendant la croissance des cultures. Ce contrôle mécanique vise à lutter contre les adventices dans l'entre-deux-rangées (Cédra, 2009). Le binage est effectué sur des cultures présentant de grandes rangées comme le maïs et le soja, mais il est également largement utilisé sur les céréales qui sont semées avec de plus grandes inter-rangées. Toutefois, le binage inter-rang dans les céréales implique d'augmenter le taux de semis pour maintenir le rendement. Le binage est une technique intéressante pour maintenir le niveau de menace bas dans un champ et permettre

l'intervention à la période de stockage la plus basse des adventices vivaces pendant le printemps. Le binage doit se faire à 10 à 12 feuilles (Hochstrasse et al., 2012). Néanmoins, le biange ne peut pas être utilisé comme méthode curative. En effet, les binages inter-rangées contrôlent les racines entre les rangs, mais pas dans la rangée. Par conséquent, les vivaces contrôlées remobilisent leurs stocks de carbone dans les pousses qui restent dans la rangée. Le binage est tout simplement inefficace pour *E. repens*: les rhizomes sont trop minces, et les outils utilisés pour le binage dispersent le chiendent. L'efficacité du binage est régie par : i) les outils utilisés, (ii) la météo et (iii) le nombre de passages.

Le principe de la coupe sélective est de couper la mauvaise herbes sans nuire à la culture en place. Nous pouvons distinguer deux types de coupe sélective : couper au-dessus de la culture et couper dans la culture. Pour couper l'adventices au-dessus de la culture, les adventices doivent être plus grandes et plus développées que la culture. Par conséquent, la fenêtre d'opportunité est brève et ce n'est que dans les cultures courtes ou jeunes que la technique peut être utilisée. Pour cette méthode, nous visons la fleur: pour les adventices annuelles, il éviter la propagation de nouvelles graines et pour les adventices vivaces, la floraison correspond à un point de stockage faible de la mauvaise herbe avec l'utilisation de stocks de carbone (Tavaziva, 2012). La coupe sélective ne devrait pas être effectuée trop tôt, le chardon des champs semble être en mesure d'induire une deuxième floraison lorsque la tige est perturbée (Hochstrasse et al., 2012). La deuxième méthode peut être utilisée à n'importe quel stade de la culture avec le ComboCut d'avril à octobre.

Tableau 2: Contrôle mécanique de C. arvense, S. arvensis et E. repens

	<i>Cirsium arvense</i>	<i>Sonchus arvensis</i>	<i>Elytrigia repens</i>
Labour	<ul style="list-style-type: none"> • Conditions sèches • Après la récolte ou le printemps pour viser le faible niveau de stockage • 20-25cm de profondeur 	<ul style="list-style-type: none"> • Conditions sèches • Après la récolte ou le printemps pour viser le faible niveau de stockage • 20cm de profondeur 	<ul style="list-style-type: none"> • Conditions sèches • Automne • 10cm de profondeur
Déchaumage	<ul style="list-style-type: none"> • Conditions sèches • Au point de compensation • Les outils discaux répandent le chardon • Utiliser des outils avec une couverture de 100% pour couper les racines • 3 à 4 travail du sol séparés par 12 jours minimum 	<ul style="list-style-type: none"> • Efficacité modérée • Conditions sèches • Au point de compensation • Les outils discaux répandent le laiteron • Utiliser des outils avec une couverture de 100% pour couper les racines • 3 à 4 travail du sol séparés par 12 jours minimum 	<ul style="list-style-type: none"> • Conditions sèches de 8 à 10 jours • Au point de compensation • Utiliser des outils d'extraction pour apporter l'herbe à la surface

Binage inter-rang	<ul style="list-style-type: none"> • Efficacité modérée • Conditions sèches • À l'étape de 10 à 12 feuilles • Outils : part de pied d'oie ou d'aile • 2 à 5 cm de profondeur • Au moins 3 fois 	<ul style="list-style-type: none"> • Efficacité modérée • Conditions sèches • À l'étape de 10 à 12 feuilles • Outils : part de pied d'oie ou d'aile • 2 à 5 cm de profondeur • Au moins 3 fois 	<ul style="list-style-type: none"> • Inefficace
Coupe sélective	<ul style="list-style-type: none"> • Efficacité modérée • Sous une pluie importante • Avant la floraison ou pendant la croissance • 2 fois 	<ul style="list-style-type: none"> • Efficacité modérée • Avant la floraison ou pendant la croissance • 2 fois 	<ul style="list-style-type: none"> • Inefficace

L'herbicide représente la plus grande dépense de pesticides dans le monde avec plus de 45% de la dépense totale en 2008 (Atwood, Paisley-Jones, 2017). On signale souvent que les herbicides sont moins efficaces sur les adventices vivaces. Cependant, les doses maximales sont plus élevées sur les adventices vivaces que sur les adventices annuelles. L'une des périodes les plus favorables pour traiter les adventices est à l'interculture grâce au glyphosate, au 2,4-D, au MCPA ou au Dicamba. Le glyphosate est l'herbicide le plus utilisé et est responsable de 15% de la consommation de produits phytopharmaceutiques en France (Babeau, 2017). Il appartient à la famille des aminés-phosphonates et est un herbicide foliaire systémique. Le glyphosate est un inhibiteur de la biosynthèse 3-phosphate de l'acide 5-enolpyruvylshikimique et supprime la production de métabolites aromatiques (Baer, Marcel, 2014). Ce processus induit un dysfonctionnement de la photosynthèse. Roundup® est le produit le plus emblématique contenant du glyphosate et a été développé en 1974 par La Société Monsanto. Sa non-sélectivité en fait un herbicide très efficace. En 2014, c'est l'herbicide le plus utilisé au monde avec plus de 800 000 t vendus (Pariisse, 2019). Cependant, l'utilisation d'herbicides n'est pas sans risque. Outre les risques pour la santé, les herbicides sont préoccupants par le risque environnemental lié à la contamination des eaux souterraines et des eaux de surface (Tilman et al., 2002), même si des améliorations sont apportées pour minimiser la persistance du sol, comme l'utilisation du 2,4-D qui persiste 1 mois au lieu du MCPA qui persiste de 2 à 3 mois (Zimdahl, 2015). MCPA diffère de 2,4-D par la substitution d'un groupe méthyle pour le chlore. L'utilisation d'herbicides est également loin d'être durable, avec l'observation de nombreuses populations de résistance dans toute la sélection de plantes résistantes (Kudsk, Streibig, 2003). L'augmentation de la résistance peut conduire à une augmentation du nombre d'herbicides utilisés, mais aussi à une augmentation des doses pour essayer de garder un contrôle efficace. 218 espèces de plantes ont été déclarées résistantes aux herbicides (Burke, Bell, 2014). Le glyphosate a été déclaré non cancérigène par plusieurs instituts Français (EFSA, ANSES et ECHA) mais est également à l'origine de nombreuses incertitudes quant à sa dangerosité pour la santé humaine. En France, depuis le 6 février 2014, la loi « LABBÉ » régleme l'utilisation des produits phytopharmaceutiques. De nombreuses utilisations de produits pharmaceutiques sont déjà interdites au public depuis le 1er janvier 2017. Il s'agissait principalement de l'entretien des parcs et des espaces verts. Pour les particuliers, cette interdiction est effective depuis le 1er janvier 2019. Nous pouvons mentionner que tous les produits pharmaceutiques sont concernés, à l'exception des produits de biocontrôle, des produits agricoles biologiques et des produits à faible risque. En ce qui

concerne l'agriculture, dans le blé par exemple, seulement 4 % des herbicides utilisés contiennent du glyphosate et entre 100 et 250 g/ha sont utilisés dans les cultures arables. Toutefois, en 2008, un objectif de réduction de 50 % de l'utilisation en 10 ans dans les produits phytopharmaceutiques a été mis en œuvre. Cet objectif s'inscrit dans le cadre de la directive européenne 2009/128 qui établit un cadre d'action communautaire pour parvenir à une utilisation durable des pesticides.

Les adventices vivaces sont complexes à contrôler par leur cycle de vie. Une approche à long terme est souvent nécessaire pour appréhender les adventices. L'augmentation de la compétitivité du champ sur plusieurs années peut aider à réduire l'infestation. La compétitivité de la culture est obtenue par la propriété intrinsèque de la culture pour être compétitive en ce qui concerne la lumière et les nutriments. Toutefois, l'inclusion d'une culture concurrentielle dans la rotation pour réduire l'infestation des adventices signifie souvent une diminution du revenu si la récolte a un prix bas. À long terme, un système qui ajoute des cultures compétitives à la rotation maintient un faible niveau de menace de ravageurs, ce qui permet à l'agriculteur de maintenir un faible coût de production avec des produits de protection des cultures réduits et des coûts de travail du sol.

La méthode la plus efficace pour lutter contre les adventices vivaces est l'introduction de prairie dans la rotation. Ce système est déjà largement utilisé par les agriculteurs biologiques. La prairie permet aux agriculteurs de réduire la pression des adventices, d'augmenter l'apport de matière organique et l'augmentation de la biodiversité des pollinisateurs et des auxiliaires (Mellender, 2018). Pour *C. arvensis* et *S. arvensis*, l'efficacité du pré est régie par : (i) le nombre d'années de pré, (ii) le nombre d'années avant le retour de la prairie dans la rotation, (iii) les espèces semées pour le pré, et (iv) le nombre de coupes ou de pâturage de la prairie par an.

Les couverts végétaux sont une pratique efficace de conservation des sols pour améliorer la qualité des sols, réduire le ruissellement et l'érosion hydrique, accroître la fertilité du sol en tant que fumier vert et agir comme concurrent sur les adventices (Ramesh et al., 2019). L'effet des couverts végétaux est le même que celui des prés : les couverts végétaux étouffent le sol et les adventices vivaces, créant un environnement défavorable pour leurs croissances. Les conditions météorologiques domineront l'efficacité des couverts végétaux ; maximiser la croissance dans des conditions favorables permettra d'étouffer correctement les adventices. Les couverts végétaux ne sont pas une méthode curative comme le pré peut l'être. Les couverts végétaux ne maintiennent la menace qu'à un faible niveau entre deux productions agricoles.

Pour maintenir un faible niveau de menace des adventices vivaces, il est pertinent d'encourager l'utilisation de cultures compétitives. La concurrence des cultures peut se faire par plusieurs moyens: i) l'utilisation d'espèces ou de variétés portant des propriétés morphologiques ou physiologiques compétitives, ii) la date de semis et (iii) le taux de semis. Les espèces ayant des propriétés morphologiques doivent avoir un pourcentage élevé de couverture du sol. Selon une étude suivie par Agridea (Tamarcaz, 2019) de 2000 à 2017, les céréales de paille longue, le chanvre, le colza et l'avoine ont la plus forte concurrence pour les adventices vivaces. Ces cultures présentent une grande forme, et une croissance rapide leur permettant de rivaliser et de dépasser *C. arvensis*, *S. arvensis* et *E. repens*. La morphologie de la culture est importante pour réduire l'accès à la lumière au sol; cependant, la vitesse de croissance ne doit pas être oubliée.

Tableau 3: Planification et rotation des cultures comme méthodes de contrôle pour *C. arvense*, *S. arvensis* et *E. repens*

	Cirsium arvense	Sonchus arvensis	Elytrigia repens
Pré	<ul style="list-style-type: none"> • Minimum de 2 ans • Fauché deux fois par an au moins, relativement proche du point de compensation • Croissance rapide et étouffement des espèces • À peine brouté • Méthode curative 	<ul style="list-style-type: none"> • Minimum de 2 ans • Fauché deux fois par an au moins, relativement proche du point de compensation • Croissance rapide et étouffement des espèces • Retour rapide de sowthistle vivace (après 2 ans déjà) • Bon substitut d'alimentation pour le bétail • Méthode curative 	<ul style="list-style-type: none"> • Inefficace
Couverts végétaux	<ul style="list-style-type: none"> • Maintenir la pression sur les adventices • Croissance rapide et étouffement des espèces • Modérément efficace 	<ul style="list-style-type: none"> • Maintenir la pression sur les adventices • Croissance rapide et étouffement des espèces • Modérément efficace 	<ul style="list-style-type: none"> • Inefficace
Cultures compétitives	<ul style="list-style-type: none"> • Croissance rapide et étouffement des espèces • Le semis du début du printemps peut être problématique • Les semis de fin de printemps et d'automne sont plus compétitifs • L'augmentation des taux de semis est plus compétitive 		

Cette étude s'inscrit dans le cadre du projet européen AC/DC-weeds (Application and Combined Disruption and Competition for an agro-ecological management of creeping perennial weeds). L'objectif du projet AC/DC-weeds est de mettre en œuvre une gestion agro-écologique plus efficace et de meilleure qualité contre les adventices vivaces rampantes dans les cultures arables. Les espèces cibles sont les trois adventices vivaces les plus problématiques dans les cultures arables d'Europe centrale et du Nord (*Elytrigia repens* L. Gould, *Cirsium arvense* L. Scop. et *Sonchus arvensis* L.). L'objectif de ce projet est de réduire le labour dans l'agriculture biologique et conventionnelle et de remplacer le glyphosate dans ce dernier système.

Le projet AC/DC-weeds se compose de sept work package, notamment la modélisation. Le work package modélisation vise à produire des modèles qui intègrent les décisions de gestion agro-écologique pour les adventices vivaces. Des modèles ont été développés pour prédire l'émergence de graines d'adventices stockées dans le sol en fonction des conditions climatiques (Masin et al., 2012). La modélisation de l'émergence des adventices en fonction du travail du sol est également un deuxième pilier très intéressant

(Spokas et al., 2007). Ce modèle nous aide à comprendre quelles actions du sol ont retardé l'émergence des adventices afin de limiter la concurrence avec la culture pendant la germination. Toutefois, ces deux modèles ne tiennent compte que des adventices annuelles ou biennales. Les adventices vivaces fonctionnent différemment en termes de germination, de propagation et de maintien dans le sol. En raison de la réduction des intrants et de la réduction du travail du sol, on observe un fort retour des adventices, en particulier les adventices vivaces (Trichard et al., 2013). Des outils de modélisation sont donc nécessaires pour aider les agriculteurs à comprendre les périodes d'intervention et les outils à recommander, ainsi que les systèmes de culture qui peuvent être mis en œuvre pour faciliter la lutte contre les adventices pérennes. Afin de répondre au retrait du glyphosate prévu dans l'Union européenne le 01/01/2021, et la desintensification du labour profond, l'un des moyens de recherche est la modélisation afin d'explorer les différents systèmes et la gestion des sols favorables à la lutte contre les adventices actuellement gérées par cet herbicide. Un logiciel est actuellement utilisé comme outil d'aide à la décision (OAD) pour les conseillers agricoles et les agriculteurs pour la gestion du chardon : Odera-Vivaces. AgroTransfert a développé Odera-Vivaces en collaboration avec des chercheurs, des conseillers et des agriculteurs en 2016 (Favrelière et al., 2016). Des modèles matriciels sont également développés (Sosnová et al., 2014) en utilisant l'espèce biennale *Rorippa palustris* comme exemple pour modéliser sa repousse à partir des racines. Toutes les perturbations au cours des saisons n'auront pas le même impact sur la survie de l'adentice. La capacité à germer et à repousser à partir d'organes souterrains a également été modélisée (Taab et al., 2018). À ce jour, aucun modèle ne tient compte des conditions météorologiques, des pratiques agricoles et de l'environnement dans la gestion des adventices vivaces. Il est donc important de produire un modèle prédictif qui mobilise ces différents paramètres afin de proposer une approche systémique du contrôle des adventices pérennes.

Injury Profile SIMulator (IPSIM) est une plate-forme de modélisation. Cette plate-forme a été conçue pour construire des modèles qualitatifs afin de prédire les profils de blessures dans l'agroécosystème, en fonction des pratiques culturales, du sol, de la météo et de l'environnement du champ (Aubertot, Robin, 2013). Cette plateforme a de nombreux objectifs et peut être utilisée comme (i) un outil innovant pour concevoir de nouveaux agroécosystèmes, (ii) un outil de diagnostic pour les agriculteurs ou les techniciens tels que DSS ou comme (iii) une plateforme éducative. IPSIM peut être utilisé sur la modélisation d'un ravageur unique sur les cultures (Robinet al., 2013) ou sur plusieurs ravageurs dans une intégration horizontale (Aubertot, Robin, 2013).

Cette approche de modélisation vise à concevoir un arbre hiérarchique agrégé d'attributs pour intégrer verticalement les méthodes de contrôle, les conditions météorologiques et l'environnement du champ. Les modèles existants (qualitatifs ou non) prennent souvent en compte une dimension de l'agroécosystème comme les conditions météorologiques (par exemple Sosnová et al., 2014) ou les pratiques (p. ex. Odera-Vivaces). L'originalité de la plateforme de modélisation IPSIM est d'appréhender l'ensemble de l'agroécosystème et d'en produire une représentation schématique. Cette approche est particulièrement pertinente pour les adventices vivaces dont les développements sont affectés non seulement par les conditions météorologiques et les sols, mais aussi par les pratiques culturelles ou les perturbations qui se produisent au cours de la production agricole précédente, et à l'interculture. Cette approche permet aux agriculteurs et aux techniciens d'identifier les causes d'une augmentation de l'infestation des adventices ou les conséquences de l'utilisation de méthodes agricoles spécifiques sur l'infestation future des adventices vivaces. IPSIM permet aux modèles d'intégrer l'effet de multiples pratiques de culture (par exemple le travail du sol, le binage inter-rang, la date et le taux de semis, la rotation...), qui peuvent aider à l'ensemble des travaux de modélisation dans le projet AC/DC-weeds.

Pour la conception des trois modèles reposant sur la plateforme IPSIM, la méthode DEX a été utilisée. La méthode DEX, implémentée par le logiciel DEXi (Bohec, 2003) est une

méthode qui prend en charge l'agrégation des attributs hiérarchiques qualitatifs. La force de la méthode DEX est de permettre la décision multi-attributs pour la modélisation. Le principe de la méthode est de subdiviser un gros problème en sous-problématiques plus petites et moins complexes. Cette méthode est parfaitement applicable sur la modélisation de l'infestation des adventices vivaces, en tenant compte de nombreux sous-problèmes tels que les conditions météorologiques, les pratiques agricoles ou le sol. Utilisée à l'origine pour le système d'aide à la décision et l'évaluation de ces décisions, la méthode DEX a été utilisée pour modéliser l'agroécosystème complexe dans la compréhension de la maladie du blé (Robin et al., 2013). La méthode DEX permet à l'utilisateur d'implémenter des attributs, leurs échelles et leurs poids pour les regrouper plus tard dans une plus grande représentation de l'agroécosystème.

Pour la conception des attributs d'entrée, IPSIM-Cirsium, IPSIM-Sonchus et IPSIM-Elytrigia visent à représenter l'environnement de croissance des adventices au printemps, et l'historique des pratiques de culture à plus grande échelle, y compris les années précédentes (quatre ans plus tôt que la culture en cours). Le choix de ne tenir compte que des conditions météorologiques et de l'environnement au printemps était de tenir compte des conditions de croissance des adventices et de qualifier leurs croissances en fonction de leurs besoins climatiques spécifiques. IPSIM-Cirsium, IPSIM-Sonchus et IPSIM-Elytrigia sont trois modèles déterministes statiques. IPSIM-Cirsium, IPSIM-Sonchus et IPSIM-Elytrigia ont respectivement 33 attributs (20 attributs de base et 13 agrégats), 32 attributs (19 attributs de base et 13 agrégats) et 24 attributs (14 attributs de base et 10 agrégats).

Pour chaque attribut est attaché une échelle. IPSIM-Cirsium, IPSIM-Sonchus et IPSIM-Elytrigia ne prennent que trois niveaux maximum par échelle pour les attributs agrégés et les attributs d'entrée. Les échelles d'attributs de sortie des modèles sont composées de cinq niveaux (très bas, bas, neutre, haut, très élevé). Les valeurs choisies sont définies pour chaque attribut et sont représentées par des mots. Certaines échelles dépendent d'un contexte particulier, et différent entre chaque champ et culture. Par exemple, la *date de semis* est déterminée par la recommandation régionale : la même date de semis peut être considérée tardivement en France tout en étant envisagée précoce au Danemark. Le *densité de semis* dépend également du contexte régional et est discriminé à trois niveaux : inférieur à la recommandation régionale, recommandation régionale, supérieur à la recommandation régionale.

Une fois que les attributs d'entrée sont validés par des experts, des tables d'agrégation doivent être construites pour appréhender chaque décision et agrégation d'attributs. Plusieurs attributs sont regroupés et les règles de décision doivent être conçues. Ces règles suivent la fonction *si-alors* et permettent d'assembler une table avec toutes les valeurs que l'attribut agrégatif peut prendre. Les règles sont également appelées fonctions utilitaires dans le logiciel DEXi et doivent être implémentées ligne par ligne par le développeur du modèle. Chaque table agrégative prend les valeurs des attributs inférieurs dans le modèle. La conception de tables agrégatives permet au modèle de calculer l'attribut de sortie finale et, dans notre cas, l'infestation des adventices à partir des valeurs d'attribut d'entrée. Cette étape de conception de modèle prend du temps pour être correctement mise en œuvre et doit être vérifiée par des experts pour sa précision. Pour plusieurs attributs, les tables d'agrégation étaient difficiles à définir en raison du manque de consensus dans la littérature, mais aussi du manque de connaissances sur le fonctionnement d'un processus pour le chardon des champs, le laitron des champs et le chiendent. Par exemple, l'agrégation des pratiques de *culture* représente 81 attributs agrégés ensemble, représentant 81 règles de décision. Dans le processus *si-alors* il faut choisir l'échelle des pratiques culturelles en fonction de l'agrégation des valeurs de différentes méthodes de contrôle. Le développeur du modèle doit reconnaître l'efficacité de chaque méthode, leurs interactions et les comparer entre elles. Ce processus individuel est donc difficile à valider par les experts puisque les experts auront leur propre appréciation de l'efficacité de chaque méthode de contrôle. Seule la littérature pourrait éclairer le processus, mais elle n'est souvent pas consensuelle et ne regroupe pas un ensemble de pratiques

agricoles dans une même expérience, ce qui peut conduire à la subjectivité du choix d'agrégation.

Chaque attribut d'entrée ou agrégé a un poids qui va caractériser son importance. Plus le poids est élevé, plus l'attribut est influent (Bohec et al., 2007). DEXi calcule automatiquement quatre poids distinctifs : poids locaux et globaux, normalisés ou non (Bohanec, 2020). Les poids normalisés tiennent compte du nombre de valeurs pour chaque échelle de chaque attribut, ce qui contribue à améliorer la qualité du modèle pour le développeur. Les poids locaux décrivent l'influence relative des attributs dans une agrégation, tandis que les poids globaux décrivent l'influence d'un attribut par rapport au reste des attributs composant le modèle.

Une fois que le design de tous les attributs, de base et agrégés sont terminés, leurs échelles remplies et les tables agrégées complétées, les modèles peuvent créer une version simulée de l'infestation de adventices. Cette évaluation de l'infestation de adventices est calculée par DEXi en compilant toutes les valeurs d'attributs agrégées suivant les variables qualitatives des attributs d'entrée, la hiérarchie conçue pour assembler les attributs et les tables agrégées conçues pour agréger les attributs.

IPSIM-Cirsium obtient un kappa Cohen à 0,6359 qui rend la qualité prédictive substantielle selon la gamme d'Altman (1999) et Landis et Koch (1977). IPSIM-Cirsium a une qualité prédictive équitable. La précision du modèle est de 0,538, ce qui signifie que plus de la moitié des valeurs seraient évaluées correctement. La plus grande précision des valeurs évaluées a été obtenue pour la classe élevé avec un score de 0,823 score.

Cependant, le F1-score a montré une mauvaise fiabilité du modèle, classant globalement seulement 33% des valeurs correctement. Le F1-score nous aide à considérer le biais de précision causé par la classe majoritaire *très faible*, lui donnant alors un poids équitable par rapport à d'autres classes. L'utilisation de la F1 au lieu de précision est ici justifiée par la représentation élevée d'une classe d'infestation de adventices au lieu d'une représentation homogénéisée de toutes les classes.

Dans un environnement d'infestation faible d'adventices, l'IPSIM-Cirsium est jugé satisfaisant, mais dans un plus large éventail de profils, IPSIM-Cirsium doit être réévaluer pour présenter une sensibilité plus élevée à l'infestation élevée d'adventices.

I. Introduction

A. Presentation of AGIR unit INRAE Auzeville-Tolosane

The INRAE Centre of Occitanie-Toulouse, located in Auzeville-Tolosane, brings together 1200 researchers, engineers and technicians and accounts for more than 11% of the scientific research published by INRAE. The centre's research focuses on biology, biotechnology and agronomy; animal and plant sciences and health management; and economic, social and information sciences. The INRAE Centre in Occitanie-Toulouse aims to address three challenges through research: (i) the establishment of more sustainable agriculture and forestry adapted to weather change; (ii) the integration of human and animal health management into food production and environmental sustainability; and (iii) the construction of new processing chains for the emergence of a regional bio-economy.

The aim of the AGIR joint research unit is to participate in the research of methods and materials for the adaptation of integrated agroecosystems in their chains and territories. The knowledge established by the UMR AGIR is produced through field experiments, surveys and participatory co-design workshops. Through modelling, UMR AGIR seeks to bring this knowledge together, test new systems and share their work with different actors in the value chain. The UMR AGIR's core business is to design and assess new technical itineraries and innovative sustainable cropping systems. This action is carried out collectively and is part of a territory-wide approach, particularly in terms of sharing the knowledge acquired.

B. Context of the study

1. State of the art of European perennial weeds

AGIR Unit is part of the AC/DC-weeds project who aim at the modelling of three major perennial weeds. Perennial weeds are often a massive problem for farmers, especially in organic farming. Their behaviour and reproduction cycle are so particular that their management can only be done on a long-term control. Perennials mostly rely on their root system or rhizomes to spread.

a) *The three most problematic perennial weeds in Europe*

(1) Canada thistle

Canada thistle (*Cirsium arvense* (L.) Scop.) is one of the most problematic perennial weeds in Europe. It originates from South-Eastern Europe and the Eastern Mediterranean. Present in most temperate countries of the world, it has been subject to compulsory control in France since 2000. If individual owners or farmers do not control the proliferation of weeds, they may be punished by up to six months' imprisonment and/or a fine of up to €30,000 (articles L. 251-20 and 21 of the rural code). This weed is present on the A1 lists and on the lists of quarantine pests defined by EPPO in Argentina, Brazil, Mexico, Israel, Jordan and USA. The registration of Canada thistle as a quarantine pest in USA dates from 1989. The harmfulness of Canada thistle is based on yield loss but also on inconvenience at harvest. Yield loss in cereal production reaches 35% from 15 thistles per m² and can exceed 50% when 30 thistles per m² are reached (Favrelière, 2019 ; Hodgson, 1968). Rasmussen and Nielsen (2020) were able to establish a linear relationship between the coverage of the field by thistles and yield loss. Yield loss is also explained by the simultaneous harvesting of thistle seeds, which prevents the crop from drying properly. The GNIS (Groupement National Interprofessionnel

es Semences et Plants [1]¹) also defines crop impurity standards that financially penalize seed harvests classified as impure. Thistle seeds are difficult to sort for crops such as alfalfa, red clover and carrot. The harmful periods for Canada thistle are spring and summer, corresponding to the weather conditions of dormancy emergence. This weed is the most cited concern of organic farmers, especially on farms without temporary grassland or alfalfa. This weed is found in every crop, from cereal to vegetables but this weed can also be observed in many pastures. For an infested alfalfa field, loss due to the weed can reach 16.5 tonnes/ha in 4 year (Schreiber, 1967). In another measure, Canada thistle can be host to insects such as bean aphids or stalk borer, which attacks surrounding crops.

Canada thistle is a perennial weed that adapts to any soil type (Rogers, 1928 ; Moore, 1975). It is a member of the Asteraceae family, resisting well in compacted soils and is able to compete with crops (Hausman et al., 2010 ; Brandsæter et al., 2011 ; Hochstrasse et al., 2012). Canada thistle is found in acid, neutral and basic pH soils. The climatic requirements for Canada thistle present a very large range. The favourable temperature is found between 0°C and 32°C, and only -22°C temperatures can hope to kill the root system during winter (Detmers, 1927). The favourable rainfall is located between 400 mm and 750 mm per years (Hodgson, 1968 ; Amor, Harris, 1975). However, saturated wetlands are unfavourable to the growth of Canada thistle and fields that remain under saturated wet conditions during winter are exempted from Canada thistle (Moore, 1975 ; Laubhan, Shaffer, 2006). Canada thistle requires good light intensity, the competition for the light is the main competition observed in crop (Bakker, 1960). The fertilisation inputs do not seem to increase the growth of Canada thistle compared to the crop (Hume, 1982 ; Edwards et al., 2000 ; Líška et al., 2007).

The main reproduction of Canada thistle is vegetative thanks to its roots. Vertical roots grow up to 6m deep to reach water and nutrients. Horizontal roots (basal shoots here) are the mean for *Cirsium arvense* to spread. They spread from two to four meters a year, Rogers (1928) observed extensions of 6m in a season. Hodgson (1968) estimates that 54% of the root system is located between 7.5 and 22.5cm below the surface, 30% between 22.5 and 37.5cm and 16% between 37.5 and 52.5cm. It was observed on young and recently established plants, therefore an older plant might have a greater proportion of roots in deeper layers. It is important to note that even small pieces of 1cm long roots are able to grow new shoots (Sciegienka et al., 2011). The plants can survive indefinitely through to the root system. The growth of Canada thistle starts in February and ends in November. The sprouting of thistle is gradual and last all summer long. Aerial shoots can either grow from the vertical roots or develop from buds located on the horizontal roots.

Next to the vegetative reproduction, we have the sexual reproduction. Canada thistle starts blooming by the end of June until end of the season. The spread by sexual reproduction is rare, almost non-existing. We estimate the dispersal of plants via seeds from 3 to 5% of the news shoots (Alain Rodriguez, 2020, personal communication). Thistle is dioecious and Hodgson (1968) observed that the production of seeds was maximized when male and female plants are within 16.5m. The flowers are pollinized by insects, especially honeybees (Derscheid, Schultz, 1960). The carpellate heads of Canada thistle contain 100 florets (Bakker, 1960). According to Derscheid and Schultz (1960), the number of seeds produced is 83 and achenes are formed after 8 to 10 days. Seeds of the Canada thistle are transported thanks to floating plumes attached to the seeds. However, Bakker (1960) reports that after 10m, only 9.9% of the seeds are still attached. Long distance dispersal via wind is therefore rare and complicated. Water dispersal or human dispersal is more common. Once buried in soil, seeds of Canada thistle can survive up to 10 to 20 years (Weill, 2005a). In winter, aerial parts of

¹ 1. L'interprofession des semences et plants. *GNIS* [online]. [Accessed 21 August 2020]. Available from: [https://www.gnis.fr/Retrouvez toutes les informations du GNIS et de la filière semences et plants : variétés, réglementation, production, enjeux.](https://www.gnis.fr/Retrouvez_toutes_les_informations_du_GNIS_et_de_la_filiere_semences_et_plants_varietes_reglementation_production_enjeux)

Canada thistle dry and die, only the rosette can remain. The vegetative reproduction is possible only thanks to the storage made by Canada thistle in its roots and aerial shoots. This storage allows the thistle to grow back after every destruction or cut. However, the storage varies along the year. Knowing the storage of the perennials is crucial to plan an efficient management of the weeds, especially concerning the mechanical control. Two periods should be considered in the control of Canada thistle: (i) spring at 4 to 6-leaf stage, at the beginning of the sprouting of the new aerial shoots (Verwijst et al., 2017), and (ii) during summer, just before the mobilisation of storage to bloom. 4 to 6-leaf stage is called the compensation point. After compensation point, Canada thistle becomes capable of growing without drawing on its storage. The plant start recovering its energy reserves thanks to photosynthesis.

(2) Perennial sowthistle

Perennial sowthistle (*Sonchus arvensis* (L.)) is very common in cereal and oilseed crops of Canada, United-States and European countries. Perennial sowthistle is considered a serious weed problem (Holm et al., 1979), and is ranked as 15 most abundant weeds in field. The weed is registered on Quarantine pest list and A1 list in Brazil, Mexico, the United-States and in Israel. The first registration of this weed on Quarantine pest list dates back to 1989 in the United-States. Perennial sowthistle has been one of the first weed to be added to the Weed Control Act from 1990, which enacts the control of weed in Ontario, Canada. In France, the weed is registered as Least Concern on the Red List of the IUCN (International Union for Conservation of Nature). Losses from perennial sowthistle infestations are mainly economical and are the result of reduced crop yield. Peschken et al. (1983) observed that rapeseed yield decreased by 12% with 5 shoots of perennial thistle/m², and 18% with 10 shoots of perennial sowthistle/m² in Canada. In spring wheat, *Sonchus arvensis* reduced yield by 4.5 to 27% with a density from 3 to 15 *S. arvensis*/m² in western Russia (Shashkov et al., 1977). The direct competition of perennial sowthistle in soybean and dry edible bean is responsible for the reduction of seed weight, germination percentage and seedling growth rate of seed (Zollinger, Kells, 1993). However, in grazed meadow, perennial sowthistle is less a problem than Canada thistle. Indeed, livestock acceptance for perennial sowthistle is greater and contributes to a high feed quality grass. In France, the harmfulness of *S. arvensis* is low and is mostly not considered as a problem, even by organic farmers. However, perennial sowthistle is a host to numerous pests and diseases. Henderson (1951) observed for example the potato tuber rot nematode, *Ditylenchus destructor*, in the roots of *S. arvensis*, which could help maintain the pest in the field. Perennial sowthistle does not have any known allelopathic effect (Weill, 2005b).

Perennial sowthistle can adapt to large variety of soils as Canada thistle. Perennial sowthistle seems to be mainly observed in light soils (Alain Rodriguez and Catherine Vacher, 2020, personal communication); loamy soil and clay soil are the most favourable soil for the growth of *S. arvensis* (Weill, 2005b). Soil needs to have important input of water and keep cool and humid for a maximized growth of *S. arvensis* (Sicard et al., 2012). Perennial sowthistle is also found in acid, neutral and basic pH soils, with perhaps a small preference for alkaline and neutral soil (Stevens, 1924). The climatic requirements for perennial sowthistle are slightly different from Canada thistle. The growth of perennial sowthistle is greater in a day/night 20/15°C regime than in a 30/25 or 10/5°C regime (Zollinger, Kells, 1993). The germination of seeds is maximized with cycles of 20 to 30 to 8°C during night (Cross, 1930). The reaction to temperature is also quite different from Canada thistle and perennial sowthistle. The former is mainly temperature sensitive for the dormancy and stop its aerial shoot growth in cold winter temperature around end of November. The latter stops its growth around end of July until end of November, while temperature seems to be still adequate for the growth of perennial sowthistle. This process seems to be endodormancy (innate dormancy; (Taab et al., 2018)), and *S. arvensis* reacts to the photoperiod. When day length starts to decrease, the weed initiates the dormancy process. This dormancy has consequences on the control of the weed,

offering a tiny window of opportunity (Andersson et al., 2013). Perennial sowthistle is commonly found in region that receive the highest amount of precipitation (Lemna, Messersmith, 1990). Fertilization inputs seems to be slightly presenting an advantage for the growth of *S. arvensis*, especially with potassium input (Nurhayati, 2016).

The reproduction of *S. arvensis* is mainly vegetative spread. Buds along the root (basal shoots here, as for the Canada thistle), enable the growth of new aerial shoots. The vertical roots can reach up to 2m deep and horizontal roots (basal shoots) grow at a depth of 5 to 20cm below ground level (Weill, 2005b). Roots being shallower than the roots of Canada thistle, the mechanical management will be different for these two Asteraceae. Roots grow from 1 to 2m per year. The part of the plant above the ground dry and dies in winter, and the plant survive winter as thickened roots. Roots can survive at least 2 years (Håkansson, 1982). The growth of perennial sowthistle starts in April and, for the earliest conditions, ends in August. The emergence of new shoots is possible for 5cm long pieces, yet emergence time is longer for tinier pieces (Anbari et al., 2011). As Canada thistle, aerial shoots can either grow from the vertical roots or develop from buds located on the horizontal roots.

The sexual reproduction of *S. arvensis* is yet greater than Canada thistle and can represent in few cases, a threat as big as vegetative spread for new contamination spots. The weed has both male and female flowers. One plant can produce up to 10 000 seeds. However, self-fecundation cannot happen (Weill, 2005b) and seed production in isolated patches is therefore poor (Bond et al., 2007). As for Canada thistle, seeds are transported thanks to floating plumes attached to the seeds. Seeds can survive 6 years in the soil (Salisbury, 1961). The spread via seeds is low, maximal dispersal distances are 10m thanks to 16.4 km/h (Sheldon, Burrows, 1973). Dispersal can also happen thanks to crop harvest, or water dispersal. Nevertheless, water dispersal with irrigation for example caused the seeds to rot after 3 months (Bruns, 1965). After the germination, plants grow fast and basal roots can expend 1m in 4 months only (Weill, 2005b). Perennial sowthistle are usually able to bloom only the second year after germination or emergence.

S. arvensis also presents a nutrient storage cycle. The compensation point is reached at 4 to 6-leaf stage (Tavaziva, 2012) The second lowest point of storage is reached just before the blooming of *S. arvensis*. After this stage, perennial sowthistle become energy autonomous thanks to photosynthesis. After the compensation point, the weed start to fill its storage again before the dormancy period from end of July to mid-November (Claire Cros, 2020, personal communication).

(3) Quackgrass

Quackgrass or common couch (*Elytrigia repens* (L.) Gould) is a serious problem worldwide in large variety of crops, orchards and in forest seedling establishment areas (Westra, Wyse, 1981). Quackgrass is found throughout Europe, Mediterranean, Macaronesia, Black sea, Caucasus, and Asia (except south). Quackgrass is registered on Quarantine pest, A1 and A2 lists in United-States, Israel, Jordan and most recently Brazil (2018). *E. repens* can affect the yield in numerous crops. In cereals for example, 25 to 85% losses in corn, 19 to 55% in soybean and up to 57% for wheat (DRAAF, 2017). In vegetable fields, rhizomes can make holes in tuber vegetables. Economic losses can come from direct competition for space and nutrient. The competition is also expressed through allelopathic effects. Indeed, roots are expressing a toxic substance that inhibit the growth of adjacent plants. Economic losses are also observed with the pest that are hosted by quackgrass, for example take-all disease (*Gaeumannomyces graminis* var. *tritici*). This mushroom is responsible for necrosis of roots in cereals. Quackgrass can also cause lodging and lead to inconveniences at harvest such as humidity of seeds. Seed-crops are also subject of control of purity of crops defined by GNIS. This impurity is mostly problematic for the cultivation of seed-crops of ray-grass. Indeed, quackgrass and ray-grass seeds are similar and hard to sort. Quackgrass seeds cannot exceed 1% of the total weight of ray-grass seeds (GNIS). Having quackgrass in a ley of ray-

Table 1: C. arvense, S. arvensis and E. repens main characteristics

	<i>Cirsium arvense</i>	<i>Sonchus arvensis</i>	<i>Elytrigia repens</i>
Harmfulness	<ul style="list-style-type: none"> • Decrease yield • Provoke Inconvenience at harvest • Lower dryness of harvest • Impurity in Seed-crops • Host to pests 	<ul style="list-style-type: none"> • Decrease yield • Host to pests 	<ul style="list-style-type: none"> • Decrease yield • Impurity in Seed-crops • Host to pests
Habitat	<ul style="list-style-type: none"> • Compacted soil preference • Large range of pH • High precipitation 	<ul style="list-style-type: none"> • Light soils • Large range of pH • High precipitation 	<ul style="list-style-type: none"> • Clay soils • Preference for neutral and alkaline soils
Root system	<ul style="list-style-type: none"> • Deep vertical root (6m deep) • Basal roots (7-50cm deep) 	<ul style="list-style-type: none"> • Vertical root (2m) • Basal roots (5-20cm) 	<ul style="list-style-type: none"> • Rhizomes (0-20cm deep)
Vegetative propagation	<ul style="list-style-type: none"> • Major • Up to 6m per year 	<ul style="list-style-type: none"> • Major • 1-2m per year 	<ul style="list-style-type: none"> • Major • 1,5m
Seed propagation	<ul style="list-style-type: none"> • Inexistent or negligible 	<ul style="list-style-type: none"> • Minor 	<ul style="list-style-type: none"> • Minor
Compensation point	<ul style="list-style-type: none"> • 4 to 6-leaf stage • Before blooming 	<ul style="list-style-type: none"> • 4 to 6-leaf stage • Before blooming 	<ul style="list-style-type: none"> • 4 to 6-leaf stage

grass is a problem for the quantity of feed for livestock. Quackgrass has an equal quality nutrient content for livestock as ray-grass, but the main part of biomass is produced underground. Nevertheless, *A. repens* can be used to maintain land to avoid erosion. Its quick vegetative spread is an advantage to colonize rapidly a threatened land.

Quackgrass is able to grow in any type of soil but seems to prefer slightly rich clayed, fresh and compact soils (Njos, 1978). Quackgrass can yet be observed in a large variety of soil, and uncompact soils are also subject to infestations (Alain Rodriguez, 2020, personal communication). The weed prefers neutral or alkaline soils but can grow in acidic soil. The climatic requirements are shared with other perennials: the water needs are average (mesophilous plant), and the weed is capable of surviving dry summer thanks to its deep roots (Nkurunziza et al., 2011). Håkansson (1969) showed that light and temperature affect the growth of quackgrass. The perfect temperature range is between 20 and 25°C. No growth can happen below 2°C or above 35°C. Majek et al. (1984) observed a perfect temperature of 21°C for growth of quackgrass, stem and roots elongations, and blooming. The growth stops in November when temperatures go below-freezing temperatures and days shorten. Long days enable the weed to bloom: days shorter than 12 hours did not result in inflorescence and produced shorter plants (Majek et al., 1984). Fertilizers can cause a greater infestation even doubling the biomass produced under nitrogen inputs (Williams, 1977 ; Marshall, 1990 ; Wedin, Tilman, 1993). The weed is capable of absorbing 55% of nitrogen, 45% of phosphor and 68% of potassium that are available for plants (DRAAF, 2017). However, other experts (Alain Rodriguez, Catherine Vacher) report that quackgrass does not show higher infestation under nitrogen inputs, which could be explained by a better nitrogen intake of the crop. The effect could vary from one crop to another. Williams (1977) have shown that nitrogen fertilization in wheat increased shoot weight but had little or no effect in barley.

Quackgrass mainly reproduces and spread vegetatively. *E. repens* has a great difference with previous perennial weeds: "roots" of *E. repens* are actually rhizomes. This underground stem presents an enormous amount of buds from which aerial shoots emerge. One plant can produce up to 235 new shoots (Westra, Wyse, 1981). However, only few buds are non-dormant. The nutrient needed for aerial shoot elongation are stored in the rhizomes. The growth of *E. repens* is observed all year long in France. If the elongation of aerial shoot starts in fall, the stem might remain dormant during winter and emerge only during spring. In May, quackgrass starts producing new stems. New stems are produced from the same shoot while new rhizomes are produced from lower buds. By the end of June, the new rhizomes start producing new shoots that emerge to become aerial shoots. During winter, old stems deacease and only young ones remain. In the next spring, young shoots continue to grow, and additional shoots are produced. As for *C. arvensis* and *S. arvensis*, *A. repens* can grow back from tiny pieces of rhizomes but the capacity of regeneration decrease with the size of fragments (Hamdoun, 1972). A 5 mm long piece of rhizome is enough to produce a new shoot.

The sexual reproduction of quackgrass is very low as for other perennial weeds. However, the production of seeds can remain problematic for new contaminations. Flowers bloom from June to end of October. The rare germinations can be observed from fall to spring. One shoot can produce around 25 seeds on the main stem. Quackgrass seeds are yet far less resistant than Canada thistle and sowthistle and can only survive up to 4 years if they are stored in the 5 first centimetres of soil, but deeper than 10cm none can survive (Ivany, 1978).

For quackgrass, storage also evolve along the year and the compensation point can be observed at 4 to 6-leaf stage (Håkansson, 1967 ; 1969 ; Duval, 2008). After this stage, the weed starts producing new rhizomes; therefore, it is advised to perform tillage at this stage.

Description of *C. arvensis*, *S. arvensis* and *E. repens* is summarized in Table 1.

b) *State of the art of perennial control methods*

The control of perennial weeds needs to last on several years to show efficiency. One method alone cannot sufficiently control the weeds. The chosen methods have to be adapted to the system in order to create a synergy between rotation of crops, mechanical work and herbicide use.

(1) *Mechanical control as control methods*

Mechanical work is seen as an alternative to chemical control of weeds. However, on perennial weeds, mechanical control needs to be done in the correct conditions with the correct tools to avoid the spread of the infestation.

(a) *Inversion tillage*

Inversion tillage or plough is a common practice who consists first into cutting, and then turning over a strip of soil called the furrow. Plough is performed to prepare the soil for the next crop, to bury the organic matter and fertilizer, improve the water circulation in soil and to control weeds (Cédra, 2009). It is performed thanks to mouldboard plough or disc plough. In the control of perennial weeds, ploughing is governed by three compounds: (i) the burial depth, (ii) the weather during the inversion tillage and (iii) the date. Indeed, burying basal roots of thistles or rhizomes of quackgrass of few centimetres already decrease the sprouting capacity of the weeds. Asteraceae and Poaceae here have different efficient burial depth: 10 cm is enough for quackgrass to decrease sprouting capacity (Hamdoun, 1972), while Canada thistle requires at least 20-25 cm deep plough to have an efficient decrease of infestation. Performed once a year, plough buries root fragments. The efficiency of inversion tillage for *S. arvensis* appear to be controversial. Weill (2005b ; 2018) reports that deep ploughing is inefficient against *S. arvensis* (data collected in a two-year experiment), while Thomsen et al. (2015) reported decrease of *S. arvensis* infestation in a ploughing system. One of the negative effects of inversion tillage is the burial of roots or rhizomes, which complicate the shallow tillage. Lemieux et al. (1993) found that 94% of the rhizomes of quackgrass were found in the top 10cm of soil in no-till treatment, while 68 and 19% were found below 10 and 20cm respectively in fall-plough treatment.

The weather during and few days after the tillage is very important to avoid the spread of the weeds. Indeed, ploughing in wet conditions will enable root or stem fragments to regrow (Sciegienka et al., 2011 ; Hochstrasse et al., 2012). Inversion tillage aims at the depletion of the root system for Canada thistle and perennial sowthistle. Inversion tillage stimulates the root system, destroy the new shoots, and provokes the growth and exhaustion of root system. For quackgrass, inversion tillage aims at reducing the growth capacity of the rhizomes by burying them or dry them. Mechanical control can also lead to the emergence or the stimulation of buds. Ploughing in dry conditions enables the farmer to have an efficient control by exhausting the roots that will not be able to rely on their deep vertical root to access water. Dry summer are the easiest conditions to control *C. arvensis*, *S. arvensis* and *E. repens*.

Date seems to be key for inversion tillage. Plough during the dormancy of weeds will only spread them in the field without provoking any growth and depletion of the storage (Boström, Fogelfors, 1999). For *S. arvensis*, the long dormancy period implies to perform the inversion tillage close to summer harvest or during spring when dry weather conditions are available. Inversion tillage can be performed during spring to aim at the low storage of weeds. However, in spring, days with dry weather and dry soil are harder to find. Weill (2005a ; 2005b) reports that *C. arvensis* and *S. arvensis* need to be controlled in spring to match with their compensation point. Thomsen et al. (2015) also reported a weak control of perennials when the ploughing was performed in autumn. For *C. arvensis* it seems that the great depth of its roots might give the plant a strong growth potential. We can even observe a temporality in ploughing in autumn: early autumn ploughing seems to be more efficient than late autumn ploughing (Boström, Fogelfors, 1999). However, date is important to quantify the efficiency of ploughing, late autumn ploughing remains more effective than no ploughing at all (Boström, Fogelfors, 1999). For *E. repens*, spring inversion tillage seems to be less effective than autumn

ploughing (Njos, Borresen, 1991). This could be explained by the different life cycle of quackgrass, with a larger growing period ending in November.

Deep inversion tillage can improve the quality of soil and create a decompacted soil in the 30 first centimetres. This decompaction is useful for the control of weeds, creating drying conditions where air can circulate but also create an unfavourable environment for Canada thistle for example. Compacted soil host most of the Canada thistle and to some extent to quackgrass as well (Njos, 1978). But the date of tillage might also determine the quality of soil. Spring plough instead of fall plough led to a decrease of yield in barley and oat (Njos, Borresen, 1991). Lower quality of soil means lower competitiveness of crop in regards of perennials, which can better adapt to poor soils thanks to their deep roots.

However, deep ploughing is a practice that goes against the life in the soil by considerably reducing microbial activity. A single tillage alone can significantly reduce the abundance of microorganisms (Kraut-Cohen et al., 2020). Intensive inversion tillage to reduce weed pressure is also very fuel consuming. It is estimated that one hectare of ploughing is equivalent to a consumption of 20 to 40 litres of fuel oil/ha depending on the type of soil, and simply reducing the working depth can reduce consumption by 50% (Demazeau, 2008). It is also estimated that soil erosion in conventional systems with deep tillage results in an average soil loss of 17Mg/ha/year in Europe (Holland, 2004) and solely switching to a system with shallow tillage reduces this erosion by 58% (Ouvry, Lebissonais, 2008).

(b) Stubble tillage

Stubble tillage is a shallow or deep treatment, happening after the harvest who aims at burying the straws, stubbles and other remain of the previous crop. This tillage is performed once or several times along the year. Stubble tillage is performed to control weeds as a destruction of roots and young plants such as emerged perennials. Stubble tillage can also homogenize the dispersal of crop residues and manure on the top 15cm of soil. The mixing of soil and residues will then start the humification processes. This tillage is performed to lesser extent to improve soil texture and prepare the seedbed (Cédra, 2009). The efficiency of stubble tillage is governed by (i) the date of intervention, (ii) the tools used, (iii) the number of tillage and (iv) the weather during and after the tillage. Stubble tillage is often associated with plough, for *E. repens*, stubble tillage followed by ploughing help decrease by 90% the biomass of the weed compared to a system without stubble tillage (Boström, Fogelfors, 1999). However, stubble tillage can also be inefficient in some cases for *S. arvensis*. Boström and Fogelfors (1999) observed that late ploughing not preceded by stubble cultivation better controlled perennial sowthistle.

Stubble tillage, as for inversion tillage should aim at the destruction of weeds at their lowest storage point: the compensation point. However, this date is often unavailable for the farmer because of the growing of crop. As we have seen with the plough, there are two strategies of control of perennials: the exhausting method and the extraction method. The exhausting method is indicated for Canada thistle and perennial sowthistle. For quackgrass, we should aim at the extraction method of the rhizomes. The date of intervention is important in the exhausting method because the storage must always deplete and not get filled up during the growth of the weeds. If the tillage is performed too early, the depletion of the root storage will not happen, and the tillage will only spread the weeds in the field. If the tillage is performed too late, weeds can be under dormancy and the tillage will not have any effect on the weed control (Rodriguez, 2007). The summer between crop is therefore the most suitable period to have efficient carbon storage outflow, and before mid-August for *E. repens*, when storage goes downward to the rhizomes to survive winter (Pierre Delpérié, 2020, personal communication; Arny, 1932).

The choice of tools to perform the stubble tillage is essential. In the exhausting method, we should aim at the cutting of the entire root system. Disc tools are reported to be spreading

the root system for *C. arvensis*, *S. arvensis* and *E. repens* (Hochstrasse et al., 2012 ; Weill, 2018). But an experiment in 2004 and 2005 in Centre region in France, showed that Covercrop (a disc tool) was as effective as goosefoot tillage for the control of Canada thistle (Moulin, 2011). Disc tools cut the roots or rhizomes but not on their entire length and contribute to spread small pieces of 2 to 5 cm of roots in the field. This effect is also observed with tine tools or chisel that are not cutting 100% of the root system. It is interesting to notice that the depth of stubble tillage is less important than the covering of the tool (Rodriguez, 2007). Weill (2005a ; 2005b ; 2018) advises to use chisel with goosefoot that intersect. Wing share can also be efficient (Lukashyk et al., 2008). In the second method, the extraction method, tools chosen should aim at bringing rhizomes to the surface to make them dry on the open. We can cite chisel plough or tines but, to bring the rhizomes on the surface of the soil, curved wings are advised. Using disc tools does not disturb deeply the soil and help maintain moisture in soil (Pierre Delpérié, 2020, personal communication). Wet soils help the regrowth of quackgrass.

To have an efficient stubble tillage and an efficient control of perennial weeds, we should consider the number of tillage. Having only one tillage per year is worse than not having any (Hochstrasse et al., 2012). Only one tillage will spread the roots of weeds and stimulate the burst of buds on roots and lead to an increase of emergence of perennials. Having a second tillage would therefore control the new emergences, contributing to the exhaustion of weeds. The second tillage cannot be too close from the first tillage; disturbed roots need to have enough time to produce new shoots. Two tillage should be separated from 10 to 12 days to let the weed produce shoot back to 4 to 6-leaf stage (Tamarcaz, 2019). In order to obtain an efficient control, Thomsen et al. (2015) reported that tillage should be performed at least three to four times a year. It is possible to use less efficient tools such as tines or stubble plough if the repetition of tillage is great enough (Lukashyk et al., 2008), and the coverage of tillage is great enough (Régis Hélias, 2020, personal communication).

Weather is key to control *C. arvensis*, *S. arvensis* and *E. repens*. We often hear that wet years are Canada thistle years or quackgrass years. It is less correlated to the weather during the growing period of the weeds than the weather during tillage. Dry summer are reported to be the most efficient weather to control perennial weeds (Weill, 2018). Indeed, as inversion tillage, stubble tillage should be performed in the driest conditions possible. The control of quackgrass requires 8 to 10 days of dry weather to perform the extraction method (Alain Rodriguez, 2020, personal communication). For Canada thistle and perennial sowthistle, climatic requirements during tillage are less demanding and require only few days of dry weather during and after the tillage to avoid the regrowth of the cut-off roots and to provoke only the regrowth of deep roots.

As for inversion tillage, deep stubble tillage with chisel plough or deep tines can help loosening the soil, creating poor soil conditions for *C. arvensis* and *E. repens* (Hochstrasse et al., 2012).

(c) Inter-row hoeing

Hoeing is a shallow tillage performed during the crop growth. This mechanical control aims at the control of weeds in the inter-row (Cédra, 2009). Hoeing is performed on crops presenting large inter-row such as maize and soybeans but is also widely used on cereal that are sown with larger inter-rows. However, inter-row hoeing in cereal implies to increase the sowing rate, to maintain the yield. Hoeing is an interesting technique to maintain the threat level low in a field and allow treatment at the lowest storage period of perennial weeds during spring. Hoeing should be done at 10 to 12-leaf stage (Hochstrasse et al., 2012). Nevertheless, hoeing cannot be use as a curative method. Indeed, inter-row hoeing control the roots in-between the rows but not in the row. Therefore, controlled perennials remobilise their carbon stocks into the shoots that are remaining in the row. Hoeing is simply ineffective for *E. repens*: rhizomes are too thin, and tools used for hoeing just spread quackgrass. The efficiency of hoeing is governed by: (i) the used tools, (ii) the weather and (iii) the number of hoeing.

Table 2: Mechanical control of C. arvense, S. arvensis and E. repens

	<i>Cirsium arvense</i>	<i>Sonchus arvensis</i>	<i>Elytrigia repens</i>
Inversion tillage	<ul style="list-style-type: none"> • Dry conditions • Post-harvest or spring to aim at the low storage level • 20-25cm deep 	<ul style="list-style-type: none"> • Dry conditions • Post-harvest or spring to aim at the low storage level • 20cm deep 	<ul style="list-style-type: none"> • Dry conditions • Autumn • 10cm deep
Stubble tillage	<ul style="list-style-type: none"> • Dry conditions • At compensation point • Disc tools spread the weed • Use tools with 100% coverage to cut the roots • 3 to 4 tillage separated by 12 days minimum 	<ul style="list-style-type: none"> • Moderate efficiency • Dry conditions • At compensation point • Disc tools spread the weed • Use tools with 100% coverage to cut the roots • 3 to 4 tillage separated by 12 days minimum 	<ul style="list-style-type: none"> • Dry conditions from 8 to 10 days • At compensation point • Use extraction tools to bring weed at the surface
Inter-row hoeing	<ul style="list-style-type: none"> • Moderate efficiency • Dry conditions • At 10 to 12-leaf stage • Tools: goosefoot or wing share • 2 to 5 cm deep • At least 3 times 	<ul style="list-style-type: none"> • Moderate efficiency • Dry conditions • At 10 to 12-leaf stage • Tools: goosefoot or wing share • 2 to 5 cm deep • At least 3 times 	<ul style="list-style-type: none"> • Inefficient
Selective cutting	<ul style="list-style-type: none"> • Moderate efficiency • Under significant rain • Before blooming or during the growth of the weed (10-leaf stage resulted in the highest efficiency of control) • 2 times 	<ul style="list-style-type: none"> • Moderate efficiency • Before blooming or during the growth of the weed • 2 times 	<ul style="list-style-type: none"> • Inefficient

Hoeing to control *C. arvensis* and *S. arvensis* requires strong tools that are cutting on the whole width of the inter-row. As for stubble tillage, Weill (2005a ; 2018) reports that inter-row hoeing must be aggressive, and the use of goosefoot or wing share should be used. In Denmark in winter wheat, goosefoot showed good results in the reduction of infestation of *C. arvensis* (Rasmussen et al., 2006). Spike harrow is useless on the control of deep-rooted weeds such as Canada thistle and perennial sowthistle.

In order to maintain the threat at a low level, hoeing must be performed in dry conditions. Hoeing is not deep (2 to 5cm) and is meant to cut shoots just below the ground. However, hoeing in wet conditions can result in the spread of Canada thistle or perennial

sowthistle as we can observe for any other tillage. One or two days are enough to dry the roots and avoid the propagation through cuttings [2]².

Hoeing, performed on 10 to 12-leaf stage, must be at least repeated three times during the growing period of the crop to maintain low level of infestation (Vanhala et al., 2006). It has been reported to be efficient only if complementary methods were performed. Hoeing can be seen as a backup method or an additive method to stubble tillage or inversion tillage. Vanhala et al. (2006) observed a poor control on *S. arvensis* with inter-row hoeing compared to stubble cultivation on barley and oat.

(d) Selective cutting

The principle of selective cutting is to cut the weed without harming the crop under it. We can distinguish two kinds of selective cutting: cutting above the crop and cutting in the crop. To cut the weed above the crop, the weed needs to be taller and more developed than the crop. Therefore, the window of opportunity is brief and only in short or young crops can the technique be used. For this method, we aim at the flower: for annual weeds it avoid the spread of new seeds and for perennial weeds, flowering corresponds to a low storage point of the weed with the use of carbon stocks to bloom (Tavaziva, 2012). Selective cutting should not be performed too early, Canada thistle seems to be able to induce a second blooming when the stem is disturbed (Hochstrasse et al., 2012). The second method can be use at any stage of the crop with the ComboCut from April to October. However, few conditions must be respected: a physical difference must exist between the crop and the weed. For example, the weed must be stiffer or thicker than the culture or the weed can present a different branching pattern. In thick crops, the selective cutting can only be done above the crops (e.g. salad or potato). This selective cutting can be performed earlier than the above cutting, and high efficiency of the selective cutting is observed at 10-leaf stage for *C. arvensis* (Verwijst et al., 2017 ; V J Tavaziva et al., 2019). The selective cutting significantly reduces the number of shoots of *C. arvensis* and *S. arvensis*, however, *E. repens* does not respond positively to selective cutting (Alain Rodriguez, 2020, personal communication). This could be explained by the different strategies of control: exhaustion on *E. repens* is limited and extraction should be favoured. Selective cutting does not contribute to the extraction of the rhizomes.

Selective cutting is similar to the mowing process in meadow or temporary meadow. The exhaustion of the plant, yet greater if roots are disturbed, can also be performed by stem disturbance. As for mowing, selective cutting should be performed at least twice a year to have a significant effect (Verwijst et al., 2017 ; V J Tavaziva et al., 2019).

Weather is not limiting the control of Canada thistle and perennial sowthistle as we can observed for the other mechanical control. However, significant rain can help reduce the

2. Pratiquer le désherbage mécanique sur l'inter-rang - Binage - GECO. [online]. [Accessed 30 July 2020]. Available from: https://geco.ecophytopic.fr/geco/Concept/Pratiquer_Le_Desherbage_Mecanique_-_Binage

infestation of *C. arvensis* while cutting the weeds (Bourdôt et al., 2011). All the mechanical control methods are summarized in Table 2.

(2) Herbicide control

Herbicide represent the largest expense of pesticides in the world with more than 45% of the total expense in 2008 (Atwood, Paisley-Jones, 2017). Herbicides are often reported to be less effective on perennial weeds. However, maximal doses are higher on perennial weeds than on annual weeds. One of the most favourable periods to treat the weed is between crop thanks to glyphosate, 2,4-D, MCPA or Dicamba. Glyphosate is the most widely used herbicide and is responsible for 15% of the consumption of plant protection products in France (Babeau, 2017). It belongs to the amino-phosphonate family and is a systemic foliar total weed killer. Glyphosate is an inhibitor of 5-enolpyruvylshikimic acid 3-phosphate biosynthesis and suppresses the production of aromatic metabolites (Baer, Marcel, 2014). This process induces a dysfunction of the photosynthesis. Roundup® is the most emblematic product containing glyphosate and was developed in 1974 by Monsanto Company. Its non-selectivity makes it a very effective herbicide. In 2014, it is the most widely used herbicide in the world with more than 800,000t sold (Parisse, 2019). The success of this herbicide is also due to its low price and low toxicity compared to other herbicides developed earlier. The chemical control of perennial weeds needs to be performed on several years to be efficient (Ludovic Bonin, 2020, personal communication). The mode of action of herbicides on perennial weeds must be systemic to reach the roots. To increase the efficiency of herbicide on perennial weeds, it is important to have sufficient leaf area to maximize the absorption of the product. Tavaziva et al. (2019) advise the use of MCPA on 8 to 10-leaf stage to maximise the leaf area but still treat during the low storage period of *C. arvensis*. The efficiency of herbicide depends on climatic requirements especially on rainfall, temperature, and hygrometric level [3³]. All these climatic requirements are essential to allow great absorption of herbicides.

Some crops present a larger window of treatment possibility, according to the possible uses registered at the marketing authorization. In the control of *C. arvensis* and *S. arvensis*, Poaceae crops are more easily treated (Ludovic Bonin, 2020, personal communication). Therefore, rotation of crops can be designed to maximize the chemical treatment on crops. In the case of *E. repens*, the window of treatment is very wide and allows simple chemical control of the weed, especially concerning the sulfonylureas (Kearney, Kaufman, 1975). Catherine Vacher (Arvalis) hypothesize that widely use herbicides such as glyphosate for years are responsible of the low infestation of quackgrass in France.

However, the use of herbicides is not without any risk. Apart from health risks, herbicides grows concerns on environmental risk with the contamination of ground water and surface water (Tilman et al., 2002), even if improvements are made to minimize the persistence in soil, such as the use of 2,4-D which persists 1 month instead of MCPA which persists 2 to 3 months (Zimdahl, 2015). MCPA differs from 2,4-D by the substitution of a methyl group for chlorine (ANNEXE 1). The use of herbicide is also far from being sustainable, with the observation of numerous resistance population throughout selection of resistant plants (Kudsk, Streibig, 2003). The increase of resistance can lead to an increase of number of herbicides

3. Réussir ses traitements : l'importance de la météo. [online]. [Accessed 31 July 2020]. Available from: <https://www.arvalis-infos.fr/pulverisation-sur-cereales-soigner-les-conditions-d-application-ds-phytos-@/view-14762-arvarticle.html>

4. INTERNATIONAL HERBICIDE-RESISTANT WEED DATABASE. [online]. [Accessed 21 August 2020]. Available from: <http://weedsience.org/Home.aspx>

used but also to an increase of doses to try to keep an efficient control. 218 species of plants have been reported resistant to herbicides (Burke, Bell, 2014 ; [4]). Glyphosate has been declared non-carcinogenic by several French institutes (EFSA, ANSES and ECHA) but is the cause of many uncertainties regarding its dangerousness for human health as well. In France, since 6th of February 2014, "LABBÉ"'s law regulates the use of phytopharmaceutical products. Numerous uses of pharmaceutical products are already forbidden to all the public since 1st of January 2017. It concerned mostly the maintenance of parks and green spaces. For private individuals, this interdiction is effective since 1st of January 2019. We can mention that all pharmaceutical products are concerned, except biocontrol products, Organic farming products and low risk products. Concerning agriculture, in wheat for example, only 4% of herbicides used contain glyphosate and between 100 and 250g/ha are used in arable crops. However, in 2008, an objective of 50% use reduction in 10 years in plant protection products has been implemented. This objective is part of the 2009/128 European directive who establish a framework for Community action to achieve the sustainable use of pesticides.

(3) Crop planning and rotation methods

Perennial weeds are complex to control by their life cycle. A long-term approach is often needed to apprehend the weeds. Increasing the competitiveness of the field on several years can help reduce the infestation. The competitiveness of the crop is obtained by the intrinsic property of the crop to be competitive concerning light and nutrients. However, the inclusion of competitive crop in the rotation to reduce weed infestation often mean a decrease of the income if the crop has low price quotation. On the long-term, a system that add competitive crops on the rotation maintains low threat level of pest, which allow the farmer to keep low production cost with reduced crop protection products and tillage cost.

(a) Introduction of a meadow

The most efficient method to control perennial weeds is the introduction of meadow in the rotation. This system is already widely used by organic farmers, more known as ley farming: the alternate growing of crops and grass. Ley farming allows farmer to reduce weed pressure, increase organic matter input and the increase of the biodiversity of pollinators and auxiliaries (Mellender, 2018). Ley farming integrate crop and livestock and support a sustainable system of fertilized resilient system. Therefore, ley farming is more beneficial for polyculture-livestock farming to avoid a large economic loss for the addition of the meadow. For *C. arvensis* and *S. arvensis*, the efficiency of meadow is governed by: (i) the number of years of meadow, (ii) the number of years before the return of the meadow in the rotation, (iii) the species sown for the meadow, and (iv) the number of cuts or grazing of the meadow per year. *E. repens* did not show any depletion of the infestation in meadow treatment, *E. repens* even increased and spread (Marshall, 1988 ; 1990 ; Duval, 2008). Cutting the stem of *E. repens* above the ground is useless to reduce the infestation; control method is not based on the exhaustion of the rhizomes but the extraction of the latter.

Meadow can only be efficient if is implemented on 2 years at least (DRAAF, 2017). Meadow lasting less than 2 years have a slight reduction of the number of shoots of *C. arvensis* and *S. arvensis*, but the infestation resumes the following year. Hodgson (1968) reported a decrease of 99% of the original population of *C. arvensis* for a 4-year long meadow, mown twice a year. It is possible to maintain a high competitive level to *C. arvensis* and *S. arvensis* and continue the effect of the meadow by choosing a competitive crop (Lötjönen et al., 2005).

Even for long meadow rotation, if the last meadow is further than 4 years, weeds start to reappear. Canada thistle seems to reappear after 3 to 4 year in low density, while perennial sowthistle reappear 2 years after the meadow, in low density (Catherine Vacher, 2020, personal communication). The effect of the meadow will continue as long as the crops are being competitive with the weeds (Weill, 2018). The introduction of uncompetitive crop such as hoed crops or wide row crops more generally will enable the weeds to access light and nutrient more easily.

The main competition for perennial weeds is the competition with light, and meadow are effective by the smothering effect. Therefore, it is crucial to introduce species that have large morphological characteristics. In order to be competitive, it is important to have a fast growth of the meadow to overrun the growth of *C. arvensis* or *S. arvensis*. Alfalfa (*Medicago sativa*) is recognised to be the most effective plant in meadow to control Canada thistle and perennial sowthistle (Ominski et al., 1999 ; Weill, 2018). Lukashyk et al. (2008) report ryegrass-clover ley (*Trifolium pratense* (L.) and *Lolium multiflorum* (Lam.)) to have a cover of 90% of the ground, making it a high competitor for light towards *C. arvensis* and *S. arvensis*. However, ryegrass-clover ley has a slow growth and can be overrun by the weeds. Alfalfa on the other hand has a relative high growth speed and overrun the weeds at every cut. The choice of the species must also be on the long run and it is advised to avoid annual species. Forage grass are shown to be less effective in the control of weeds, offering a lower density. Donald (1990) still reports some exception with cocksfoot (*Dactylis glomerata* (L.)), with a high speed growth allowing three to four cuts, which can be as efficient as alfalfa.

The efficiency of meadow is only possible on *C. arvensis* and *S. arvensis* because of the depletion of carbon storage. To deplete the storage, management of the meadow must be performed, and the number of cuts or grazing will determine the efficiency of the control of weeds. Bourdôt et al. (2011) report that mowing twice a year decrease more strongly the infestation, especially if the mowing is performed under the rain. This effect might be explained by the rotting of the stem through the wound. Meadow are also managed through grazing. *S. arvensis* does not handle the grazing and suppression of the weed is as effective as mowing, *S. arvensis* even present some good quality feed for livestock (Weill, 2005b). However, Canada thistle is more problematic. The shape of the leaves and the hard stem make the plant hard to graze. Livestock usually does not appreciate *C. arvensis* and the selection of the weed is therefore increasing the infestation. Pywell et al. (2010) yet report that grassland can be managed through grazing when *C. arvensis* is young enough and grazing density strong enough. To counter the effect of the low grazing on *C. arvensis* it is possible to mow locally the patches. Mowing must be executed at low storage point. Compensation point is hardly available in meadow, due to the poor recognition of the leaf stage but also because of the mowing process, which is too high above the floor to disturb the weed. Thus, *C. arvensis* and *S. arvensis* need to be mown just before the blooming, an energy consuming process of the weeds (Weill, 2018).

Having two to three years without crops can be financially hard for some farmers and some of them tried to have a shorter meadow or spring fallow to perform high competition on perennial weeds within one year only. However, this strategy is reported to be inefficient because of the low and short disturbance implemented on weeds (DRAAF, 2017). The period of spring fallow is also too late compared to nutrient cycle of perennial weeds, *C. arvensis* for example already filled back its storage in the roots.

(b) Cover crops

Cover crops are an effective soil conservation practice to improve soil quality, reduce runoff and water erosion, increase fertility of soil working as green manure and act as a competitor on weeds (Ramesh et al., 2019). The effect of cover crops is the same as the meadow: cover crops smother the soil and perennial weeds, creating an unfavourable environment for their growths. Weather will rule the efficiency of cover crops; maximizing the growth under favourable conditions will enable right smothering of weeds. Cover crops are not a curative method as meadow can be. Cover crops only keep threat at a low level between two crop productions. Cover crops are only efficient on *C. arvensis* and *S. arvensis*. *E. repens* is not regulated by cover crops and can grow in the cover crops without any difficulty (Soon, Darwent, 1998). Species chosen in the cover crops qualify the efficiency of the method. They need to have high ground cover and a high growth speed. Thomsen et al. (2015) reports red clover and white clover to be efficient as cover crops on Canada thistle.

Table 3: Crop planning and rotation as control methods for C. arvense, S. arvensis and E. repens

	Cirsium arvense	Sonchus arvensis	Elytrigia repens
Meadow	<ul style="list-style-type: none"> • 2 years long minimum • Mown twice a year at least, relatively close to compensation point • Fast growth and smothering species • Hardly grazed • Curative method 	<ul style="list-style-type: none"> • 2 years long minimum • Mown twice a year at least, relatively close to compensation point • Fast growth and smothering species • Fast come back of perennial sowthistle (after 2 years already) • Good feeding substitute for livestock • Curative method 	<ul style="list-style-type: none"> • Inefficient
Cover crops	<ul style="list-style-type: none"> • Maintain pressure on weed • Fast growth and smothering species • Moderately efficient 	<ul style="list-style-type: none"> • Maintain pressure on weed • Fast growth and smothering species • Moderately efficient 	<ul style="list-style-type: none"> • Inefficient
Competitive crops	<ul style="list-style-type: none"> • Fast growth and smothering species • Early spring sowing can be problematic • Late spring and autumn sowings are more competitive • Increased sowing rate crops are more competitive 		

Cover crops, as other methods, are a complement to other control methods. Stubble tillage followed by cover crops are a significant way to maintain high pressure and competition on perennial weeds. Cover crops are mainly used to maintain the competitiveness of the agroecosystem towards the weeds, thwarting perennial weeds' regrowth. Cover crops compared to stubble tillage remain poorly efficient and too short to reduce infestation (Brandsæter et al., 2012).

(c) Choice of competitive crops in the rotation

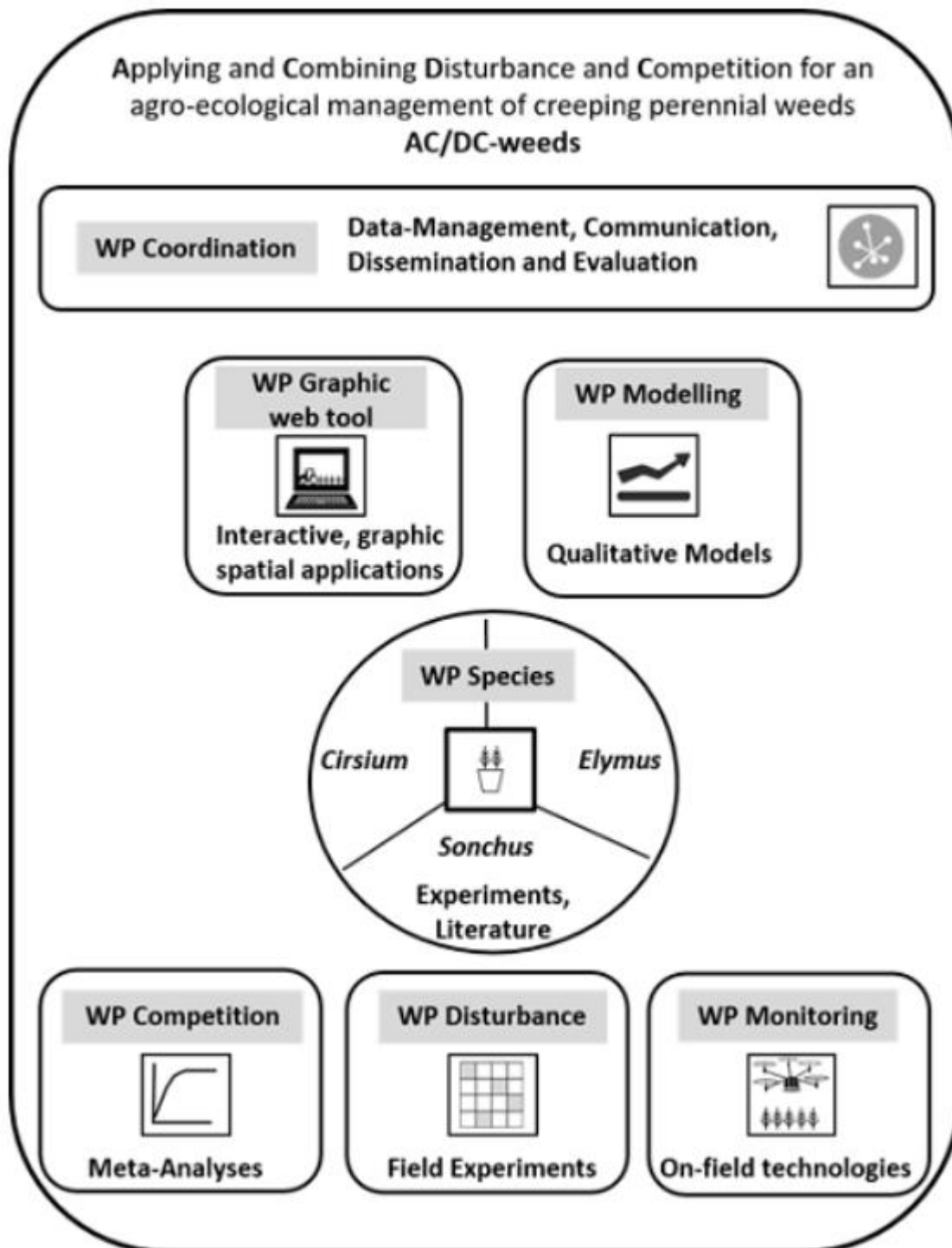
To maintain a low level of threat from perennial weeds, it is relevant to encourage the use of competitive crops. The competition of crops can be achieved through several means:

(i) the use of species or varieties bearing morphological or physiological competitive properties, (ii) the sowing date and (iii) the sowing rate. Species bearing morphological properties must have a high coverage percentage of the ground. According to a study followed by Agridea (Tamarcaz, 2019) from 2000 to 2017, long straw cereal, hemp, rapeseed oil and oat have the highest competition towards perennial weeds. These crops present a large shape, and a fast growth allowing them to compete and overrun *C. arvensis*, *S. arvensis* and *E. repens*. The morphology of the crop is important to reduce the light income to the floor; however, the speed of growth is not to be forgotten. For *S. arvensis*, only late growth plant that are sown in spring allow the weed to grow and be a problem in the crop (Vanhala et al., 2006). Species bearing physiological properties such as allelopathy can also be used to control or compete with *C. arvensis*, *S. arvensis* and *E. repens*. Allelopathy is a biological process when a plant releases chemical compounds that can affect other plants (Karlen et al., 1994). Buckwheat (*Fagopyrum esculentum*) is for example use as cover crops or normal crop production and maintain low threat level for perennial weeds.

The most sensitive crops to perennial weeds infestation are species that present a late growth in spring (DRAAF, 2017). Establishment of *C. arvensis*, *S. arvensis* and *E. repens* starts early in spring, with emergence time around beginning of March. In order to compete with perennial weeds, crops must develop earlier and faster. When crop is sown in autumn, such as winter cereals, the establishment of the crop is far greater than perennial weeds and competition is often bearable for the crop. However, when crops are sown in early spring, the growth must be relatively fast compared to perennial weeds to expect an overrun. For spring crops, it is advised to sow early only fast growth species. For late growth species, it is advised to wait for higher temperature by the end of spring in order to have a fast growth of the crop (Wedryk, Cardina, 2012). Late sowing date is often linked with higher number of tillage in spring, which enable a greater control of the weeds. Sowing date does not seem to affect the infestation of *E. repens*.

To smother the perennial weeds, it is possible to increase the density of crops to maximise the ground coverage. Pilipavicius et al. (2011) observed that *C. arvensis* and *S. arvensis* proportionally declined when they increased the sowing rates of spring barley (*Hordeum vulgare* (L.)). However, this increase of seed rate did not increase the number of stands and hence did not increase the yield of barley. This can be explained by higher competition between barley stands. *E. repens* is also sensitive to seeding rate increase. A decrease of seeding rate of wheat (*Triticum aestivum* (L.)) and barley (*Hordeum vulgare* (L.)) increased *E. repens* infestation of 25% (Williams, 1977). The increase of density is not always preferred to increase the competition of crops. Some systems heighten the distance between rows to implement an inter-row hoeing. Therefore, some crops have a poor density competition to weeds but are often weeded to increase the mechanical control (Weill, 2005a). Soybean (*Glycine max* (L.) Merrill) for example, have a poor competition at the early stages of its development, worsen by a wide row sowing. Yet, this crop is competitive to maintain perennial weeds at low threat level thanks to its repeatedly inter-row hoeing. The crops become later thick with large leaves and inhibit light for the perennial weeds. Crop planning and rotation methods are summarized in Table 3.

Figure 1: Organisation chart of AC/DC-weeds project, Work Package organisation



(WP= Work package)

2. Context Project AC/DC-weeds

This study is part of the European AC/DC-weeds project (Applying and Combining Disturbance and Competition for an agro-ecological management of creeping perennial weeds). The objective of the AC/DC-weeds Project is to implement a more efficient and better quality agro-ecological management against creeping perennial weeds in arable crops. The target species are the three most problematic perennial weeds in arable crops in Central and Northern Europe (*Elytrigia repens* L. Gould, *Cirsium arvense* L. Scop. and *Sonchus arvensis* L.). The aim of this project is to reduce ploughing in organic and conventional agriculture and to replace glyphosate in the latter system.

The AC/DC-weeds project consists of seven Work Packages including the Work Package Modelling (Fig. 1). The Work Package Modelling aims to produce models that integrate agro-ecological management decisions for perennial weeds. Models have been developed to predict the emergence of weed seeds stored in the soil as a function of climatic conditions (Masin et al., 2012). Modelling weed emergence as a function of tillage is also a very interesting second pillar (Spokas et al., 2007). This model helps us understand which soil actions have delayed weed emergence in order to limit competition with the crop during germination. However, these two models only take into account annual or biennial weeds. Perennial weeds function differently in terms of germination, spread and maintenance in the soil. As a result of reduced inputs and reduced tillage, a strong return of weeds is observed, particularly perennial weeds (Trichard et al., 2013). Modelling tools are therefore needed to help farmers understand the intervention periods and tools to be recommended, as well as the cropping systems that can be implemented to facilitate perennial weed control.

In order to respond to the glyphosate withdrawal planned in the European Union on 01/01/2021, and the de-intensification of deep ploughing one of the ways of research is modelling in order to explore the different systems and soil management favourable to the control of weeds currently managed by this herbicide.

A software is currently used as a Decision Support System (DSS) for agricultural advisers and farmers for the management of thistle in field crops: Odera-Vivaces. AgroTransfert developed Odera-Vivaces in collaboration with researchers, advisors and farmers in 2016 (Favrelière et al., 2016). Matrix models are also developed (Sosnová et al., 2014) using the biennial species *Rorippa palustris* as an example to model its regrowth from the roots. Not all disturbances during the seasons will have the same impact on the survival of the weed. The ability to germinate and regrow from underground organs was also modelled (Taab et al., 2018). To date, no model considers weather, agricultural practices and the environment in the management of perennial weeds. It is therefore important to produce a predictive model that mobilizes these different parameters in order to propose a systemic approach to perennial weed control.

3. Context IPSIM Modelling

Injury Profile SIMulator (IPSIM) is a modelling platform. This platform was designed to build qualitative models in order to predict injury profiles in agroecosystem, as a function of cultural practices, soil, weather and environment of the field (Aubertot, Robin, 2013). This platform has numerous purposes and can be used as (i) an innovative tool to design new agroecosystems, (ii) a diagnosis tool for farmers or technicians such as DSS or as (iii) an educational platform. IPSIM can be used on the modelling of one unique pest on crop (Robin et al., 2013) or on several pests in a horizontal integration (Aubertot, Robin, 2013).

This modelling approach aims to design an aggregative hierarchical tree of attributes to integrate vertically methods of control, weather and environment of the field. Existing models (qualitative or not) are often taking one dimension of the agroecosystem such as weather (e.g. Sosnová et al., 2014) or practices (e.g. Odera-Vivaces) into account. The originality of the

IPSIM modelling platform is to apprehend the whole agroecosystem and to produce a schematic representation of it. This approach is particularly relevant for perennial weeds which developments are impacted not only by weather and soil, but also by the cultural practices or disturbances that occur during previous, between and current crop production. This approach allows farmers and technicians to identify the causes of an increase of weed infestation or the consequences of the use of specific farming methods on future weed infestation. IPSIM allows models to integrate the effect of multiple cropping practices (e.g. tillage, inter-row hoeing, sowing date and rate, rotation ...), that can help assist the modelling work package in AC/DC-weeds project.

Figure 2: Attribute tree of IPSIM-Cirsium

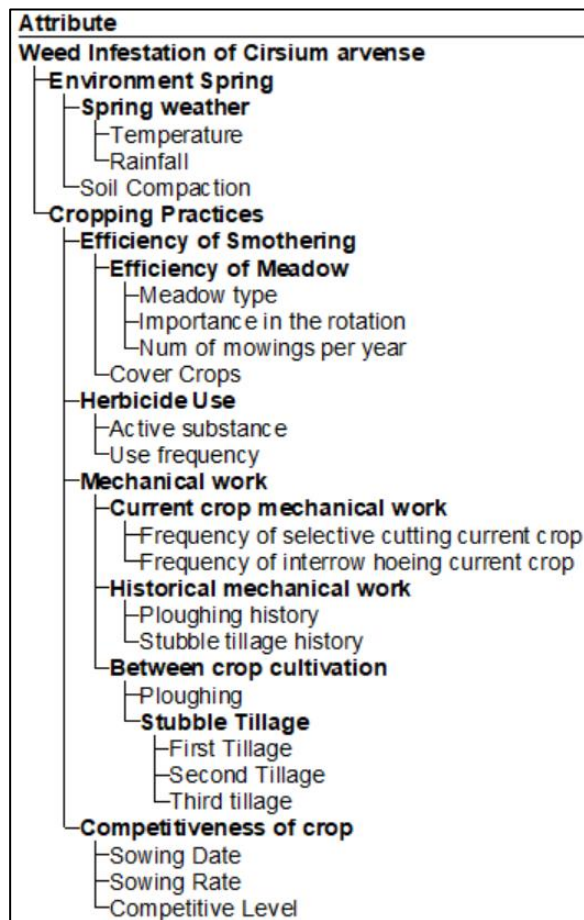


Figure 4: Attribute tree of IPSIM-Sonchus

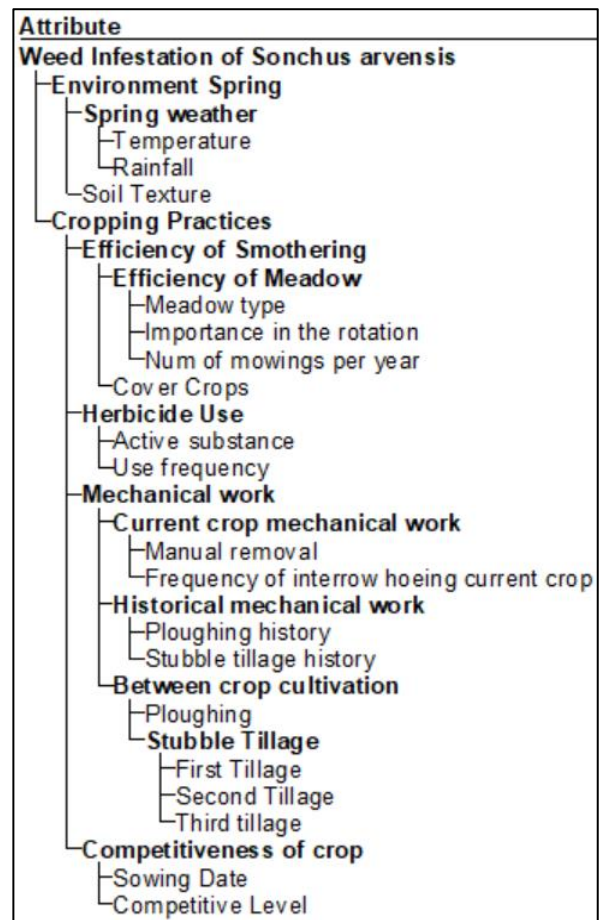
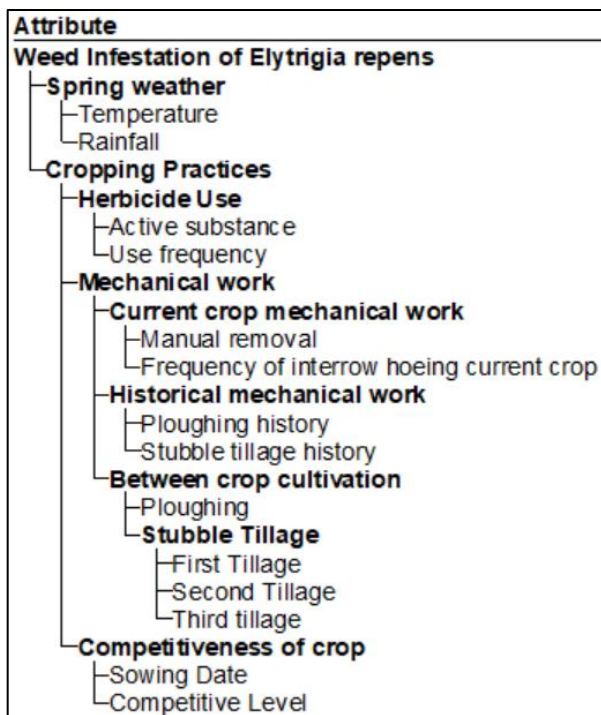


Figure 3: Attribute tree of IPSIM-Elytrigia



II. Materials and Methods

A. General approach of DEX method

For the conception of the three models relying on the IPSIM platform, the DEX method was used. The DEX method, implemented by the software DEXi (Bohanec, 2003) is a method, which supports qualitative hierarchical attribute aggregation. The strength of the DEX method is to enable multi-attribute decision for the modelling. The principle of the method is to subdivide a large problem into smaller and less complex subproblems. This method is perfectly applicable on weed infestation modelling, by taking into account numerous subproblems such as weather, crop practices or soil. Originally used for Decision Support System and evaluation of these decisions, DEX method was used to model complex agroecosystem in the understanding of wheat disease (Robin et al., 2013). DEX method allows the user to implement attributes, their scales and their weights to aggregate them later into a larger representation of the agroecosystem.

B. Design of *Cirsium*, *Sonchus* and *Elytrigia* models

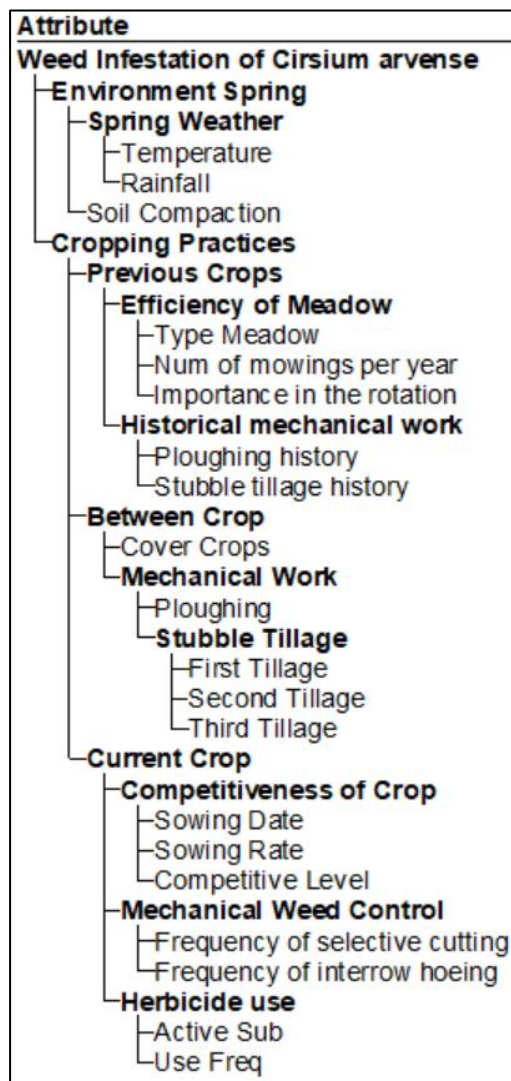
1. Definition of attributes

For the designing of input attributes, IPSIM-*Cirsium*, IPSIM-*Sonchus* and IPSIM-*Elytrigia* aim at representing the growth environment of the weeds in spring, and the history of cropping practices on a larger scale, including previous years (four years earlier than the crop production year). The choice to only consider the weather and environment in spring was to consider the growth conditions for the weeds and qualify their growths according to their specific climatic requirements. IPSIM-*Cirsium*, IPSIM-*Sonchus* and IPSIM-*Elytrigia* are three static deterministic models.

All three models' hierarchies are presented in Figure 2, 3 and 4 and represents the distribution of all the factors considered in the growth or the control of the perennial weeds. Terminal attributes also called input or basic attributes are the input variables that the user will specify while using the models and the final aggregated attribute is the output of the model, here the weed infestation. Between the input and output attributes, the models are composed of nodes that are aggregated attributes (**Bold** in Fig. 2, 3 and 4), representing different categories of control method or growth factors: *Environment* with weather and soil component, *Cropping practices* with different methods of control. Every attribute used in the models is a qualitative variable. Attributes can be ordinal or nominal and takes discrete values, such as words instead of numbers (e.g. "low, medium, high" for ordinal variables and "ploughing, stubble tillage, no-till").

IPSIM-*Cirsium*, IPSIM-*Sonchus* and IPSIM-*Elytrigia* have respectively 33 attributes (20 basic attributes and 13 aggregates), 32 attributes (19 basic attributes and 13 aggregates) and 24 attributes (14 basic attributes and 10 aggregates). During the process of the construction, some attributes were chosen to be omitted because their weights on the final weed infestation were too small to be relevant. For example, according to experts and literature, the leaf stage of the intervention for inter-row hoeing, selective cutting or stubble tillage were relay important to control weeds and have an efficient control. However, during the aggregation of all the attributes, the leaf stage input was overlooked in the construction and was sentenced 0 as global weight because of a numerous other basic attribute, aggregated on the same node. The choice of input attributes was first made by the literature presented in the first part of the memoire. This literature was built first thanks to the article bank from AC/DC-weeds

Figure 5: Hypothetical Attribute tree of IPSIM-Cirsium during the process of developing



library, collecting the data on *C. arvensis*, *S. arvensis* and *E. repens* from the past 50 years. Then, the literature was built according to a general pattern of keywords involving the three perennial weeds, the usual factors for growth (e.g. Temperature, Rainfall, Soil, Relative Humidity, Photoperiod) and control methods (e.g. Competitive crops, Cover crops, Tillage, Cropping practices, ...). These researches were made on Google Scholar (scholar.google.com), databases accessible for INRAE agents (e.g. EconLit, Food Science Source, Web of Science, MEDLINE®, Saga Web, Scopus, TAIR) and free databases produced by INRAE (e.g. Agricola, ProDINRA, PubMed).

To help assess the main factors of control and development of *C. arvensis*, *S. arvensis* and *E. repens*, co-design workshops were organized: one with AC/DC-weeds members in April, two with French actors of the sector of weed control, especially perennial weeds (ANNEXE 2 and ANNEXE 3) respectively in April and July. The experts were chosen nationally from research institutes (e.g. INRAE, Arvalis, Terres Inovia, Acta, Chambres d'Agriculture, ...). These co-design workshops aimed at verifying the correct input attribute choices and to identify new attributes that could have been omitted.

To aggregate the attributes in the weed infestation models, there are two possibilities. In the first one, *Environment* and *Cropping Practices* are chosen to be aggregative nodes and then control method factors are aggregated per year (i.e. *Previous Crop*, *Between Crop* and *Current Crop*) to form the greater node that is *Cropping Practices* (Figure 5). Yet, this method shows a weak spot: control methods are overlooked in the mass of all the practices. For example, *Herbicide Use* in the first method is completely overlooked and results in 4% of global weight to qualify the weed infestation in IPSIM-Cirsium. Having such a low weight for a high-performance control is inadequate. However, the second method is more suitable. The second method starts with the discerning of growth factors in the *Environment* and control methods in *Cropping Practices* as in the first method. But this time, control methods are organized per methods (i.e. *Smothering Effect*, *Herbicide Use*, *Mechanical Work* and *Competitiveness of Crop*) (Figure 2). This aggregation allows the user to distinguish methods of control in an easy way and to give adequate weight to each method according to their performances.

The first sub-trees *Environment* describes the biological conditions required for the growth of perennial weeds:

- (i) *Spring weather*: Spring weather is determined regarding three months that will best qualify the growth of *C. arvensis*, *S. arvensis* and *E. repens*: March, April and May. *Spring weather* is defined by Temperature and by Rainfall during March, April and May.
- (ii) *Soil compaction* or *Soil texture*: Soil components (respectively compaction for *C. arvensis* and texture for *S. arvensis*) describe the growth or limitation of Canada thistle and perennial sowthistle. Soil compaction seems to favour Canada thistle's growth (Hausman et al., 2010 ; Brandsæter et al., 2011 ; Hochstrasse et al., 2012) and perennial sowthistle has a superior growth in rich clay soil (Weill, 2005b).

The second sub-trees describe the *Cropping Practices* implemented to control or prevent weed infestations:

- (i) *Smothering Effect*: Meadow implement in the rotation helps reduce *C. arvensis* and *S. arvensis* (2005a ; 2005b). The meadow is qualified by the species used in the ley (*Meadow type*), and efficiency is greater when the ley is quickly smothering and has a high regrowth potential after every cutting. Meadow is also a method that functions on the long term and needs to be implemented several years and return often in the rotation to prove to be an efficient control method (*Importance in the rotation*). The number of cuttings per year is prevalent to qualify the efficiency of meadow (*Num of mowings per year*) and discriminates the ley performed in dry summer conditions and wet summer conditions. Wet conditions enable the meadow to be cut more than three times

Figure 6: Attribute scales of IPSIM-Cirsium

Attribute	Scale
Weed Infestation of Cirsium arvense	Very high; High; Neutral; Low; Very low
Environment Spring	Unfavourable spring environment; Moderately favourable spring environment; Favourable spring environment
Spring weather	Unfavourable spring weather; Moderately favourable spring weather; Favourable spring weather
Temperature	High temperature; Average temperature; Low Temperature
Rainfall	High amount of rain; Average amount of rain; Low amount of rain
Soil Compaction	High compaction; Moderate compaction; Low compaction
Cropping Practices	Inefficient practices; Moderately efficient practices; Highly efficient practices
Efficiency of Smothering	Inefficient rotation; Moderately rotation; Efficient rotation
Efficiency of Meadow	Low efficiency of meadow; Moderate efficiency of meadow; High efficiency of meadow
Meadow type	Unfavorable meadow type; Moderately favorable meadow type; Highly favorable meadow type
Importance in the rotation	Minor; Neutral; Major
Num of mowings per year	Low; Neutral; High
Cover Crops	Unfavourable cover; Moderately favourable cover; Favourable cover
Herbicide Use	Inefficient herbicide use; Moderately efficient herbicide use; Efficient herbicide use
Active substance	Unfavourable active substance; Favourable active substance
Use frequency	Low; Moderate; High
Mechanical work	Inefficient mechanical work; Moderately efficient mechanical work; Efficient mechanical work
Current crop mechanical work	Inefficient current crop practices; Moderately efficient current crop practices; Efficient current crop practices
Frequency of selective cutting current crop	unsatisfying num of repetition; neutral; satisfying num of repetition
Frequency of interrow hoeing current crop	unsatisfying num of repetition; neutral; satisfying num of repetition
Historical mechanical work	Inefficient previous cropping practices; Moderately efficient previous cropping practices; Efficient previous cropping practices
Ploughing history	Low intensity; Average intensity; High intensity
Stubble tillage history	Low intensity; Average intensity; High intensity
Between crop cultivation	Inefficient mechanical work; Moderately efficient mechanical work; Efficient mechanical work
Ploughing	No; Yes
Stubble Tillage	Inefficient stubble tillage; Moderately efficient stubble tillage; Efficient stubble tillage
First Tillage	Inefficient first tillage; Moderately efficient first tillage; Efficient first tillage
Second Tillage	Inefficient second tillage; Moderately efficient second tillage; Efficient second tillage
Third tillage	Inefficient third tillage; Moderately efficient third tillage; Efficient third tillage
Competitiveness of crop	Low competitiveness; Moderate competitiveness; High competitiveness
Sowing Date	Spring Early; Spring Normal; Spring Late or Autumn
Sowing Rate	<Regional recommendation; Regional recommendation; >Regional recommendation
Competitive Level	Open canopy; Moderately closed canopy; Closed canopy

Figure 7: Attribute scales of IPSIM-Sonchus

Attribute	Scale
Weed Infestation of Sonchus arvensis	Very high; High; Neutral; Low; Very low
Environment Spring	Unfavourable spring environment; Moderately favourable spring environment; Favourable spring environment
Spring weather	Unfavourable spring weather; Moderately favourable spring weather; Favourable spring weather
Temperature	High temperature; Average temperature; Low Temperature
Rainfall	High amount of rain; Average amount of rain; Low amount of rain
Soil Texture	High quality of soil for Sonchus; Moderate quality of soil for Sonchus; Low quality of soil for Sonchus
Cropping Practices	Inefficient practices; Moderately efficient practices; Highly efficient practices
Efficiency of Smothering	Inefficient rotation; Moderately rotation; Efficient rotation
Efficiency of Meadow	Low efficiency of meadow; Moderate efficiency of meadow; High efficiency of meadow
Meadow type	Unfavorable meadow type; Moderately favorable meadow type; Highly favorable meadow type
Importance in the rotation	Minor; Neutral; Major
Num of mowings per year	Low; Neutral; High
Cover Crops	Unfavourable cover; Moderately favourable cover; Favourable cover
Herbicide Use	Inefficient herbicide use; Moderately efficient herbicide use; Efficient herbicide use
Active substance	Unfavourable active substance; Favourable active substance
Use frequency	Low; Moderate; High
Mechanical work	Inefficient mechanical work; Moderately efficient mechanical work; Efficient mechanical work
Current crop mechanical work	Inefficient current crop practices; Moderately efficient current crop practices; Efficient current crop practices
Manual removal	No; Yes
Frequency of interrow hoeing current crop	unsatisfying num of repetition; neutral; satisfying num of repetition
Historical mechanical work	Inefficient previous cropping practices; Moderately efficient previous cropping practices; Efficient previous cropping practices
Ploughing history	Low intensity; Average intensity; High intensity
Stubble tillage history	Low intensity; Average intensity; High intensity
Between crop cultivation	Inefficient mechanical work; Moderately efficient mechanical work; Efficient mechanical work
Ploughing	No; Yes
Stubble Tillage	Inefficient stubble tillage; Moderately efficient stubble tillage; Efficient stubble tillage
First Tillage	Inefficient first tillage; Moderately efficient first tillage; Efficient first tillage
Second Tillage	Inefficient second tillage; Moderately efficient second tillage; Efficient second tillage
Third tillage	Inefficient third tillage; Moderately efficient third tillage; Efficient third tillage
Competitiveness of crop	Low competitiveness; Moderate competitiveness; High competitiveness
Sowing Date	Spring Early; Spring Normal; Spring Late or Autumn
Competitive Level	Open canopy; Moderately closed canopy; Closed canopy

Figure 8: Attribute scales of IPSIM-Elytrigia

Attribute	Scale
Weed Infestation of Elytrigia repens	Very high; High; Neutral; Low; Very low
Spring weather	Unfavourable spring weather; Moderately favourable spring weather; Favourable spring weather
Temperature	High temperature; Average temperature; Low Temperature
Rainfall	High amount of rain; Average amount of rain; Low amount of rain
Cropping Practices	Inefficient practices; Moderately efficient practices; Highly efficient practices
Herbicide Use	Inefficient herbicide use; Moderately efficient herbicide use; Efficient herbicide use
Active substance	Unfavourable active substance; Favourable active substance
Use frequency	Low; Moderate; High
Mechanical work	Inefficient mechanical work; Moderately efficient mechanical work; Efficient mechanical work
Current crop mechanical work	Inefficient current crop practices; Moderately efficient current crop practices; Efficient current crop practices
Manual removal	No; Yes
Frequency of interrow hoeing current crop	unsatisfying num of repetition; neutral; satisfying num of repetition
Historical mechanical work	Inefficient previous cropping practices; Moderately efficient previous cropping practices; Efficient previous cropping practices
Ploughing history	Low intensity; Average intensity; High intensity
Stubble tillage history	Low intensity; Average intensity; High intensity
Between crop cultivation	Inefficient mechanical work; Moderately efficient mechanical work; Efficient mechanical work
Ploughing	No; Yes
Stubble Tillage	Inefficient stubble tillage; Moderately efficient stubble tillage; Efficient stubble tillage
First Tillage	Inefficient first tillage; Moderately efficient first tillage; Efficient first tillage
Second Tillage	Inefficient second tillage; Moderately efficient second tillage; Efficient second tillage
Third tillage	Inefficient third tillage; Moderately efficient third tillage; Efficient third tillage
Competitiveness of crop	Low competitiveness; Moderate competitiveness; High competitiveness
Sowing Date	Spring Early; Spring Normal; Spring Late or Autumn
Competitive Level	Open canopy; Moderately closed canopy; Closed canopy

per year, which contributes to a great reduction of Canada thistle and perennial sowthistle (Weill, 2005a ; 2005b ; 2018). Cover crops help reduce or maintain the threat of weed infestation at low level for Canada thistle and perennial sowthistle only (Thomsen et al., 2015).

- (ii) *Herbicide use*. Herbicides are used as a curative method and the correct effective *Active substances* need to be use several years (*Use frequency*) to be efficient (Ludovic Bonin, 2020, personal communication). Registered maximum doses must be used to have a proper control of perennial weeds (Tavaziva et al., 2019). *Herbicide use* is considered to be at registered maximum dose, with correct equipment and climatic requirements in the sake of simplicity of the models.
- (iii) *Mechanical work*. Curative method such as *Ploughing* or *Stubble tillage* qualify the mechanical control of *C. arvense*, *S. arvensis* and *E. repens* using either an exhaustion of the roots or an extraction of the rhizomes (Hamdoun, 1972 ; Boström, Fogelfors, 1999). Historical uses of ploughing and stubble tillage are also considered to qualify the mechanical control (Alain Rodriguez, 2020, personal communication). Backup control methods such as *Inter-row hoeing* and *Selective cutting* are also part of the *Mechanical work*. These two methods are only efficient on Canada thistle and perennial sowthistle.
- (iv) *Competitiveness of crop*. To overrun *C. arvense*, *S. arvensis* and *E. repens*, production crops must be more competitive than the weeds. To reach this ideal, the choice of competitive crops is central, especially regarding their growth speeds and cover percentage of the floor. *C. arvense* and *S. arvensis* can be overrun also by delaying the sowing of spring crops to put the crops in optimal growth conditions (*Sowing date*) (Weill, 2005a ; 2005b ; 2018 ; Wedryk, Cardina, 2012 ; Thomsen et al., 2015 ; Tamarcaz, 2019). The competitiveness of crop against *C. arvense*, *S. arvensis* and *E. repens* is also increased with the *Sowing rate* (Williams, 1977 ; Mohler et al., 2001 ; Pilipavicius et al., 2011 ; Wedryk, Cardina, 2012 ; Bourdôt et al., 2015 ; Roy, 2017).

2. Definition of attribute scale

To each attribute is attached a scale. IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia only take maximum three levels per scale for aggregated attributes and input attributes (Figure 6, 7 and 8). Output attribute scales of the models are composed of five levels (i.e. Very low, Low, Neutral, High, Very high). The chosen values are set for each attribute and are represented by words.

Scales usually represent three levels (i.e. Unfavourable in red, Moderately Favourable in grey and Favourable in green, Fig. 6, 7 and 8), the scales representing the quality or efficiency of each methods or growth factors to control and limit the development of *C. arvense*, *S. arvensis* and *E. repens*, “Favourable” being the highest efficiency level and “Unfavourable” the lowest level to control the weed. Basic attributes are sometimes only composed of two levels. For example, *Active substance* used for the herbicides is either Favourable for the control of the weed or Unfavourable for the control of the weed. Here two levels are enough, the herbicide being either efficient or not on *C. arvense*, *S. arvensis* or *E. repens*.

Some scales are dependent of a peculiar context, different to each field and crop. For example, the *Sowing date* is determined by the regional recommendation: the same sowing date can be considered late in France while being considered early in Denmark. *Sowing rate* is also dependent of the regional context and are discriminated on a three levels-scale: Inferior as regional recommendation, Regional recommendation, Superior as regional recommendation.

Table 4: Converter for Tools for Stubble Tillage Attribute of IPSIM-Cirsium

Tools	Scale Value
subsoiler	Moderately favourable tool
subsoiler goosefoot	Favourable tool
tiller	Moderately favourable tool
tiller goosefoot	Favourable tool
tiller wings	Favourable tool
cultivator	Moderately favourable tool
cultivator goosefoot	Favourable tool
subsoiler wings	Favourable tool
loosener	Moderately favourable tool
loosener goosefoot	Favourable tool
loosener wings	Favourable tool
chisel spikes	Moderately favourable tool
s-tines	Moderately favourable tool
chisel goosefoot	Favourable tool
chisel wings	Favourable tool
mouldboard plough	Favourable tool
plough	Favourable tool
disc plough	Moderately favourable tool
hoe	Moderately favourable tool
rotary hoe	Moderately favourable tool
rotary harrow	Unfavourable tool
spike harrow	Unfavourable tool
cover crop	Unfavourable tool
rollers	Unfavourable tool
rototiller	Unfavourable tool
no till	Unfavourable tool

Figure 9: Aggregative table of Environment Spring of IPSIM-Cirsium

	Spring weather	Soil Compaction	Environment Spring
1	Unfavourable spring weather	High compaction	Unfavourable spring environment
2	Unfavourable spring weather	Moderate compaction	Unfavourable spring environment
3	Unfavourable spring weather	Low compaction	Moderately favourable spring environment
4	Moderately favourable spring weather	High compaction	Unfavourable spring environment
5	Moderately favourable spring weather	Moderate compaction	Moderately favourable spring environment
6	Moderately favourable spring weather	Low compaction	Favourable spring environment
7	Favourable spring weather	High compaction	Unfavourable spring environment
8	Favourable spring weather	Moderate compaction	Favourable spring environment
9	Favourable spring weather	Low compaction	Favourable spring environment

Weather scale values are determined according to a threshold for the weed to grow. Here, it is hypothesised that *C. arvensis*, *S. arvensis* and *E. repens* have the same biology wherever the model is used. Therefore, their answers to Temperature and Rainfall will remain the same and a threshold can be designed to qualify their growths. *Temperature* and *Rainfall* scales follow the same pattern (i.e. High, Neutral and Low; *High* being detrimental for the control of the weed, and *Low* being beneficial for the control of the weed). The aggregated weather attribute scale is then qualified as Unfavourable, Moderately favourable, and Favourable.

The choice of the scales is either nominal or ordinal. Quantitative variables are translated into qualitative variables, and qualitative variables estimated by user are directly used. For several scales, input variables need a convertor to qualify their action on the weed. For example, the tools (e.g. Covercrop, Chisel plough, ...) used for *Stubble tillage* are described either as Unfavourable, Moderately favourable, or Favourable for the control of the weed (Table 4). These convertors are designed through Excel to assist the user in entering the nominal values and returning nominal variables used in the scale of the models. The values of the scales were designed with the help of technical publications, data from experiments or expert knowledge.

3. Definition of aggregative tables

Once input attributes are validated by experts, aggregative tables must be constructed to apprehend every decision and aggregation of attributes. Several attributes are aggregated together, and decision rules must be designed. These rules follow the function *if-then* assembled to build a table with all the values that the aggregative attribute can take. The rules are also called Utility function in the DEXi software and needs to be implemented row by row by the developer of the model. Each aggregative table takes the values of the immediate descending attributes in the model. The designing of aggregative tables allows the model to calculate the final output attribute and in our case the weed infestation from input attribute values.

In the Figure 9, an example of an aggregative table for the *Environment spring* shows nine rules for the decision of the ordinal values of the environment in spring. These possible combinations are the result of the compaction of soil and the weather in spring. *Soil Compaction* has three levels and *Spring Weather* has three levels, and their combinations make nine aggregation possibilities. Here, a “Moderately favourable spring weather” aggregated with a “High compaction [of soil]” result in an “Unfavourable spring environment” for the control of *C. arvensis*.

This step of model designing takes time to be correctly implemented and needs to be checked by experts for its accurateness. For several attributes, the aggregative tables were hard to define because of the lack of consensus in the literature but also for the lack of knowledge about the functioning of some process for Canada thistle, perennial sowthistle and quackgrass. For example, the aggregation of *Cropping practices* represents 81 attributes aggregated together, representing 81 decision rules. In the *if-then* process of choosing the scale of *Cropping practices* according to the aggregation of values of different control methods, the developer of the model needs to acknowledge the efficiency of each method, their interactions and compare them between each other's. This individual process is therefore hard to validate by experts since experts will have their own appreciation of the efficiency of each control method. Only literature could enlighten the process but is often not consensual and does not regroup a set of agriculture practices in a same experiment, which can lead to subjectivity of choice.

The aggregative tables of IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia have been designed according to literature and expert's knowledge, summarized in ANNEXE 4, ANNEXE 5 and ANNEXE 6 respectively.

Figure 10: Attribute weights, normalized or not, of IPSIM-Cirsium

Attribute	Local	Global	Loc.norm.	Glob.norm.
Weed Infestation of Cirsium arvense				
Environment Spring	50	50	50	50
Spring weather	37	19	37	19
Temperature	50	9	50	9
Rainfall	50	9	50	9
Soil Compaction	63	31	63	31
Cropping Practices	50	50	50	50
Efficiency of Smothering	17	9	17	9
Efficiency of Meadow	63	5	63	5
Meadow type	25	1	25	1
Importance in the rotation	38	2	38	2
Num of mowings per year	38	2	38	2
Cover Crops	38	3	37	3
Herbicide Use	33	16	33	16
Active substance	67	11	57	9
Use frequency	33	5	43	7
Mechanical work	34	17	34	17
Current crop mechanical work	24	4	24	4
Frequency of selective cutting current crop	33	1	33	1
Frequency of interrow hoeing current crop	67	3	67	3
Historical mechanical work	36	6	36	6
Ploughing history	43	3	43	3
Stubble tillage history	57	3	57	3
Between crop cultivation	40	7	40	7
Ploughing	47	3	37	3
Stubble Tillage	53	4	63	4
First Tillage	33	1	33	1
Second Tillage	33	1	33	1
Third tillage	33	1	33	1
Competitiveness of crop	16	8	16	8
Sowing Date	15	1	15	1
Sowing Rate	35	3	35	3
Competitive Level	50	4	50	4

Figure 11: Attribute weights, normalized or not, of IPSIM-Sonchus

Attribute	Local	Global	Loc.norm.	Glob.norm.
Weed Infestation of Sonchus arvensis				
Environment Spring	33	33	33	33
Spring weather	57	19	57	19
Temperature	50	10	50	10
Rainfall	50	10	50	10
Soil Texture	43	14	43	14
Cropping Practices	67	67	67	67
Efficiency of Smothering	15	10	15	10
Efficiency of Meadow	63	6	63	6
Meadow type	25	2	25	2
Importance in the rotation	38	2	38	2
Num of mowings per year	38	2	38	2
Cover Crops	38	4	37	4
Herbicide Use	33	22	33	22
Active substance	67	15	57	13
Use frequency	33	7	43	9
Mechanical work	32	21	32	21
Current crop mechanical work	24	5	24	5
Manual removal	47	2	37	2
Frequency of interrow hoeing current crop	53	3	63	3
Historical mechanical work	36	8	36	8
Ploughing history	57	4	57	4
Stubble tillage history	43	3	43	3
Between crop cultivation	40	8	40	8
Ploughing	67	6	57	5
Stubble Tillage	33	3	43	4
First Tillage	33	1	33	1
Second Tillage	33	1	33	1
Third tillage	33	1	33	1
Competitiveness of crop	20	13	20	13
Sowing Date	38	5	38	5
Competitive Level	62	8	63	8

4. Definition of attribute weights

Each input or aggregated attribute has weight which characterized its importance. The higher the weight, the more influential the attribute (Bohanec et al., 2007). DEXi automatically calculates four distinctive weights: local and global weights, normalized or not (Bohanec, 2020). Normalized weights consider the number of values for each scales of each attributes, which help improve the quality of the model for the developer. Local weights describe the relative influence of attributes in an aggregation, while global weights describe the influence of an attribute in regard to the rest of the attributes composing the model. Weights of IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia are represented in Figure 10, 11 and 12, respectively.

Here weights were not defined directly by the developer but are the mirror of the decisions taken during the construction of aggregative tables (it is possible to design aggregative tables directly by setting local weights, however, particular aggregation are treated as general cases). All the aggregative tables set weights of attributes used in the aggregation, until the final aggregation: the output attribute.

For the sake of simplicity of the models, few attributes that had a global weight of 0 were omitted (e.g. *Leaf stage of the weed during tillage*, *Weather during tillage*). These input attributes had little role on the final evaluation of the weed infestation.

5. DEXi's evaluations

Once all the attributes, basic and aggregated are completed, their scales filled out and the aggregative tables supplemented, the models can create a simulated version of weed infestation. This evaluation of the weed infestation is calculated by DEXi by compiling all aggregated attribute values following the qualitative variables of input attributes, the hierarchy designed to assemble the attributes, and the aggregative tables designed to aggregate attributes. The weed infestation of Canada thistle is evaluated in Figure 13 for two different systems: reduced tillage (*No-Till*) and intensive tillage (*Till*) as a theoretical example.

C. Evaluation of the predictive quality of models

The evaluation of the predictive quality of models will only be perform on IPSIM-Cirsium in the beginning, IPSIM-Sonchus and IPSIM-Elytrigia will be evaluated in a second time because of a lack of dataset for *Sonchus arvensis* and *Elytrigia repens* and a delay of expertise validation due to Covid-19 crisis.

1. Dataset

To assert the predictive quality of IPSIM-Cirsium, it is necessary to have a large window of conditions of field and weather to evaluate *Cirsium arvense* infestation. Having data in diversified conditions enables the model to be more robust and to validate the application of the model in any conditions. For a dataset to be used, it needs to fulfil all the input attribute or the maximum of them. Each input variables are either directly qualitative variables or quantitative and translated into qualitative variables. The translation of data is made according to convertors built thanks to Excel. Once the translation is done, and all the variables are qualitative ones, it is possible to use IPSIM model and to assess an evaluation of the weed infestation.

The dataset used here is composed of two set of data: one dataset from organic farmers in Gers, south of France (Régis Hélias, Arvalis, 2020, personal communication) and one from Dotnuva, Central Lithuania (Kadziene et al., 2020). The first one is a network of organic farmers with the study of different mechanical methods adapted to control *Cirsium*

Figure 12: Attribute weights, normalized or not, of IPSIM-Elytrigia

Attribute	Local	Global	Loc.norm.	Glob.norm.
Weed Infestation of Elytrigia repens				
Spring weather	50	50	50	50
Temperature	50	25	50	25
Rainfall	50	25	50	25
Cropping Practices	50	50	50	50
Herbicide Use	44	22	44	22
Active substance	67	15	57	13
Use frequency	33	7	43	9
Mechanical work	44	22	44	22
Current crop mechanical work	24	5	24	5
Manual removal	47	2	37	2
Frequency of interrow hoeing current crop	53	3	63	3
Historical mechanical work	36	8	36	8
Ploughing history	57	5	57	5
Stubble tillage history	43	3	43	3
Between crop cultivation	40	9	40	9
Ploughing	67	6	57	5
Stubble Tillage	33	3	43	4
First Tillage	33	1	33	1
Second Tillage	33	1	33	1
Third tillage	33	1	33	1
Competitiveness of crop	12	6	12	6
Sowing Date	38	2	38	2
Competitive Level	62	4	63	4

Figure 13: Evaluation of No-Till and Intensive Till with IPSIM-Cirsium

Option	No-Till	Intensive Till
. Weed Infestation of Cirsium arvense	Neutral	Very low
.. Environment Spring	Favourable spring environment	Favourable spring environment
... Spring weather	Favourable spring weather	Favourable spring weather
.... Temperature	Low Temperature	Low Temperature
.... Rainfall	Average amount of rain	Average amount of rain
... Soil Compaction	Moderate compaction	Moderate compaction
.. Cropping Practices	Inefficient practices	Highly efficient practices
... Efficiency of Smothering	Moderately rotation	Moderately rotation
.... Efficiency of Meadow	Moderate efficiency of meadow	Moderate efficiency of meadow
..... Meadow type	Highly favorable meadow type	Highly favorable meadow type
..... Importance in the rotation	Neutral	Neutral
..... Num of mowings per year	Neutral	Neutral
.... Cover Crops	Moderately favourable cover	Moderately favourable cover
... Herbicide Use	Inefficient herbicide use	Inefficient herbicide use
.... Active substance	Unfavourable active substance	Unfavourable active substance
.... Use frequency	Low	Low
.. Cropping Practices	Inefficient practices	Highly efficient practices
... Efficiency of Smothering	Moderately rotation	Moderately rotation
.... Efficiency of Meadow	Moderate efficiency of meadow	Moderate efficiency of meadow
..... Meadow type	Highly favorable meadow type	Highly favorable meadow type
..... Importance in the rotation	Neutral	Neutral
..... Num of mowings per year	Neutral	Neutral
.... Cover Crops	Moderately favourable cover	Moderately favourable cover
... Herbicide Use	Inefficient herbicide use	Inefficient herbicide use
.... Active substance	Unfavourable active substance	Unfavourable active substance
.... Use frequency	Low	Low
... Mechanical work	Inefficient mechanical work	Efficient mechanical work
.... Current crop mechanical work	Efficient current crop practices	Inefficient current crop practices
..... Frequency of selective cutting current crop	satisfying num of repetition	unsatisfying num of repetition
..... Frequency of interrow hoeing current crop	satisfying num of repetition	unsatisfying num of repetition
... Historical mechanical work	Inefficient previous cropping practices	Efficient previous cropping practices
.... Ploughing history	Low intensity	High intensity
.... Stubble tillage history	Low intensity	High intensity
... Between crop cultivation	Inefficient mechanical work	Efficient mechanical work
.... Ploughing	No	Yes
.... Stubble Tillage	Inefficient stubble tillage	Efficient stubble tillage
..... First Tillage	Inefficient first tillage	Efficient first tillage
..... Second Tillage	Inefficient second tillage	Efficient second tillage
..... Third tillage	Inefficient third tillage	Efficient third tillage
... Competitiveness of crop	High competitiveness	High competitiveness
.... Sowing Date	Spring Normal	Spring Normal
.... Sowing Rate	Regional recommendation	Regional recommendation
.... Competitive Level	Closed canopy	Closed canopy

arvense in 2015-2016. The second one is a long-term study in 2013-2018 to assess the performance of cover crops and tillage. These datasets are relevant for the evaluation from their description of input attributes for weather, soil and cropping practices, on a long-term study to evaluate history of cropping practices. The level of infestation is observed from the number of shoots of *Cirsium arvense* per quadrat meter. A large variety of crops are described in the experiment with a large variety of cropping practices. The dataset combined 169 observed values in 30 different pedoclimates, and expressed 73%, 7%, 3%, 10% and 4% representing *Very low, Low, Neutral, High* and *Very high* level of threat, respectively.

For some data, the previous cropping practices were not observed (e.g. *Historical mechanical work*) and therefore the evaluation of the weed infestation was done for every level possible taken by *Ploughing history* and *Stubble tillage history* (i.e. 0, 1-2, 3-4 and 0-1, 2, 3-4 respectively). This method developed by Robin et al. (2013) enable the data not to be lost and ignored. The results are an acknowledgment of the worst-case scenario combining detrimental values of aggregated attributes (i.e. 0 for *Ploughing history* and 0-1 for *Stubble tillage history*) and the best-case scenario combining beneficial values of aggregated attributes (i.e. 3-4 for *Ploughing history* and 3-4 for *Stubble tillage history*). This method gives us a range of weed infestation for the evaluation of the predictive quality of IPSIM-Cirsium. Sometimes the global weight of the attribute is light enough not to affect the final infestation.

2. Statistical tools

The evaluation of the predictive quality is based on the comparison of the evaluated values from IPSIM-Cirsium and the observed values from the dataset. The model predicts the weed infestation in June, but the dataset observations are not always dating from June. The observed values in the dataset are quantitative values and were translated into five classes: *Very low, Low, Neutral, High, Very High* corresponding to 0-3 plants/m², 3-7 shoots/m², 7-15 shoots/m², 15 -30 shoots/m², more than 30 shoots/m² respectively.

To assess the predictive quality of IPSIM-Cirsium, a confusion matrix was built to compare the evaluated values from the model and the observed values from the dataset. The confusion matrix consists of a table layout: each row corresponds to observed values, each column to evaluated values. To obtain the predictive quality of the model, accuracy and quadratic weighted Cohen's kappa was used (Cohen, 1960). Accuracy is the proportion of correctly evaluated values among all the evaluated values. It is described as:

$$Accuracy = \frac{A}{N}$$

where A is the number of correctly assigned simulated values and N the number of simulated values. Cohen's kappa expresses a score of level of agreement between two annotators: the expressed value and the observed value. It can be described as:

$$\kappa \equiv \frac{p_o - p_e}{1 - p_e}$$

where p_o is the relative observed agreement among annotators and p_e is the expected agreement when both annotators are randomly chosen. Cohen's kappa lies between -1 and 1, 0 represents an agreement between observed and evaluated values when evaluated values are randomly chosen. According to Fleiss et al. (2003), kappa above 0.60 indicates an

adequate agreement. There are different ways to calculate Cohen's kappa: with linear weight or with quadratic weight. Linear weight method considers every class or disagreement equally important, with weights going from 1.00 to 0 linearly (e.g. with five classes: 1.00; 0.75; 0.50; 0.25; 0.00). While quadratic weight method considers the disagreement unequally important. Therefore, the weights here describe the closeness of agreement between categories with different importance (e.g. with five classes: 1.00; 0.94; 0.75; 0.43; 0.00). Here the difference between one class is small (0.94), thus it is more suitable for our biological model. Furthermore, quadratic weighed kappa can be interpreted as the variability of the model.

However, when the dataset is unbalanced, such as 79% of *Very low* weed infestation of Canada thistle, in our dataset, *Accuracy* cannot be considered as a reliable measure because the majority class gets an overoptimistic evaluation. Another test to verify the accuracy of the model is the F1-score. F1-score is calculated from the precision p of the model (number of correctly identified values divided by the number of equal evaluated values) and the recall r (the number of correctly evaluated results divided by the total number of evaluated values). F-measure is the harmonic mean of precision and recall of all class, calculated as:

$$F1 - score = \frac{\sum_{i=1}^N F_i = 2 * \frac{p_i * r_i}{p_i + r_i}}{N}$$

with N the number of class, F_i the F-measure for class i , p_i the precision of class i and r_i the recall for class i . Precision for class 1 and Recall for class 1 are described as:

$$p_1 = \frac{True\ Class1}{\sum Observed\ Class1} \quad \text{and} \quad r_1 = \frac{True\ Class1}{\sum Evaluated\ Class1}$$

with *True Class1* the number of correctly assigned evaluated values for class 1, *Observed Class1* the number of observed values for class 1, and *Evaluated Class1* the number of evaluated values for class 1.

These calculations were performed using RStudio Version 1.1.456 – © 2009-2018 RStudio, Inc.

Figure 14: Cohen's quadratic weighted kappa of IPSIM-Cirsium

	value	ASE	z	Pr(> z)
unweighted	0.2447	0.04841	5.055	4.310e-07
weighted	0.6359	0.05527	11.504	1.253e-30

weights:

	[,1]	[,2]	[,3]	[,4]	[,5]
[1,]	1.0000	0.9375	0.7500	0.4375	0.0000
[2,]	0.9375	1.0000	0.9375	0.7500	0.4375
[3,]	0.7500	0.9375	1.0000	0.9375	0.7500
[4,]	0.4375	0.7500	0.9375	1.0000	0.9375
[5,]	0.0000	0.4375	0.7500	0.9375	1.0000

Figure 15: Confusion Matrix of IPSIM-Cirsium

	simulated 1	simulated 2	simulated 3	simulated 4	simulated 5
observed 1	73	43	3	5	0
observed 2	5	1	2	4	0
observed 3	2	1	3	3	0
observed 4	0	2	1	14	0
observed 5	0	2	1	4	0

Figure 16: Precision and Recall for each class of IPSIM-Cirsium output

	Precision	Recall
very low	0.58870968	0.91250000
Low	0.08333333	0.02040816
Neutral	0.33333333	0.30000000
High	0.82352941	0.46666667
very high	0.00000000	0.00000000

Figure 17: Accuracy and F1-Score of IPSIM-Cirsium

	Accuracy	F1-Score
[1,]	0.5384615	0.3320015

III. Results

A. Statistical analyses of the predictive quality of IPSIM-Cirsium

IPSIM-Cirsium obtain a Cohen's kappa at 0.6359 which makes the predictive quality Substantial according to the range of Altman (1999) and Landis and Koch (1977). IPSIM-Cirsium has a fair predictive quality. The Accuracy of the model is 0.538, which means that more than half of the values would be evaluated correctly. The highest precision of evaluated values was obtained for the class *High* with 0.823 score (Fig. 14). Confusion matrix of IPSIM-Cirsium is presented in Figure 15, Precision and Recall for each class is presented in Figure 16.

However, F1-score showed a bad reliability of the model, classifying overall only 33% of the values correctly (Fig. 17). F1-score help us to consider the bias of precision caused by the majority class *Very low*, giving it a accurate weight compared to other classes. The use of F1 instead of Accuracy is here justified by the high representation of one class of weed infestation instead of a homogenize representation of all classes.

In a low weed infestation environment, IPSIM-Cirsium is judged satisfactory, yet in a wider range of profiles, IPSIM-Cirsium needs to be reviewed to present a higher sensibility to high weed infestation.

B. Analysis of aggregated attribute weights

1. Smothering effect reduced weight

Smothering effect was hardly evaluated with the dataset. Indeed, no observation was done in a ley-farming system and the meadow effect was therefore not validated in the model. The second aspect of *Smothering effect* was the use of *Cover crops*. Here, the use of cover crops did only improve evaluation from *Neutral* to *Low* when *Mechanical work* was rated *Moderately efficient*. This effect is a recurring issue where small weighted attributes only contribute to the decrease of weed infestation level when they are combined to other attributes. Therefore, DEX multi-attribute method is perfectly valid to assess the control of perennial weeds which consists into numerous small actions to achieve a great weed control.

Smothering effect accounts for 8% and 13% of the global weights for IPSIM-Cirsium and IPSIM-Sonchus respectively (Fig. 10 and 11), IPSIM-Sonchus having higher importance in the aggregation of *Cropping practices* and *Environment Spring*.

2. Herbicide use, significative control method

The use of herbicide was tested for 120 values in the dataset and showed a great reduction of the final infestation. The number of years of *Herbicide use* was described here in order to discriminate the different use of herbicide: as a curative method (i.e. Used *Four years out of four*), or as a backup plan (i.e. *One year out of four*). When herbicide was used every year, the final infestation of perennial weeds lied between *Very low* and *Low*, depending on the pedoclimate. Indeed, *Herbicide use* as a curative method insure the highest rate for *Cropping practices* (i.e. *Efficient*). However, *Herbicide use* as a backup plan, with discrete use, enabled the final weed infestation to lie between *Very low* and *High*. The variability is far greater and can be explained by the lower efficiency of *Herbicide use* in this method. A moderately efficient cropping practice needs to be an additional control method to achieve high efficiency of *Cropping practices*.

Herbicide use accounts for 16% for IPSIM-Cirsium, and 22% for IPSIM-Sonchus and IPSIM-Elytrigia of the global weights (Fig. 10, 11 and 12). The variation of weights can be

explained either by the variation of aggregative tables for each model or the lower number of attributes in IPSIM-Elytrigia, which then increase the global weight of aggregated attribute *Herbicide use*.

3. Mechanical work, an alternative to herbicide with great control significance

Mechanical work clusters many cropping practices but the designing of aggregative tables enable some cropping practices to be less efficient than other. For example, high efficiency of cultivation (i.e. *Ploughing* and *Stubble tillage*) will enforce a *Moderately efficient Mechanical work* at least, while high efficiency of *Historical mechanical work* alone only achieves an *Inefficient Mechanical work*. This choice was made during the build of models and their aggregative tables, according to expertise and literature. *Mechanical work*, if rated with the highest grade, is sufficient to reach *Efficient Cropping practices*. The choice in this aggregative table was made to illustrate the control of perennial weeds according to mechanical control methods only. However, this High efficiency is to put into perspective: *Efficient Mechanical work* can only be achieved by the combination of several mechanical works (i.e. *Historical mechanical work*, *Inter-row hoeing* or *Selective cutting*, *Ploughing* or *Stubble tillage*).

Mechanical work accounts for 17%, 21% and 22% of global weights for IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia, respectively (Fig. 10, 11 and 12). The greatest importance of *Mechanical work* for IPSIM-Sonchus can be explained by the promoting of *Cropping practices* over *Environment Spring* in the final aggregative table. For IPSIM-Elytrigia it can be explained by the lowest number of aggregative attributes in *Cropping practices*.

4. Competitiveness of crop, a useful additional method

Only IPSIM-Cirsium considered the *Sowing rate* of the crop. However, the dataset used for the validation of the model never contained sowing rate of the crop. For the validation, every level of sowing rate was tested (i.e. *<Regional recommendation*, *Regional recommendation* or *> Regional recommendation*) to see the impact on the final weed infestation. *Sowing rate* never played a role in the evaluation of weed infestation. *Competitiveness of crop*, as for *Smothering effect*, played a little role in the evaluation of weed infestation and was considered useful only as part of a gathering of numerous moderately efficient cropping practices.

Competitiveness of crop accounts for 8%, 13% and 10% of the global weights for IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia, respectively (Fig. 10, 11 and 12). Here again, IPSIM-Sonchus receive a higher performance on the *Competitiveness of crop* thanks to the aggregation between *Cropping practices* over *Environment Spring* in the final aggregative table.

C. Aggregation of Environment Spring and Cropping Practices: weight description

The aggregation of *Environment Spring* (*Spring weather* only for IPSIM-Elytrigia) and *Cropping practices* is the final aggregation of IPSIM perennial weed models. This aggregation is represented in an aggregative table (Fig. 16). This aggregative table set the final level of weed infestation. The aggregative table was designed in order to forbid *Very low* level of infestation if the pedoclimate is not beneficial to the control of weed. However, rating the weight of *Environment Spring* and *Cropping practices* with 50% and 50% may be responsible for the low accuracy of IPSIM-Cirsium. Indeed, pedoclimate might play a reduced role in the weed infestation when cropping practices are highly efficient, which might be here overestimated.

IV. Discussion

A. Interests and limits of IPSIM modelling method

The three models were built following a long process where omission and addition of factors had to be made to try to have a fair model. Having a qualitative modelling approach brought many possibilities and interests for the modelling of perennial weeds. However, IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia reached some limits due to a lot of unknown factors concerning perennial weeds.

1. Interests of IPSIM method in weed infestation modelling

a) *Innovative model builders*

The three models are expressing a level of threat for weed infestation according to an agroecosystem. This qualitative modelling approach allow the users to have a qualitative assessment regarding the system they are using. Another model for the risk of *Cirsium arvense* infestation already existed (OderaVivaces), yet IPSIM-Cirismus tries to bring more accurateness to the modelling by implying and adding weather and soil factors to explain the risk. In this multi-attribute modelling approach, larger factors were considered (e.g. meadow, cover crops and herbicide use). This approach enabled a representation of the effects of these factors but also their interactions. IPSIM models are innovative agroecosystem builders in their way of considering a broad range of control methods by simplifying the effect of each method to their efficiency of action on the weed. In the case of perennial weeds, control without chemical products often consist of a combination of little efficiency control methods that interact between each other. IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia try to consider as many efficient cropping practices as possible. The efficiency of cropping practices, especially mechanical control methods are related to the weather and the soil. Therefore, IPSIM method enables the building of innovative systems compatible with the weather and soil considered in the region of the system.

In the first steps of the process, many factors were taken into account (e.g. *Pasture density, leaf stage of Cirsium, ...*) that all have their role in the modelling of weed infestation. However, thanks to the weights calculated by DEX software and the expert knowledge, omissions of “insignificant” attributes have been possible. DEX method allows a representation of the attributes to communicate simply with experts and have an efficient communication mean. The weights calculated by DEX software can also be a tool for users to indirectly decide which part of the agrosystem is to improve. By focusing on important factors of weed infestation, the building of innovative agroecosystem is simplified.

The hierarchy of qualitative attributes through DEX software is well suited to handle the complexity of systems such as agrosystems. In fact, DEX method tackles a multitude of attributes without a high level of precision to evaluate a comprehension of a whole system. This qualitative modelling allows an aggregation of different variables such as sowing dates, tillage tools, rainfall ... in a simple way to process all the factors that play an important role in the representation of the weed infestation. The principal strength of IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia are their simple aggregative tables that enable to describe every interaction between cropping practices that are often overlook during experiments or simply too complicated to apprehend as a whole complex of control methods. The complexity of interactions of many cropping practices with pedoclimate is interesting too. It makes the conception of innovative agroecosystem integrated in their environment. We can see for example that fields with high water regime and great temperature in spring will have more difficulty to control perennial weeds and should implement competitive crops or ley in the rotation if they want to abandon the use of herbicide as a control method.

b) *Large horizontal transfer*

The process of modelling perennial weed infestation allowed a gathering and transfer of information between experts, technicians, and farmers. The main point of exchange of information and knowledge was the co-design workshops. These three co-design workshops enabled actors of the perennial weeds to meet and discuss about their observations and experiences with the weeds, in specific pedoclimate contexts.

- i) The first transfer observed is the transfer of knowledge between French actors and experts. The modelling of three models focused on perennial weeds enabled discussions of the different factors to consider in the model and the understanding of weather and soil parameters in the weed infestation. During the workshops, at least three regions of France were discussed: Bourgogne-Franche-Comté, Occitanie and Hauts-de-France. This wide transfer of information between different actors from different region enable the consideration of a wide panel of cropping practices, adapted or linked to pedoclimate. Numerous actors of the region Occitanie were part of a former project based on Canada thistle and Curly dock (*Rumex crispus* L.) in France (CAPABLE Project), this transfer of information also enabled a transfer of data for the validation of IPSIM-Cirsium.
- ii) The second transfer of information was European with the sharing of information between AC/DC-weeds partners. Having an international sharing of information and data can be complicated for the wide window of weathers and soil observed, but also for the cropping practices that are performed on various crops, adapted to certain regions or countries. However, many cropping practices need to be considered and implemented in the model as alternative control methods to herbicide. Diversified climatic conditions also bring a larger explanation of the weed infestation: *Sonchus arvensis* in France is not considered to be a threat to any crop, yet in Denmark, Sweden or Germany, *Sonchus arvensis* can reduce drastically the yield. Therefore, it is important to consider climatic conditions, soils and cropping practices that are different from the ones we observe in France to understand and model the weed infestation of perennial sowthistle.

Beside the process of modelling, the models themselves are perfect tools for the transfer of information. Indeed, DEX software allows a ludic way of presenting the information of weed infestation through three colours, easily understood (i.e. Red for detrimental, Grey for neutral and Green for beneficial). This transfer of information can be done in different ways:

- i) Transfer to the farmers. Through IMPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia, farmers can assess their threat level for each field and can directly try to improve the competitiveness of their agroecosystem. DEX software enables them to focus on specific cropping practices and visualize the negative and positive sides of their system. This software can also have an educational prospect to inform farmers about other cropping practices that can be efficient in the control of perennial weeds (e.g. ISPIIM-Chayote: Deguine et al., 2020)
- ii) Transfer to technicians. IPSIM models are a great tool to test and learn which method is adapted to the pedoclimate considered and be able to advise farmers on the control methods. It gives technicians a tool to compare different systems that can be observed in a large panel of fields.
- iii) Transfer to research. The modelling of weed infestation enabled the creation of an indicator of weed pressure and risk of the field towards three perennial weeds. This can be reuse in a qualification of complex agroecosystem to promote adapted solutions less reliant on herbicides.

c) *Long-term appreciation of control methods*

Perennial weeds are often considered to be only manageable through long period of time. Consequently, a long-term approach needed to be designed. Here, with IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia, historical practices were added to consider the long-term control. By the biology of perennial weeds and more particularly their storage cycle, it is important to consider exhausting method on a longer term (Weill, 2018). *Herbicide use* and *Historical of Mechanical work* were considered on the 4 previous years. While stubble tillage is often performed every year to participate to the depletion of the root storage of perennial weeds, ploughing is less systematic. However, systems that present a poor reliance on ploughing (e.g. ploughing less than two times in the last four years) can still have a Low or Very low weed infestation indicator when other methods such as competitiveness of crops and stubble tillage are intensive and efficient enough. Long-term appreciation of methods is necessary to factor the complexity of the biology of the perennial weeds. As much as herbicide can be efficient to control weed, in the case of perennial weeds, it is crucial to consider the use of herbicide on large scale of time. Root storage depletion can only be efficiently reached when systemic herbicide reaches the root. Therefore, considering herbicide as a “catching-up” method is a mistake. Considered this way in the models, curative method weights are better balanced, and need to be considered several years to show efficiency on perennial weeds.

Previous cropping practices such as ley implements are also considered and enable the user to have a larger look at the rotation as a control method. If ley farming is sometimes seen as a fertility improvement method, it can also be use in a control method for weeds and more specifically perennial weeds (Mellender, 2018). Being able to implement the ley farming rotation in the models is a solution to design innovative agroecosystems with low level threat to perennial weeds. During the process of designing of the models, rotation in its whole was decided not to be considered. Indeed, while ley can present a curative aspect, competitive crops in the rotation are simply prophylactic methods, therefore they only appear on a short-term appreciation. Ley-farming is considered as a curative method thanks to the mowing. A two-year alfalfa meadow itself would not reduce a weed infestation (Alain Rodriguez and Régis Hélias, 2020, personal communication).

Long-term approach with IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia can assist the user in the building of an innovative agroecosystem, competitive towards perennial weeds. To simply imagine the weed infestation on longer scale of time, the user can repeat the use of the model while implementing new cropping practices. Long-term appreciation of mechanical work, herbicide use, and smothering effect such as ley, will support the decisions of the user and express an indicator of the threat of perennial weeds for a larger scale of time. The strength of IPSIM method is the appreciation of many attributes, with different variables (date, weather and cropping practices). Evaluation of the threat level on several years cannot be done with the climatic conditions because of the static state of IPSIM models. However, it is possible for the user to imagine several cases scenarios and have a range of threat levels of weed infestation according to their cropping practices.

2. *Limits*

When developing of the models, experts always want to add factors that seem relevant to model weed infestations. However, for the sake of simplicity and validation of the models, it is often necessary to exclude few factors that present less weight to keep a simplified but accurate evaluation of the weed infestation for *C. arvensis*, *S. arvensis* and *E. repens*.

a) *Simplified qualitative models*

In IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia, the variables used are qualitative variables. This can be a strength to assess an accurate model of complex variables. However, the use of qualitative variables also brings a bias to the models. Indeed, the user

can implement qualitative variables (e.g. *Sowing rate: Recommended sowing rate*) that can be hard to interpret objectively. To limit this bias, convertor have been designed to help assist the user in the translation of quantitative values into qualitative ones. Yet, this is limited and can bring complexity to use and inadequacy to the region. A convertor is unfortunately related to a pedoclimate and a region, and therefore, to offer a model that can be used in a large scale of pedoclimate, it is important to keep the qualitative interpretations to the user. The IPSIM method prefers to maintain accuracy of the predictive quality rather than precision of the attributes (Aubertot, Robin, 2013). Numerous attributes have been simplified to keep simple and fair models, easily evaluated. Nevertheless, increasing the number of basic attributes would improve the predictive quality of the model, but requires a high precision of experimental data.

The accuracy of the models does not only rely on the model but also on the dataset used for the validation of the models. In the dataset used, it is important to assess the large variety of soils, weathers, cropping practices and infestation threat levels. In IPSIM-Cirsium validation, only two datasets with two pedoclimate were used. Even if the weather can vary through years of experiment, it can create a bias in the evaluation of the predictive quality of the model. The second bias is coming from the poor number of *Very high* level of infestation of *C. arvense* in the dataset, which leads to an underestimation, or a mismatch of the final infestation of weed. To tackle this issue, it is possible to integrate a larger dataset for the evaluation of the predictive quality: (i) by using other countries' data, or (ii) have specific experiments with an increase of the number of perennial weeds.

b) *Pedoclimate importance*

To evaluate the weed infestation, it is crucial to consider the cropping practices, the environment but mostly the pedoclimate. To evaluate the pedoclimate, climatic forecasting models and soil models can be used. Here in IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia, users qualitatively observed soil compaction directly. This method allows a simplification of the input data but also enables the user to estimate relatively the compaction in regard to the region. Defining threshold can be complicated for different conditions and relying on qualitative evaluation frees the model to any region requirement. Nevertheless, for the climatic requirements of perennial weeds, thresholds were defined, based on biology of perennial weeds. These two methods bring limitation to the model and a decrease of precision. Defining thresholds can produce different evaluations according to the weather but brings few regions at a maximal threat level, no matter which cropping practices are performed. To simplify the models, the different biotypes of perennial weeds were not considered. This can conduct to an overestimation or underestimation of the threat level of infestation.

The second limit to the DEX method is the acknowledgement of the same attribute in different parts of the model, especially concerning the weather. Weather is key to qualify the efficiency of cropping practices, yet it is related to the type of cropping practices. Dry weather is required in numerous cases such as inter-row hoeing, inversion tillage, stubble tillage (Weill, 2018). Still, significant rain is sometimes advised to perform an efficient cropping practice (Bourdôt et al., 2011). Implementing weather in the model needs to be done in many subtrees and causes many repetitions of the information. Yet, the global weight of weather will be attributed to each "sub" attribute in each subtree, decreasing the global weight of weather. This method of implementing the same attribute in numerous subtrees decreases the predictive quality of the model and complicate the hierarchical tree of attributes. Weather impact on cropping practices efficiency was thus dropped out.

c) *Output of the models*

The qualitative output of the models was chosen accordingly to the technical demands of experts (i.e. engineers, technicians and farmers). It needs to express a threat level for the

farmers to be able to understand the severity and to react in time. It needs to be an accessible and accurate tool for searchers to be used in research, and for advisors to have a fair indicator of the efficiency of cropping practices in regard to pedoclimate.

To evaluate the predictive quality of the models, coverage data of *C. arvense* was translated into qualitative levels of weed infestation. Yet numerous scientific reviews qualify the infestation thanks to dry biomass of plants. Literature about dry biomass of perennial weeds to assess the potential severity on yield is difficult to obtain, if not non-existent. Currently, yield decrease was only related to *C. arvense* cover percentage (Rasmussen, Nielsen, 2020). This yield loss is related to the crop. Therefore, it is complicated to estimate a general level of weed infestation to link to any severity. To tackle this issue, it would be advised to review the models to implement an output related to each crop. These models do not take into account the severity of each weed according to the agrosystem. IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia only provide an indicator of the level of weed infestation in June, no matter which system or crop is implied.

A second default to the output of the models is the difficulty to generalize the evaluation to the entire field. The distribution of perennial weeds is discrete and not homogenous as we can observe for annual species (e.g. wild oat (*Avena fatua* (L.))). The level of weed infestation is here only an average of the entire field. This evaluation is far from observation. It is complicated to assess an estimation of the field without decreasing the quality of the evaluation. Considering the infestation as an overall mean of discrete infestation plots also decreases the quality of the output of the models, with for example an overestimation of infestation that can be caused by an anecdotal rich infestation plot. An abundance scale developed by Barralis (1975) could help resolve this problem of infestation rating but not the impact on yield.

B. Prospects

1. Model improvement

Model improvements can be made, while keeping the models simple and accurate. It is possible to improve the predictive quality of IPSIM-Cirsium thanks to aggregative tables and the redefinition of aggregative weights. This new assessment of aggregative tables will be in agreement with expertise throughout the process. To improve the predictive quality of the models, dataset with a larger window of weather, soil and cropping practices will be tested, with a higher number of repetitions. Revising the aggregative tables will enable the models to consider few attributes more strongly in order to evaluate the weed infestation.

Redefining hierarchical tree can increase the weight of some attributes and maximise the interaction of few cropping practices between each other. For example, *Leaf stage* in IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia was abandoned because of its small global weight. Yet, the leaf stage is reported to be highly correlated to the efficiency of mechanical control of perennial weeds. To improve the precision, it might be possible to consider a wider range of factors to better describe control methods. But IPSIM modelling should always stay simple. IPSIM models do not aim at the precision but at accurate evaluations (Aubertot, Robin, 2013).

Each model aims at the evaluation of the weed infestation. However, as observed earlier evaluation of the weed infestation is tricky and can be complicated to apply directly as an indicator for the user. An improvement to the models could be made to consider the sensibility of the agroecosystem towards the level of weed infestation. This improvement could be a grade attributed to each system. This improvement requires only an additional basic attribute which describes the system on a scale from *Insensitive to weed infestation* to *Highly sensitive to weed infestation*. This improvement could provide a second indicator for farmers to set a context of threat for the weed infestation.

Here, three models of Injury Simulation were developed to evaluate the weed infestation of three perennials: *C. arvensis*, *S. arvensis* and *E. repens*. The aim of the Modelling Work Package is to contribute to the understanding of these three perennial weeds. A final incidence of weed infestation needs to be developed to compile three submodels in one. This improvement could bring a final understanding of the general perennial weed infestation through the main common and problematic weeds in Europe. Yet, this improvement may trigger some surreal evaluation and unknown interactions between perennial weeds (e.g. competition, symbiosis ...). It is unlikely that weed infestation might be at their maximum in the field, however, nothing stops the model to parameterize *C. arvensis*, *S. arvensis* and *E. repens* at their maximum level of weed infestation. This issue was encountered for the designing of IPSIM-Wheat (Aubertot, Robin, 2013). These would be limitations to a new global approach of perennial weed infestation.

2. Future uses of the models

IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia were designed to assess an evaluation of the weed infestation. Many applications arise from the models and the main one would be the beforehand evaluation of a variety of agroecosystems regarding their weed infestation likelihood. This evaluation is key for the designing of any innovative cropping system less reliant on herbicide and deep plough in accordance with pedoclimate. This method of modelling enables the interaction of many cropping practices and enables an evaluation of the weed infestation. The use of the model would need to be additional to expertise, other models and diagnoses in field to achieve the conception of innovative models less reliant on herbicide and intensive deep ploughing, IPSIM perennial weed models are one of many tools of conception.

The second use of the models aims to be an educational tool for technicians, advisers, farmers and teachers. The models will need to improve their graphic interfaces in order to become more ludic and easily handled. Convertors are already designed under Excel and will enable simple use of the models and facilitate the translation of quantitative attributes to qualitative ones.

IPSIM-Cirsium, IPSIM-Sonchus and IPSIM-Elytrigia can be a source of many cropping practices and the understanding of the factors responsible for the weed infestation. This gathering of cropping practices can be used as a database for cropping practices source of innovation, and these models can be seen as the first three models of the understanding and modelling of a global Injury Profile SIMulation of perennial weeds.

V. Conclusion

The development of perennial weed control methods provides an answer to the recall of some chemical control methods and the de-intensifying use of deep ploughing. Herbicides are the most used protection of plants products and society is more and more calling their recall into question.

Numerous cropping practices exists to tackle the recall of glyphosate and other systemic herbicides; however, the adoption of alternative cropping practices remains poor. One of the main reasons are the poor evaluation of the weed infestation of perennial weeds according to the transition to alternative cropping practices. Multi-attributes qualitative modelling gives an answer and enables users to visualize qualitative weed infestation for *C. arvensis*, *S. arvensis* and *E. repens*. IPSIM perennial weed models help assess the effect of cropping practices and their interactions. The process of modelling permitted a gathering of all efficient control methods and a horizontal transfer of knowledge between actors of the designing of IPSIM models.

The models enable the conception of innovative agroecosystem, less reliant on herbicide and deep ploughing. This study brings a first answer for the qualitative modelling in the framework of AC/DC-weeds. Nevertheless, aggregative tables need to be reviewed to bring more accuracy to the models. In order to improve the models, new studies should be performed to better understand the different efficiency of cropping practices and their interactions, new co-design workshops should be done to increase the sharing of knowledge and finally new evaluations and dataset should be completed to increase the statistical significance of the models in various weathers, soils and agrosystems.

IPSIM-Sonchus and IPSIM-Elytrigia did not receive a review from experts yet concerning the weights and the build of aggregative tables. They are still in the process of conception with expertise, and evaluation of the predictive quality. Due to exceptional sanitary condition, meetings with farmers and experts have been slightly reduced. The process of model conception is in constant link with expertise in order to assess the different factor effects but also the output of the models.

Modelling weed infestations according to pedoclimate and cropping practices is a tool to provide a sustainable system of production of crops, with low reliance on herbicides and deep inversion tillage. Such indicator enables the technicians, advisers and farmers to visualize the impact of the choice of cropping practices on a long-term and to appreciate a level of perennial weed infestation. This level of weed infestation is only an indicator to the user, and it is up to them to define the threshold of severity, according to considered system.

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PERSONAL COMMUNICATION

BONIN, Ludovic, 2020. Weed expert at Arvalis, France.

CROS, Claire, 2020. Perennial weed expert at Agro Transfert, France.

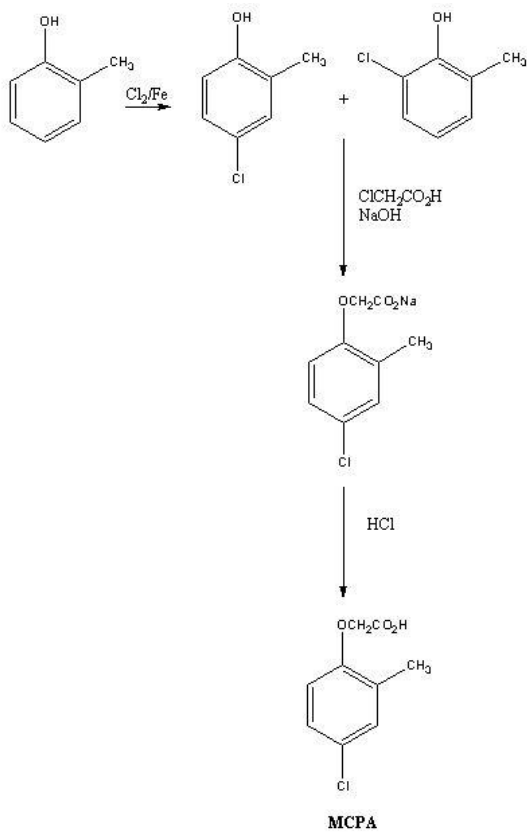
DELPÉRIÉ, Pierre, 2020. Agro-equipment teacher, France.

HÉLIAS, Régis, 2020. Weed expert at Arvalis, France.

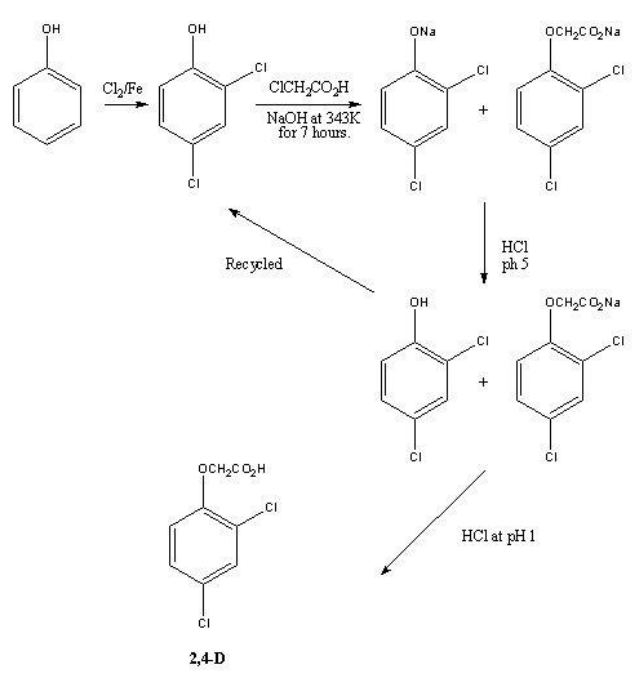
RODRIGUEZ, Alain, 2020. Weed expert at Acta, France.

VACHER, Catherine, 2020. Weed control expert at Arvalis, France.

ANNEXE I: MCPA and 2,4-D



Synthesis of MCPA



Synthesis of 2,4-D

Compte-rendu atelier de co-conception

PROJET ACDC- WEEDS

- LES PARTICIPANTS :

Alain Rodriguez : Spécialiste flore adventice chez Acta, participe au projet Capable.

Pierre Pujos : Agriculteur AB dans le Gers, travail superficiel du sol, céréales et élevage.

Jean-Luc Verdier : Spécialiste système de culture chez Arvalis.

Régis Hélias : Ingénieur chez Arvalis, expert désherbage, participe au projet Capable, suit des essais sur chardon et retour d'un réseau d'agriculteurs.

Claire Cros : Gestion des vivaces chez Agrotransfert, suit des essais agricoles pluriannuels.

Ludovic Bonin : Spécialiste flore adventice chez Arvalis.

Bruno Chauvel : Chercheur à l'INRAE de Dijon, UMR Agroécologie.

Catherine Vacher : Spécialiste désherbage pomme de terre, tabac, ... chez Arvalis, participe au projet Capable.

Fanny Vuillemin : Spécialiste flore adventice chez Terres Inovia, participe au projet Capable, anime des essais longue durée.

Enguerrand Burel : Chargé de mission au CREAB, partenaire du projet Capable.

Jean Arino : Ingénieur conseil en AB à la chambre d'Agriculture du Gers.

Camilo Corrales : Chercheur postdoctoral en analyse et modélisation qualitative à l'UMR AGIR INRAE d'Auzeville, partenaire du projet ACDC-weeds.

Jean-Noël Aubertot : Chargé de recherche en protection des cultures et modélisation à l'UMR AGIR INRAE d'Auzeville, partenaire du projet ACDC-weeds.

Marie-Hélène Robin : Enseignante-chercheuse en Protection des cultures, chercheuse associée INRAE UMR AGIR, partenaire du projet européen ACDC-weeds.

Octave Lacroix : Stagiaire Master 2 à l'UMR AGIR INRAE d'Auzeville, dans le cadre du projet ACDC-weeds, sous l'encadrement de Marie-Hélène Robin.

- DEROULEMENT DE L'ATELIER :

L'atelier débute par un rapide tour de table afin de permettre à tous les participants de se présenter rapidement, raconter leur expériences avec la flore adventice vivace et plus particulièrement le chardon des champs.

Enguerrand présente ensuite la bioécologie du chardon et les problèmes rencontrés par la présence du chardon. Il présente les nuisibilités directes du chardon sur le rendement (jusqu'à 50% de perte), les impuretés des grains et la difficulté de la récolte, les moyens de reproduction ou dissémination du chardon via les racines secondaires et dans une moindre mesure par les graines et enfin les stades de stockage des réserves énergétiques au sein du système racinaire. Pour l'écologie du chardon, le type de sol semble peut important avec une forte tolérance du chardon pour tous types de sol. Le chardon supporte bien le tassement des sols, mais craint les températures élevées. La croissance aérienne s'observe des températures dépassants les 10°C, la floraison quant à elle arrive avec les fortes chaleurs. Il expose ensuite les résultats d'enquête réalisée en 2018 dans le cadre du projet Capable avec 160 répondants sur l'ensemble du territoire français avec une forte participation dans la région Occitanie. Les principales pratiques de lutte contre le chardon utilisées par les

agriculteurs bio sont le travail superficiel du sol avec des outils à dents, le labour et la luzerne. Le travail du sol sans inversion, écimage, arrachage manuel, les outils à disques, la prairie temporaires, la culture annuelle fauchée ou la culture intermédiaire sont quant à eux moins fréquemment utilisées par les agriculteurs en bio. Les stratégies soulevées par les agriculteurs qui ont réussi à maîtriser le chardon sont diverses. Certains préconisent le travail du sol important réparti sur toute l'année avec une longue interculture pour des travaux du sol nombreux, suivi d'un sarclage de la plante et d'un arrachage manuel pendant la culture, ou bien encore par de nombreux passages d'outils pour la maîtrise du chardon dans le champ avec 4 à 9 écimages et de nombreux déchaumages d'automne. D'autres agriculteurs préfèrent étouffer le chardon par la présence d'une luzerne broyée 4 à 5 fois, des faux-semis en interculture, d'arrachages manuels et de déchaumages par outils à dents à pattes d'oie. En stratégie d'étouffement, les couverts d'interculture sont également mis en avant avec un mélange semé mais efficace sur les jeunes pousses uniquement.

Octave présente ensuite le projet ACDC-weeds et plus particulièrement le work package Modélisation et ses objectifs. Après une présentation des acteurs du projet et des attendues, il présente les moyens mis en œuvre pour modéliser les trois adventices pérennes : *Cirsium arvense* (L.) Scop, *Sonchus arvensis* (L.) Scop et *Elymus repens* (L.) Gould. La stratégie de modélisation s'appuiera sur la méthode DEX avec l'utilisation d'IPSIM (Injury Profile SIMulator) afin de prédire l'impact des pratiques culturales, du sol, du climat et de l'environnement du champ sur les infestations de plantes vivaces. Il poursuit ensuite en exposant les étapes de l'élaboration du modèle, par la définition des attributs, des échelles, puis la construction des tables d'agrégation, la constitution d'une base de données et enfin l'évaluation de la qualité prédictive du modèle. Il vient ensuite à la présentation de la structure de l'arbre hiérarchique du modèle qualitatif de l'infestation du chardon. Il présente la logique d'agrégation des attributs d'entrée jusqu'à la sortie du modèle, puis donne un exemple rapide des échelles produites pour chaque attribut d'entrée sous Excel avec les différents niveaux pris par les attributs d'entrée : Favorable pour le développement du chardon, Moyennement favorable au développement du chardon, Défavorable pour le développement du chardon.

Des axes de discussions sont ensuite suggérés afin de démarrer les échanges. Les échanges débutent avec tout d'abord la discussion des attributs d'entrée et leur agrégation.

• DISCUSSION AUTOUR DE LA STRUCTURE DE L'ARBRE :

Attributs agrégés sous Environnement :

- La compaction du sol ne doit pas prendre en compte la partie superficielle du sol. En effet, les chardons sont plus tolérants à la compaction grâce à leurs racines profondes pouvant atteindre 70 cm de profondeur. La compaction la plus problématique est donc la compaction profonde du sol provoquée majoritairement par le travail profond du sol, en humidité relative élevée. L'indice de battance ne jouerait donc aucun rôle dans la compaction du sol concernant le chardon. Le tassement du sol joue donc ici le rôle de changement de compétitivité du chardon.
- La fertilité du sol n'est pas un argument suffisant pour déterminer la nuisibilité du chardon. En effet, bien que moins développé en condition de fertilité du sol faible, le chardon garde la même nuisibilité pour la culture en place.
- Le chardon, par ses racines profondes et ses organes de réserves, possède une forte résistance à la sécheresse en été. Une sécheresse d'été pendant la présence d'une culture lui donnerait donc un avantage compétitif sur la culture en place.
- La gestion des bords de champs est également évoquée mais est confirmée comme peu significative comme foyer d'infestation avec une viabilité des graines très faible. Concernant l'infestation végétative par racines secondaires, elles sont en effet capables d'infester un nouveau champ. La gestion par broyage n'est pas suffisante pour épuiser les chardons des bandes enherbées, et seul le travail répété du sol avec inversion à 30cm de profondeur deux à trois fois par an semble suffisant pour limiter cette infestation par la bande enherbée entre deux champs d'après une étude réalisée dans le Gers en 1994.

Attributs agrégés sous Pratiques culturelles des Précédents :

- La rotation semble avoir un impact très faible voire nul sur le contrôle du chardon. En effet, par la forte implémentation du chardon et ses organes de réserves en profondeur, le chardon est observé dans toutes cultures. Cependant la rotation est intéressante pour permettre une gamme de travaux du sol à des périodes différentes au cours de l'année, avec une forte nécessité du travail du sol avant le stockage des réserves en sucres par le chardon. Les cultures de printemps sont intéressantes pour permettre un travail du sol intensif en inter-rang, et des écimages nombreux. La rotation de culture devrait également tenir compte de la proportion de culture binables tardivement au printemps pour le contrôle prolongé du chardon. La rotation a également l'intérêt de présenter des cultures avec des larges gammes pour les herbicides afin de permettre le contrôle chimique des vivaces. On peut par exemple citer les graminées dans la rotation qui permettent une utilisation plus large d'herbicides très performants pour maîtriser les adventices.
- La gestion des prairies par pâturage est à préciser avec l'importance de la densité en pâturage. Lors de forte densité, le pâturage n'est pas sélectif du chardon, et permet donc un contrôle égal à la tonte.
- La prise en compte du climat se fait également au niveau de la rotation avec l'étouffement plus ou moins fort de la prairie semée vis-à-vis du chardon. En effet, dans le cadre d'une luzerne sur une ou plusieurs années, un climat favorable à la pousse de la luzerne permettra un étouffement fort du chardon, avec un épuisement des réserves du chardon avec des broyages répétés au cours de l'année.
- Il est cependant intéressant de connaître les pratiques des précédents qui seront prépondérants dans la biologie du chardon dans la culture actuelle. Les champs anciennement gérés en conventionnel ou bio ont en effet des chardons possédant des biologies différentes. La connaissance des pratiques des précédents permet donc de prédire une probabilité d'infestation plus ou moins forte.

Attributs agrégés sous Pratiques culturelles de l'Interculture :

- L'importance des couverts est sûrement sous-estimée, et doit tenir compte du climat afin de qualifier la pousse du couvert d'interculture pour étouffer mais également épuiser les réserves du chardon. On retrouve ici la forte dépendance de la stratégie de compétition par le couvert (ou les prairies semées) au climat pour favoriser leur développement et leur capacité de gestion du chardon.
- La pratique du faux semis est soulignée par tous les acteurs comme inefficace contre le chardon, l'observation de plantules de chardon n'a été observé qu'à de très rares occasions.
- La catégorisation du travail du sol par le mode d'action des outils proposée précédemment par les experts d'ACDC-weeds est favorablement reçue lors de cet atelier. Le travail du sol doit également tenir compte de la surface de travail de l'outil. En effet, un outil à disque utilisé en plusieurs passages de recoupement qui permet de couper 100% des racines permet un travail similaire au passage d'un outil à dents pattes d'oie qui propose un recouvrement de 100% du champ lors d'un unique passage. Le travail secondaire du sol semble être conseillé afin de prévenir le stockage des réserves du chardons pendant sa croissance.
- Les herbicides lors de l'interculture sont, sauf de rares cas, toujours utilisés à une unique répétition maximum. Le glyphosate est toujours conseillé pour permettre un bon contrôle contre le chardon, notamment au niveau des racines avec un bon transfert du produit systémique au sein du phloème jusqu'au racine. Mais la gestion par les herbicides n'est efficace que si elle est répétée sur plusieurs années.

Attributs agrégés sous Pratiques culturelles de la Culture actuelle :

- Le climat est à prendre en compte, notamment concernant l'irrigation des cultures de soja ou bien de maïs qui proposent une compétition très forte contre le chardon par leur port et leur taille importante. Cependant, la limitation en eau perturbe cette compétition face au chardon qui est plus tolérant à la sécheresse.

- Les cultures préconisées pour une forte compétitivité sont le sarrasin avec un effet allélopathique et une forte couverture de l'inter-rang, le soja qui en se développant bas permet des écimages et des binages ou sarclage très nombreux et propose un port couvrant important avec un semis à 55 plantes au m² et une compétition à l'eau intéressante et le maïs qui propose lui aussi une compétition importante au niveau de la lumière et de l'eau mais la montée du maïs est plus importante et rapide et ne permet donc pas de passages très nombreux du travail en cours de culture.
- Le climat est également à prendre en compte pour la lutte mécanique en cours de culture. En effet, le binage sera plus efficace et nombreux en climat sec. De plus, les actions en cours de culture sont à quantifier, avec une efficacité plus grande lorsque le nombre de passages de l'écimeuse augmente.
- Le chardon ne présente pas toujours la même compétition face à la culture, en effet de simples pieds isolés auront peu d'impact sur le rendement, tandis qu'un rond de chardon réduira considérablement le rendement de la culture. Il faut donc prévoir une différenciation du seuil de nuisibilité du chardon.

Sortie du modèle :

Le modèle d'infestation en chardon ne peut pas se résumer seulement à une surface exploitée par le chardon au sein de la culture. La notion de risque pour l'agriculteur doit apparaître dans la sortie du modèle afin de connaître la perte de rendement éventuelle. En effet, dans le cadre d'une gestion du chardon sous un seuil de nuisibilité, il est nécessaire de définir le seuil d'acceptation du chardon au sein de la culture. La corrélation des pratiques avec le coût de ces pratiques semble également importante afin de conseiller des pratiques permettant une réduction des utilisations d'énergie fossile à fort coût environnemental et budgétaire. La sortie du modèle d'une infestation (en proportion de rond de chardon par exemple) au mois de juin est appuyée par l'ensemble des participants. Une probabilité d'extension du chardon semble également très pertinente pour les agriculteurs afin de connaître ses pratiques à risque.

SUITES A L'ATELIER DE CO-CONCEPTION :

A l'issue de cet atelier deux articles seront rédigés. Le premier article sera un article scientifique décrivant la définition des attributs d'entrée du modèle, la hiérarchisation de ces attributs et toutes les étapes de construction du modèle. Le second article sera à vocation de vulgarisation scientifique avec une présentation de lutte contre le chardon des champs à l'aide d'une combinaison des pratiques. Les participants se disent intéressés par la rédaction, ou relecture, sur la hiérarchisation des pratiques et conditions environnementales favorisant le chardon et les préconisations proposées par le modèle *Cirsium arvense*.

Compte-rendu atelier de co-conception

PROJET ACDC-WEEDS

Octave Lacroix
17 JUILLET 2020



- LES PARTICIPANTS :

Alain Rodriguez : Spécialiste flore adventice chez Acta, participe au projet Capable.

Pierre Pujos : Agriculteur AB dans le Gers (céréales et élevage) avec un travail superficiel du sol.

Claire Cros : Gestion des vivaces chez Agrotransfert.

Bruno Chauvel : Chercheur à l'INRAE de Dijon, UMR Agroécologie.

Catherine Vacher : Spécialiste désherbage chez Arvalis, participe au projet Capable.

Fanny Vuillemin : Spécialiste flore adventice chez Terres Inovia, participe au projet Capable, anime des essais longue durée.

Enguerrand Burel : Chargé de mission au CREAB, partenaire du projet Capable.

Isabelle Merle : Chargée de Recherche à l'INRAE Grignon, partenaire du projet européen ACDC-weeds.

Marie-Hélène Robin : Enseignante-chercheuse en Protection des cultures, chercheuse associée INRAE UMR AGIR, partenaire du projet européen ACDC-weeds.

Octave Lacroix : Stagiaire Master 2 à l'UMR AGIR INRAE d'Auzeville, dans le cadre du projet ACDC-weeds, sous l'encadrement de Marie-Hélène Robin.

- DEROULEMENT DE L'ATELIER :

Les différents participants de l'atelier se présentent rapidement à tour de rôle afin d'exposer leur poste actuel, leur participation à un projet ou des projets en lien avec la thématique et l'expertise qu'ils peuvent apporter sur le laiteron des champs et le chiendent rampant.

Octave présente la biologie de *Sonchus arvensis* (L.) Scop et *Elytrigia repens* (L.) Gould afin de proposer un rappel pour les différents participants. Cette présentation a pour but de mettre à niveau les connaissances de l'habitat, du cycle de développement et de reproduction des adventices. Puis, il présente l'approche de modélisation hiérarchique qualitative adoptée dans le cadre du modèle européen ACDC-weeds dans le workpackage Modelling. Cette approche s'appuiera sur la méthode DEX avec l'utilisation d'IPSIM (Injury Profile SIMulator) afin de prédire l'impact des pratiques culturales, du sol, du climat et de l'environnement du champ sur les infestations de plantes vivaces. Il poursuit ensuite en exposant les étapes de l'élaboration du modèle, par la définition des attributs, des échelles, puis la construction des tables d'agrégation, la constitution d'une base de données et enfin l'évaluation de la qualité prédictive du modèle. Il vient ensuite à la présentation de la structure de l'arbre hiérarchique du modèle qualitatif de l'infestation du laiteron des champs puis du chiendent. Il présente la logique d'agrégation des attributs d'entrée jusqu'à la sortie du modèle, puis donne un exemple rapide des échelles produites pour chaque attribut d'entrée avec les différents niveaux pris par les attributs d'entrée.

Des axes de discussions sont ensuite suggérés afin de démarrer les échanges. Les échanges débutent avec la discussion des facteurs favorisant tout d'abord le contrôle du laiteron et du chiendent ensuite.

• DISCUSSION AUTOUR DE LA STRUCTURE DU MODELE SONCHUS :

Attributs agrégés sous Environnement :

- La texture de sol est discutée. Il semblerait que l'infestation du laiteron des champs soit plus forte dans les sol limoneux, sols légers. Le laiteron a plus de mal à se développer dans les sols lourds. Cependant, des laiterons sont observés dans les sols limoneux-argileux battants.
- La gestion des bords de champs ne semble pas primordiale pour le laiteron des champs. La reproduction par graine est très faible, voire inexistante et les infestations de nouvelles parcelles ne sont pas par des racines des laiterons de bords de champs mais plutôt par le transport des outils de travail du sol, principale source de contamination. L'attribut d'entrée de gestion des bords de champs est donc abandonné.
- Le climat est important pour la quantification du développement du laiteron mais également pour définir les travaux du sol. Il faudra donc prendre en compte la pluviométrie au niveau du travail du sol.

Attributs agrégés sous Pratiques culturelles des Précédents :

- L'impact des prairies est à nuancer, en particulier l'utilisation de luzerne pour réduire la pression du laiteron. Après broyage d'une luzerne de 2 ans, le laiteron qui semblait disparu, refait surface dès la première année.
- Cependant le laiteron supporte mal la compétition à la lumière et seule les espèces semées tardivement au printemps ou bien à large inter-rang sont sujet à cette compétition du laiteron. On peut par exemple citer le maïs non sarclé.
- Les fertilisations à base de potassium (type vinasse par exemple) semblent favoriser le développement du laiteron.

Attributs agrégés sous Pratiques culturelles de l'Interculture :

- Le travail du sol est très important dans la gestion du laiteron puisque la lutte se fait par la même stratégie que pour le chardon : la lutte par épuisement des réserves. Cependant, l'entrée en dormance précoce du laiteron ne permet d'appliquer les mêmes pratiques. L'entrée en dormance a été observée très tôt dès fin juillet.
- Les conditions de travail du sol sont plus importantes que la profondeur ou bien la saison de travail. Il faut miser sur la forte répétition des perturbations du laiteron dans des conditions sèches, pour le labour comme pour le déchaumage.
- Il faut se méfier des interventions qui visent les adventices annuelles telles que le faux semis qui ont tendances à multiplier et disséminer les racines de laiteron des champs.

Attributs agrégés sous Pratiques culturelles de la Culture actuelle :

- L'écimage est à abandonner pour le laiteron avec une efficacité nulle. Aucun épuisement des réserves n'en résulte et la montée à graines ne produit pas de graines viables ou faiblement viables.
- Le binage peut être intéressant sous conditions d'avoir un binage réalisé avec des dents qui couvrent la totalité de l'inter-rang, avec recoupage entre-elles, type pates d'oies. Cependant, le binage inter-rang ne permettra pas de contrôler les laiterons présents dans le rang. Seul un arrachage manuel pourra éventuellement supprimer les laiterons du rang.

Sortie du modèle :

- Pour renseigner l'utilisateur sur l'impact des adventices vis-à-vis de sa culture, il a été discuté de la possibilité d'intégrer une sortie qualitative de sensibilité du système de production par rapport à l'adventice. Cela permettrait de renseigner le risque encouru pour chaque système en fonction de sa sensibilité et du niveau d'infestation de l'adventice vivace. Par exemple, un système intégrant des périodes de prairies longues dans la rotation sera peu sensible au laiteron des champs, tandis qu'un système céréales uniquement présentera une sensibilité plus accrue face au laiteron des champs.

- DISCUSSION AUTOUR DE LA STRUCTURE DU MODELE ELYTRIGIA :

Attributs agrégés sous Environnement :

- Les sols frais et compactés semblent favoriser les chiendents, mais il est possible de trouver de nombreux contre-exemples. Nous faisons le choix d'abandonner le tassement du sol.
- Le chiendent semble supporter le stress hydrique, cependant cette hypothèse est à reconfirmer.
- La contamination des parcelles peut se faire par les bords de champs. La fauche ne permet pas de venir à bout du chiendent qui supporte bien la fauche et lui rend donc service face aux autres adventices.

Attributs agrégés sous Pratiques culturelles des Précédents :

- L'utilisation de prairies ou de couverts est inefficace pour la gestion du chiendent qui est une plante qui s'accommode très aisément aux prairies. Le chiendent est très peu concurrencé par d'autres espèces, en particuliers les dicotylédones. De plus, la gestion de ces prairies par pâturage n'est pas possible pour toutes les animaux. Les brebis ne consomment par exemple pas le chiendent.
- L'historique d'usage intensif d'herbicides pourrait expliquer la très faible population de chiendent observée ces dernières années.

Attributs agrégés sous Pratiques culturelles de l'Interculture :

- Le travail du sol doit être réalisé dans des conditions très sèches, qui durent jusqu'à 10 jours après l'intervention afin de maximiser le dessèchement des rhizomes.
- La gestion sans labour n'est pas conseillée. S'en passer augmente donc le risque d'infestation par le chiendent.

Attributs agrégés sous Pratiques culturelles de la Culture actuelle :

- L'écimage et le binage sont deux pratiques inutiles face au chiendent. Nous abandonnons donc ces attributs d'entrée.
- L'arrache manuel est inutile dans la lutte contre le chiendent.
- L'apport d'azote ne semble pas plus favoriser le chiendent qu'une autre espèce. De plus, l'azote n'est que faiblement accessible pour le chiendent qui possède ses racines à 40cm de profondeur. L'azote n'est pas retenu comme attribut d'entrée dans le modèle.

Sortie du modèle :

- Sortie identique au modèle Laiteron des champs, cependant les agrégations finales entre système considéré et niveau d'infestation seront différents. En effet, le chiendent est insensible à la prairie et s'y développe très bien.

- SUITES DE L'ATELIER DE CO-CONCEPTION :

Un retour de l'atelier sera proposé aux acteurs, et la suite des étapes de construction des deux modèles sera partagée et fera l'objet de modifications ponctuelles avec les différents experts mobilisés à ce jour. Le contact permanent avec les experts de différents instituts permet également de renseigner le cahier des charges des données nécessaires à l'évaluation de la qualité prédictive des modèles.

ANNEXE IV: Development factors of *C. arvensis*

Factor	Direction	Intensity	Impact on <i>C. arvensis</i> development	References
Water regime	+	++	Probability of emergence and biomass production of <i>C. arvensis</i> increase when water regime increases.	(Bostock, 1978 ; Wilson, 1979 ; Sciegienka et al., 2011)
Drought stress	-	++	Drought stress shown to increase efficacy of mechanical control.	(Hansen, 1918 ; Wilson, 1979 ; Lukashyk et al., 2008)
Temperature	+	+	Temperature increases the germination, until a certain limit of 27°C where all the seeds die.	(Kumar, Irvine, 1971 ; Hamdoun, 1972 ; Amor, Harris, 1975 ; Bostock, 1978 ; Wilson, 1979 ; Bochenek et al., 2009 ; Liew et al., 2012)
Photoperiod	+	+	Periods of light have shown a great increase of germination of <i>C. arvensis</i> .	(Moore, 1975 ; Amor, Harris, 1975 ; Bostock, 1978 ; Wilson, 1979)
Soil compaction	+	+	Compaction due to tractor weight don't impact the growth of <i>C. arvensis</i> , it could even give <i>C. arvensis</i> a small advantage over other plants.	(Hausman et al., 2010 ; Brandsæter et al., 2012 ; Hochstrasse et al., 2012)
Soil texture	0	0	The weed can grow in any soil except peat.	(Rogers, 1928 ; Moore, 1975)
Field boundaries unmowed	+	-/+	Contradictory results. Field boundaries are an important source of <i>C. arvensis</i> for new infestations, acting as threatening reservoirs for some authors.	(Marshall, 1988 ; Theaker et al., 1995)
Stubble tillage	-	++	Efficient mechanical control against <i>C. arvensis</i> , regrowth capacity lowered, increasing the depth exhaust the weed, need to be repeated at least every 3 weeks to have a significant impact. If followed by dry weather, uprooting the weed help the decay of it, especially before the carbohydrate mobilisation by the root system.	(Lukashyk et al., 2008 ; Armengot et al., 2015 ; Thomsen et al., 2015 ; Brandsæter et al., 2017 ; Tamarcaz, 2019)
Selective Cutting	-	++	Mechanical control such as cutting is as efficient as herbicide use against <i>C. arvensis</i> and reduces number of shoots over years	(Hansen, 1918 ; Lukashyk et al., 2008 ; Verwijst et al., 2017 ; Tavaziva et al., 2019 ; Tamarcaz, 2019)
Mowing/Grazing	-	+	Grazing, as cutting, has the effect of starving out the underground parts - long term control, in spring, autumn to sufficiently low levels	(Hansen, 1918 ; Pywell et al., 2010)
Ploughing	-	++	Ploughing above 20 cm deep enable a destruction of the root system of <i>C. arvensis</i> , added to tillage it helps the destruction of the weed	(Pekrun, Claupein, 2004 ; Brandsæter et al., 2011 ; Hochstrasse et al., 2012 ; Thomsen et al., 2015)
Herbicide	-	++	2,4-D or bomoxylinil + MCPA use, at early stage or late stage, is significant in <i>C. arvensis</i> control, reduce seed production	(Hume, 1982 ; Verwijst et al., 2017 ; Tavaziva et al., 2019)
Competitive crops or Meadow	-	++	Crop mixture covers ground and <i>C. arvensis</i> up to 100%, reduces biomass production of <i>C. arvensis</i> . Alfalfa > Hemp > Rye > Grass or leguminous meadow. Long straw cereals also help competition against Canadian thistle	(Wilson et al., 1942 ; Edwards et al., 2000 ; Lukashyk et al., 2008 ; Gruber, Claupein, 2009 ; Hochstrasse et al., 2012 ; Thomsen et al., 2015 ; Weill, 2005a ; Agrotransfert, 2016 ; Tamarcaz, 2019)
Smothering with dried material (straw, manure, ...)	-	+	Kept moist and deep enough the avoid new shoots. Reduced light transmission reduces weed biomass by almost 100%	(Rogers, 1928 ; Hettwer et al., 2002)
Sowing date	-	+	Early sown crops are more likely to get ressources competition with <i>C. arvensis</i> and on the contrary late sown crops (maize, oat, ...) are able to overrule <i>C. arvensis</i> . Depends on the crop: cover crops advantageous when sown early (alfalfa, ...).	(Weill, 2015 ; Thomsen et al., 2015 ; Wedryk, Cardina, 2012 ; Tamarcaz, 2019)
Sowing rate	-	+	High density decreases light transmission to <i>C. arvensis</i> and reduce its biomass production	(Mohler et al., 2001 ; Pilipavicius et al., 2011 ; Wedryk, Cardina, 2012 ; Bourdôt et al., 2015)

(Direction: direction of the effect, Intensity: intensity of the effect, - : detrimental for the development of the weed, + : beneficial for the development of the weed, 0: no effect, + : slight, ++ : significant)

ANNEXE V: Development factors of *S. arvensis*

Factor	Direction	Intensity	Impact on <i>S. arvensis</i> development	References
Water regime	+	++	Soil moisture increases growth, needs fresh and humid soil to develop.	(Zollinger, Kells, 1993 ; Hochstrasse et al., 2012)
Temperature	+	++	25-30°C optimal for germination, <20°C or >35°C not possible, but survival of seed only 12%, rare germination. An average increase of 3°C would cause an earlier emergence time.	(Stevens, 1924 ; Derscheid, Schultz, 1960 ; Hskansson, Wallgren, 1972 ; Torssell et al., 2015)
Photoperiod	+	++	Photoperiod seemed to regulate sprouting capacity. The proportion of sprouted buds decreased in short photoperiods, especially if combined with high temperature.	(Liew et al., 2012 ; Andersson et al., 2013 ; Taab et al., 2018)
Field boundaries unmown	-	-/+	Contradictory results. Recommended to cut and remove cuttings.	(De Cauwer et al., 2007)
Soil texture	+	++	Requires clay soil, limestone soil.	(Weill, 2005b ; Hochstrasse et al., 2012)
Mid-September to Mid-November tillage	0	0	Dormancy period for <i>S. arvensis</i> , tillage is useless, especially in warm fall.	(Liew et al., 2012 ; Andersson et al., 2013 ; Taab et al., 2018)
No Till	+	++	No-Till increases <i>S. arvensis</i> infestation.	(Streit et al., 2002)
Stubble tillage	-	++	Early autumn or after harvest harrow reduces best the perennial weed: spring harrow is less efficient, and late autumn is useless. Stubble tillage is useless if followed by plough. Higher number of shoots was observed where stubble tillage was performed alone.	(Boström, Fogelfors, 1999 ; Streit et al., 2002 ; Thomsen et al., 2015 ; Taab et al., 2018)
Inter-row hoeing	-	+	Inter-row hoeing reduces infestation of <i>S. arvensis</i> .	(Weill, 2005b ; Vanhala et al., 2006)
Ploughing	-	+	Late autumn plough is useless, but post-harvest or in spring it can help control <i>S. arvensis</i> . It does not weaken the weed but increases the emergence period.	(Boström, Fogelfors, 1999 ; Weill, 2005b ; Thomsen et al., 2015 ; Weill, 2018)
Herbicide	-	++	MCPA at 5-7 leaf stage, Clopyralid at 8-10 leaf stage (50% translocated upper parts) 85% absorption, Chlorsulfuron (90% stayed in treated leaf) 30% absorption.	(Devine, Born, 1985)
Competitive crops	-	++	<i>S. arvensis</i> hardly bears the competition on floor. Only a problem on spring crops. Use triticale or cereal + protein crop, red clover under cereal	(Vanhala et al., 2006 ; Hochstrasse et al., 2012 ; Brandsæter et al., 2012)
Meadow	-	++	2-3 years meadow helps reduce <i>S. arvensis</i> . Use alfalfa or temporary meadow. Mowing in autumn will not reduce weed infestation. Acceptable feed for livestock, good nutrient value	(Weill, 2005b ; Vanhala et al., 2006 ; Fontaine, 2011 ; Hochstrasse et al., 2012 ; Andersson et al., 2013)
Cover crops	-	++	Red and white clover cover crops before barley reduces weed infestation.	(Kwiecinska-Poppe et al., 2009 ; Kadziene et al., 2020)
Sowing date	-	++	Sowing late in spring at high temperature allows fast competition of the crop. Or in Autumn for cereal with fast growing in spring	(Weill, 2018)
Sowing rate	-	++	Increase of 10% to compete with <i>S. arvensis</i> .	(Roy, 2017)

(Direction: direction of the effect, Intensity: intensity of the effect, - : detrimental for the development of the weed, + : beneficial for the development of the weed, 0: no effect, + : slight, ++ : significant)

ANNEXE VI: Development factors of *E. repens*

Factor	Direction	Intensity	Impact on <i>Sonchus</i> development	References
Water regime	-	++	Wet years increase the biomass of <i>E. repens</i> .	(Salonen, 1992)
Drought stress	0	0	Contradictory results. Some authors found quackgrass to be drought tolerant, while others observe that it can hardly survive dry summer.	(Nkurunziza et al., 2011 ; Hochstrasse et al., 2012)
Compacted soil	+	+	Compacted soil resulted in more <i>E. repens</i> cover.	(Njos, 1978)
Temperature	+	++	21°C produce best plants, root elongation and new shoots. First, it starts with horizontal roots in spring and summer, then tiller (vertical growth) in autumn.	(Majek et al., 1984 ; Marshall, 1990)
Soil texture	0	0	Soil texture does not influence the growth of quackgrass	(Lemieux et al., 1993)
Nitrogen	+	+	Fertilization double couch grass weigh, length and bud number (32.4 kg N ha ⁻¹), higher competition towards other species for N intake.	(Williams, 1977 ; Marshall, 1990 ; Wedin, Tilman, 1993);
Stubble tillage	-	++	Disc tools cut root into pieces that increase the infestation. Rotary cultivator: 3 times or more help reduce 85% of biomass and 63% of density of <i>E. repens</i> . Goosefoot is very efficient.	(Borresen, 1993 ; Soon, Darwent, 1998 ; Rasmussen, 2002 ; Bonin et al., 2006 ; Bonin, Bibard, 2009 ; Aronsson et al., 2015)
Mowing	0	0	Slightly reduces the biomass of Couch grass, but only above 2 mowings. Even added to cover crops doesn't reduce biomass a lot.	(Harcza et al., 2013 ; Ringselle et al., 2015 ; Melander et al., 2016)
Inter-row hoeing	-	+	Spring crop in the rotation help reduce quackgrass infestation by interrow hoeing	(Fontaine, 2011)
Ploughing	-	++	Ploughing reduce <i>Elymus repens</i> . Fall (88% of reduction) better than spring (78%). Must happen until late fall. Ploughing in spring without fall stubble cultivation resulted in high couch grass cover.	(Njos, Borresen, 1991 ; Lemieux et al., 1993 ; Chandler et al., 1994 ; Boström, Fogelfors, 1999)
Herbicide	-	++	Herbicide is very efficient on <i>E. repens</i> .	(Boström, Fogelfors, 1999 ; Bonin, Bibard, 2009)
Cover crops	-	-/+	Contradictory results. It helps reduce weed, in autumn for some authors. But for other, it is only efficient when added to tillage or herbicide. Even mown, it does not reduce weed infestation.	(Melander et al., 2005 ; Aronsson et al., 2015 ; Melander et al., 2016)
Competitive crops	-	++	Use rye or late spring crop (association oat/vetch, buckwheat, hemp, ...). Rye>wheat>barley>rape>peas. Or oat>barley>wheat less access to light increase height of <i>E. repens</i> but number of shoot and dry weight decrease. Rhizome production also reduced	(Skuterud, 1984 ; Melander, 1993 ; Fontaine, 2011 ; Hochstrasse et al., 2012)
Meadow	-	-/+	The invasion of <i>A. elatius</i> and <i>H. lanatus</i> into this area, together with the stoloniferous growth form of <i>A. stolonifera</i> , may have created conditions which reduced couch growth. Dry meadow is inefficient. No longer than 3 years	(Marshall, 1990 ; Duval, 2008 ; Harcza et al., 2013)
Fallow	0	0	Fallow treatment not shown as more efficient to control <i>E. repens</i> , especially when added with chemical control. <i>E. repens</i> can settle down in temporary meadow	(Soon, Darwent, 1998 ; Hochstrasse et al., 2012)
Sowing rate	-	++	Decreasing the seed rate enable the weed seedling to make 25% more growth (e.g. density 80kg/ha for wheat or barley)	(Williams, 1977)

(Direction: direction of the effect, Intensity: intensity of the effect, - : detrimental for the development of the weed, + : beneficial for the development of the weed, 0: no effect, + : slight, ++ : significant)

ANNEXE VII: R Script

```
data<-read.table(file= 'Cirsium.txt',
                 header=T,
                 dec=".")

#Confusion matrix
A=matrix(0,nrow=5,ncol=5)
for(i in 1:length(data$Observed)){
  A[data$Observed[i],data$Simulated[i]]<-A[data$Observed[i],data$Simulated[i]]+1
}
rownames(A)<-c("Observed 1","Observed 2","Observed 3","Observed 4","Observed 5")
colnames(A)<-c("Simulated 1","Simulated 2","Simulated 3","Simulated 4","Simulated 5")
A

#Cohen's kappa
library("vcd")
res.k<-Kappa(A, weights = "Fleiss-Cohen")
res.k
summary(res.k)

#Accuracy
ACC<-0
for (i in 1:5){
  ACC<-A[i,i]+ACC
}
Accuracy<-ACC/length(data$Observed)

#Precision and Recall Confusion matrix
precision<-c(NULL)
recall<-c(NULL)
for (j in 1:5){
  if (floor(sum(A[,j]))==0){
    precision<-c(precision,0)
  }
  else {
    precision<-c(precision,A[j,j]/sum(A[,j]))
  }
  if (floor(sum(A[j,]))==0){
    recall<-c(recall,0)
  }
  else {
    recall<-c(recall,A[j,j]/sum(A[j,]))
  }
}

D<-matrix(c(precision,recall),nrow=5,ncol=2,byrow=FALSE)
colnames(D)<-c("Precision","Recall")
rownames(D)<-c("Very low","Low","Neutral","High","Very high")
D<-as.table(D)
D
```


#F1-score

```
macro_F1=0
for (f in 1:5){
  if((D[f,1]+D[f,2])!=0){
    macro_F1<-macro_F1+(2*(D[f,1]*D[f,2])/(D[f,1]+D[f,2]))
  }
}
macro_F1<-macro_F1/5
macro_F1
```

#Accuracy and F1-score

```
resultat<-matrix(c(Accuracy,macro_F1),nrow=1,ncol=2)
colnames(resultat)<-c("Accuracy","F1-Score")
resultat
```

 	Diplôme : Diplôme d'Ingénieur de l'Institut Supérieur des Sciences Agronomiques, Agroalimentaires, Horticoles et du Paysage Spécialité : Horticulture Spécialisation / option : Protection des Plantes et de l'Environnement en Horticulture Enseignant référent : LE CORFF Josiane
Auteur(s) : LACROIX Octave Date de naissance* : 28/11/1997	Organisme d'accueil : INRAE Auzeville-Tolosane Adresse : 24 chemin de Borde-Rouge - Auzeville CS 52627
Nb pages : 31 Annexe(s) : 7	31326 CASTANET-TOLOSAN CEDEX
Année de soutenance : 2020	Maître de stage : ROBIN Marie-Hélène
Titre français : Modélisation qualitative de la gestion des adventices vivaces <i>Elytrigia repens</i> , <i>Cirsium arvense</i> et <i>Sonchus arvensis</i> Titre anglais : Qualitative modelling of perennial weed management <i>Elytrigia repens</i> , <i>Cirsium arvense</i> and <i>Sonchus arvensis</i>	
Résumé : Dans un contexte de retrait du glyphosate et de remise en cause de l'utilisation intensive du labour, des outils sont nécessaires pour offrir une alternative au contrôle des adventices vivaces. Les adventices vivaces constituent un problème majeur dans les champs de production, en agriculture biologique ou conventionnelle. Pour les combattre, une approche systémique est nécessaire. C'est l'objectif du work package Modélisation du projet européen AC/DC-weeds. La modélisation qualitative multi-attributs, réalisée grâce à IPSIM (Injury Profile SIMulator), permet d'évaluer l'infestation de trois adventices vivaces : <i>Cirsium arvense</i> , <i>Sonchus arvensis</i> et <i>Elytrigia repens</i> . Les modèles prennent en compte l'effet du climat, du sol, des pratiques culturales, et de leur interaction sur l'infestation des adventices. Les trois modèles proposent différentes méthodes alternatives pour lutter contre la dépendance aux herbicides dans la lutte contre les adventices vivaces. Les utilisateurs des modèles ont la possibilité de construire un agroécosystème plus durable, moins dépendant des herbicides et du labour profond. Ces modèles peuvent également être utilisés comme outils pédagogiques pour enseigner des méthodes alternatives de lutte contre les adventices vivaces.	
Abstract: In a context of recall of glyphosate and questioning about the intensive use of ploughing, tools are needed to offer an alternative for perennial weed control. Perennial weeds are a major problem in production fields, organic or conventional farming. To control them, a System approach is required. This is the aim of the work package Modelling of the European project AC/DC-weeds. Multi-attribute qualitative modelling, performed thanks to IPSIM (Injury Profile SIMulator), enables the evaluation of weed infestation for three perennial weeds: <i>Cirsium arvense</i> , <i>Sonchus arvensis</i> and <i>Elytrigia repens</i> . The models consider the effect of weather, soil and cropping practices, and their interaction on weed infestation. The three models expressed different alternative methods to tackle the reliance on herbicide in perennial weed control. Users of the models have the possibility to build more sustainable agroecosystem less reliant on herbicide and deep ploughing. These models can also be used as an educational tools to teach alternative control methods of perennial weeds.	
Mots-clés : Adventices, Vivace, <i>Cirsium arvense</i> , <i>Sonchus arvensis</i> , <i>Elytrigia repens</i> , Modélisation qualitative, désherbage Key Words: Weeds, Perennial, <i>Cirsium arvense</i> , <i>Sonchus arvensis</i> , <i>Elytrigia repens</i> , Qualitative modelling, weeding	

* Élément qui permet d'enregistrer les notices auteurs dans le catalogue des bibliothèques universitaires