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Raphael Paut

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THESE

pour obtenir le grade de Docteur de l'Université d'Avignon
École Doctorale 536 Agrosociétés & Sciences

**Analyse des compromis entre diversité cultivée et complexité de
gestion à travers le cas d'étude du Verger-Maraîcher.
Une approche combinant modélisation et méthodes qualitatives**

Présentée et soutenue publiquement par

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le 3 Juillet 2020

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Avant-propos

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Anaïs Boury-Esnault (ISARA-Lyon) : *L'organisation du travail dans un système diversifié : cas des vergers-maraîchers. Suivi de fermes en Drôme et région Provence-Alpes-Côte d'Azur* ;

Suzanne Tharel (SupAgro Montpellier) : *Comprendre le fonctionnement et évaluer les performances des vergers-maraîchers* ;

Donatien Jeanlin (Université Paris 1 Panthéon-Sorbonne) : *Analyse des conditions de réussite de l'installation en agroforesterie maraîchère*.

Liste des productions scientifiques

Articles publiés

Paut R., Sabatier R., Tchamitchian M., 2019. Reducing risk through crop diversification: An application of portfolio theory to diversified horticultural systems. **Agricultural Systems** 168, 123–130. <https://doi.org/10.1016/j.agsy.2018.11.002y> (**Chapitre I**)

Paut R., Sabatier R., Tchamitchian M., 2020. Modelling crop diversification and association effects in agricultural systems. **Agriculture, Ecosystems & Environment** 288, 106711. <https://doi.org/10.1016/j.agee.2019.106711> (**Chapitre III**)

Chave M., Angeon V., **Paut R.**, Collombet R., Tchamitchian M., 2019. Codesigning biodiversity-based agrosystems promotes alternatives to mycorrhizal inoculants. **Agronomy for Sustainable Development** 39, 48. <https://doi.org/10.1007/s13593-019-0594-y>

¹ PEI : Projet Européen pour l'Innovation, dans le cadre de la programmation FEADER en région Provence-Alpes-Côte d'Azur

² CIVAM : Centres d'Initiatives pour Valoriser l'Agriculture et le Milieu rural

Castel L., Plessix S., Gaspari C., Warlop F., Fourrié L., Montrognon Y., Ronzon J., Labeyrie B., Ray T., Cadet D., Arlaud C., **Paut R.**, Tchamitchian M., Bouvier J-C., Jammes D., Filleron E., Sieffert A., Fanguede A., 2019. Concevoir et expérimenter des vergers agroforestiers en Agriculture Biologique (VERtiCAL). **Innovations Agronomiques** 76, 273–289.
<https://doi.org/10.15454/5zao4b>

Chave M., Angeon V., **Paut R.**, Tchamitchian, M., 2018. Du partage de connaissances à la co-conception d'innovations agroécologiques : Exemple de la mobilisation des mycorhizes en Guyane. **Innovations Agronomiques** 64, 97–111.
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Paut R., Sabatier R., Tchamitchian M. How to reconcile short-term and long-term objectives in agroforestry systems? A dynamic farm model application to mixed fruit tree - vegetable systems (**Chapitre V**)

Actes de conférence (* personne ayant présenté)

Paut R. *, Sabatier R., Tchamitchian M., 2018. Benefits of diversified horticultural systems: assessment with the modern portfolio theory, in: 13th European IFSA Symposium. Farming Systems: Facing Uncertainties and Enhancing Opportunities. July 1-5, 2018, Chania, Greece (9 p.). (**Chapitre II**)

Paut R.*, Sabatier R., Tchamitchian M., 2018. Horticultural agroforestry systems: a modelling framework to combine diversification and association effects, in: 4th European Agroforestry Conference. Agroforestry as Sustainable Land Use. May 28-30, 2018, Nijmegen, The Netherlands, pp. 437–441. (**Annexe F**)

Paut R. *, Sabatier R., Tchamitchian M., 2019. How to reconcile short-term and long-term objectives in agroforestry systems? An application of viability theory to Mixed Orchard-Market Gardening Systems, in: European Conference on Crop Diversification. Budapest, Hungary. (**Annexe G**)

Paut R., Sabatier R., Tchamitchian M., 2020. Linking scientific and empirical knowledge: an interactive web app to design agroforestry market gardening systems, in: 5th European Agroforestry Conference. Agroforestry for the transition towards sustainability and bioeconomy. Nuoro, Italy. (*soumis, présentation à venir*).

Dufils A., **Paut R.***, 2020. Grazed orchards in France: different forms of livestock integration and their implications for fruit growers' practices, in: 5th European Agroforestry Conference. Agroforestry for the transition towards sustainability and bioeconomy. Nuoro, Italy. (*soumis, présentation à venir*).

Posters

Paut R.*, Boury-Esnault A., Sabatier R., Tchamitchian M., 2019. Complementarities or complexity? The case study of Horticultural Agroforestry Systems, in: 4th World Congress on Agroforestry. Strengthening Links between Science, Society and Policy. Montpellier, France, p. 386. **(Annexe H)**

Sieffert A.*, Morinay A., Zniber T., Canet A., Lavoyer S., Maïzi-Moity P., Sabatier R., **Paut R.**, Tchamitchian M., 2019. Co-design and on-farm experimentation of practices combining conservation agriculture and agroforestry, in: 4th World Congress on Agroforestry. Strengthening Links between Science, Society and Policy. p. 390. **(Annexe I)**

Autres communications

Ne pas mettre tous ses légumes dans le même panier ! Lettre d'information du Réseau Mixte Technologique Agroforesteries. 21 février 2019. <https://www.rmt-agroforesteries.fr/fr/actualites/ne-pas-mettre-tous-ses-legumes-dans-le-meme-panier/>

Le maraîchage agroforestier, pour ne pas mettre tous ses légumes dans le même panier. Journée Internationale Agroforesterie : des arbres dans nos assiettes. 19 mai 2019. Montpellier.

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Partie A. Introduction générale

I. Introduction

1. Contexte et objectifs de la thèse

Le double enjeu productif et environnemental auquel est confrontée l'agriculture a conduit à l'émergence de nouveaux modèles de production basés sur des paradigmes écologiques : agriculture biologique (Besson, 2009; Ollivier and Bellon, 2013), agroécologie (Altieri, 1989; Gliessman, 1990; Wezel et al., 2009) et agroforesterie (Dupraz and Liagre, 2008; Nair, 1993). Ces formes reposent sur une vision écosystémique construite sur une plus grande diversité biologique alliant éléments cultivés et naturels dans l'agroécosystème. Cependant, en France comme en Europe, ces systèmes restent relativement spécialisés, la diversité étant principalement assurée par la succession des cultures plus que par leur coexistence spatiotemporelle.

Dans ce contexte, l'agroforesterie, pratique de complantation entre cultures pérennes et annuelles est aujourd'hui l'un des étendards de la transition écologique. Le projet agroécologique pour la France³ présenté en 2012 par Stéphane Le Foll place à ce titre l'agroforesterie parmi les douze actions prioritaires. Cependant, bien que développée dans de nombreux systèmes traditionnels des régions tropicales et équatoriales, et malgré ses intérêts aujourd'hui avérés pour la gestion de la fertilité du sol, pour les régulations naturelles entre bioagresseurs et auxiliaires, pour sa meilleure efficacité et sa contribution à la séquestration du carbone et à la réduction des besoins énergétiques tant en région tropicale qu'en Europe, elle ne suscite que peu d'intérêt dans les régions tempérées (Eichhorn et al., 2006). Un travail récent dans le cadre du projet européen Agforward⁴ montre qu'environ 14% de la SAU européenne peut être considérée en agroforesterie (Burgess and Rosati, 2018; Herder et al., 2015), mais que la majorité de cette surface consiste en une agroforesterie de haute valeur naturelle et culturelle (incluant en particulier des espèces non cultivées), tandis que les formes associant des arbres à valeur productive ou des grandes cultures sont minoritaires (ibid.). Ce sont pourtant, parmi les systèmes agroforestiers, ceux qui assurent la

³ <https://agriculture.gouv.fr/le-projet-agro-ecologique-en-12-cles>

⁴ <https://www.agforward.eu/index.php/fr/>

plus forte production et permettent donc de répondre au double enjeu environnemental et productif.

Parmi ces systèmes agroforestiers dont les deux strates sont cultivées, l'association de fruitiers et de maraichage, nommées « **Verger-Maraîcher** » ont récemment attiré l'intérêt de nombreux porteurs de projets (Léger et al., 2019; Sieffert et al., 2014). En raison de leur nature fortement agro-écologique, ces systèmes semblent pouvoir répondre à de nombreux défis spécifiques des régions européennes développées : **(i)** leur efficacité est un atout dans la compétition pour l'utilisation des terres dans un contexte d'urbanisation croissante ; **(ii)** leur production diversifiée est particulièrement adaptée aux besoins en produits frais des consommateurs tout en facilitant la création de lien social puisqu'elle permet des modes de commercialisation directe (magasins à la ferme, paniers, marchés, etc.) ; **(iii)** enfin, en raison de leur forte dimension agroécologique, ces systèmes semblent s'inscrire dans un processus de limitation des externalités négatives des systèmes agricoles tout en maintenant un niveau élevé de productivité.

Malgré ces nombreux atouts présumés, l'intérêt que porte la recherche aux systèmes vergers-maraîchers n'est pas à la hauteur de leur potentiel productif et surtout heuristique. Ils n'ont été que très peu étudiés en zone tempérée et de nombreuses références manquent pour leur conception et surtout leur conduite. Ces manques sont d'autant plus handicapants que l'on observe une demande croissante de références de la part du monde agricole (recensement réalisé en France dans le réseau du projet CASDAR SMART). Des travaux de recherches se mettent en place dans ce sens. Ces travaux sont principalement orientés vers l'exploration de la faisabilité d'outils pour l'accompagnement (Maqrot et al., 2016) ou vers la compréhension des processus agroécologiques à l'œuvre dans ces systèmes et en particulier vers les régulations naturelles (Imbert et al., 2019; Martin-Chave et al., 2019b, 2019a). Si ces travaux sont d'importance, ils laissent cependant les agriculteurs quelque peu démunis quant à la conduite de ces systèmes, les interactions entre processus agroécologiques et décisions n'étant pas au cœur de ces études. Pourtant, la gestion de ces systèmes est particulièrement délicate pour deux principales raisons.

La première est bien sûr leur **complexité**, puisqu'ils additionnent les difficultés intrinsèques de deux systèmes très exigeants, arboriculture et maraîchage, auxquelles s'ajoutent celles liées à l'interaction entre les conduites de ces deux systèmes. En effet, l'écologisation des systèmes agricoles est connue pour compliquer leur gestion en augmentant le nombre et la

diversité des éléments en interaction à gérer (Hendrickson et al., 2008; Moraine et al., 2012). Cette gestion intègre donc, encore plus que pour des systèmes spécialisés, une nécessité de priorisation et d'arbitrages entre objectifs et contraintes. La deuxième raison est la forte **incertitude** relative à ces systèmes : incertitude liée à l'incomplétude des connaissances sur leurs dynamiques et leurs interactions avec les actions de pilotage et incertitudes liées au caractère agroécologique de ces systèmes, mobilisant des processus biologiques fondamentalement incertains.

Tous ces éléments semblent établir une relation complexe entre la diversité des cultures qui composent les vergers-maraichers et leur impact sur l'organisation du travail et les modes de gestion correspondants. En pratique, ces systèmes font l'objet de nombreux compromis entre les bénéfices que l'on peut attendre d'une diversité d'espèces cultivées en agroforesterie, et la difficulté de leur mise en œuvre. **L'objectif de cette thèse est donc de mieux comprendre la manière dont se construisent ces compromis en fournissant des cadres d'analyse et de compréhension de ces systèmes structurellement complexes.**

2. Le Verger-Maraicher : une forme singulière d'agroforesterie

De par leur caractère fortement écologisé et situé, les vergers-maraichers se situent, à l'instar de nombreux systèmes agroforestiers contemporains, entre tradition et modernité. Dans cette section nous allons parcourir brièvement l'histoire de ces systèmes, leur disparition progressive et enfin leur réappropriation par un nouveau public d'agriculteurs.

2.1. Disparition progressive des systèmes agroforestiers traditionnels et reconception d'une agroforesterie moderne

Au cours du siècle dernier, la pratique de l'agroforesterie dite « agro-sylvicole » a fortement décliné dans toute l'Europe de l'Ouest. Selon plusieurs auteurs (Eichhorn et al., 2006; Nerlich et al., 2013) cette baisse peut être attribuée à un ensemble commun de déterminants : **(i)** les arbres dispersés dans les paysages agricoles constituaient des entraves à la mécanisation et ont été systématiquement retirés ou endommagés par les engins agricoles ; **(ii)** la dynamique d'intensification d'après-guerre nous a conduit à mettre l'accent sur la maximisation de la productivité grâce à des systèmes mono-spécifiques ; **(iii)** une réduction globale de la main-d'œuvre dans l'agriculture, réduisant ainsi le nombre de systèmes complexes et diversifiés, gourmands en ressources humaines ; **(iv)** le phénomène de remembrement à travers lequel le nombre d'exploitations diminue alors que leur superficie augmente, avec pour effets l'élimination des haies et la simplification du paysage ; **(v)** le régime de subventions de la Politique Agricole Commune (PAC) a conduit indirectement à une réduction des associations de cultures en favorisant les systèmes de culture unique ; **(vi)** enfin, en arboriculture fruitière particulièrement, des normes de qualité plus strictes appliquées aux fruits qui ont incité à normaliser et standardiser leur mode de production⁵.

⁵ Notamment le règlement CEE 1641/71 fixant des normes de qualité pour les pommes et les poires de table.

2.1.1. Aux origines, une pratique ancestrale : Joualle, *Cultura promiscuita*, Huertas, Streuobst et autres exemples d'associations de cultures horticoles en zone tempérée

La Joualle, pratique traditionnelle d'associations de cultures a été pratiquée dans plusieurs régions d'Europe, et notamment dans le sud-ouest de la France (Dupraz and Liagre, 2008) cerisiers, pruniers, abricotiers servaient de support à une vigne grimpante. Ces rangées étaient espacées d'une distance suffisante pour le passage d'un attelage de bœufs, afin de pouvoir cultiver des cultures intercalaires, notamment des légumes. L'introduction de nouvelles techniques culturales a induit une simplification de cette pratique au cours du XXème siècle, le terme « joualle » s'est progressivement déformé, se résumant d'abord à une bi-culture céréale-vigne (jusqu'aux années 60), puis à la séparation complète des cultures.

Ce mode de culture permettait une utilisation optimale des ressources. Les plantes qui composent les différentes strates ayant des besoins nutritifs contrastés peuvent être placées l'une à côté de l'autre. Elles bénéficient de l'étagement et du décalage physiologique dans le temps. Ces systèmes trouvent leurs pendant dans d'autres régions tempérées. La *Cultura promiscua* dont il ne reste plus que des reliques aujourd'hui en Italie (Toscane, Émilie, Campanie), les *Huertas* dans la péninsule ibérique (Coulon et al., 2000), les *Pomaradas* du Nord de l'Espagne (Eichhorn et al., 2006), les *Streuobst* des zones tempérées Européennes (Herzog, 1998), les cultures intercalaires de salades-pêchers du Roussillon (Dupraz, 1994), les Oliveraies traditionnelles de Grèce ou de Sicile (Papanastasis et al., 2009; Rühl et al., 2011) sont autant d'exemples qui traduisaient une volonté de densifier les systèmes agricoles par l'association de cultures pérennes et annuelles(**Figure A-1**).

2.1.2. Le *Homegarden*, semblable tropical

Les systèmes multi-stratifiés ou jardins familiaux (« Homegardens » en anglais) représentent un groupe de systèmes agroforestiers très répandus dans d'autres régions du globe, et qui assurent l'autosuffisance alimentaire de millions de familles d'agriculteurs, principalement en climat tropical (Nair, 2001; Srithi et al., 2012). Contrairement à nos systèmes fortement spécialisés, ces Homegarden sont hérités d'une agriculture paysanne et vivrière encore très présente dans de nombreuses régions. Ils sont caractérisés par la culture de multiples espèces dans des configurations étagées, l'élevage y étant parfois intégré (Torquebiau, 1992). Par conséquent de nombreuses interactions existent entre les différentes composantes du système pour le partage des ressources (Wezel and Bender, 2003).

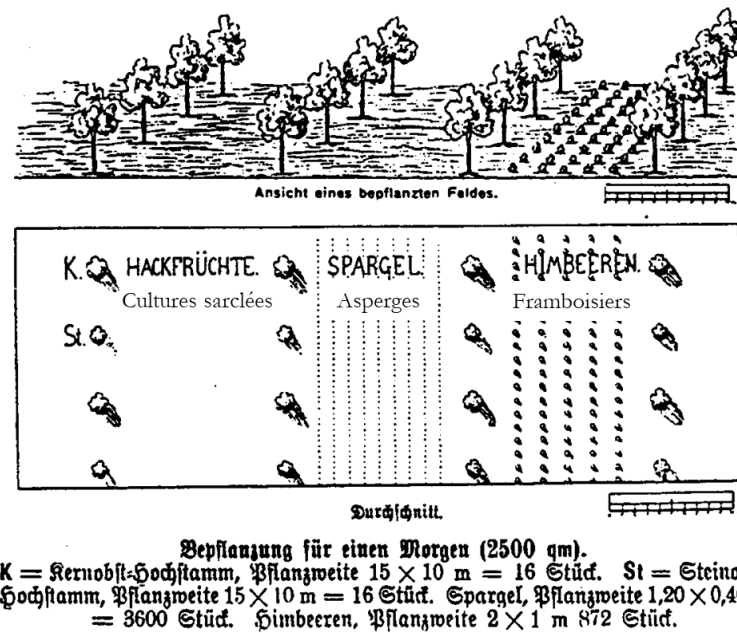


Figure A-1 : Plan pour un verger d'un demi-morgen [0,12 ha] avec des cultures sarclées ou des asperges ou des framboisiers établi entre la fin du XIXème et le début du XXème siècle. Au sein des lignes d'arbres, des fruits à pépins (K) et des fruits à noyau (St) sont alternés, la distance de plantation entre les arbres est 10x15m. (Adapté de Lott 1993)

Souvent considérés comme une analogie des « Homegardens » en climat tempéré, les vergers-maraichers s'inspirent fortement de leurs principes de fonctionnement. Cependant, ils font face aux mêmes difficultés lorsqu'il s'agit d'en étudier les caractéristiques : les quelques études qui ont été menées ont produit plus de questions que de réponses sur les « mystères » de ces systèmes. Pourtant, selon Nair (2001), les *homegardens* prospèrent aujourd'hui presque comme à l'époque pré-scientifique, et pourraient continuer à prospérer pendant longtemps, peut-être sans l'intervention de la science. Cet auteur pose le problème en ces termes : est-ce que la science échappe aux *homegardens* ou est-ce que les méthodes scientifiques que nous utilisons pour l'étude de ces systèmes sont inappropriées ?

2.2. Un regain d'intérêt accompagné d'une forte demande sociale

2.2.1. Une pratique remise au goût du jour : microfermes et agroforesterie en réponse à une forte demande sociale

Les vergers-maraichers, encore extrêmement rares au début de ce siècle, connaissent actuellement un fort engouement auprès des porteurs de projets (**Figure A-2**). Depuis le début des années 2010 et l'essor du maraichage bio-intensif (Morel, 2016; Morel et al., 2017; Morel and Léger, 2016), les formes d'agricultures écologisées sur petite surface couplant maraichage diversifié et arboriculture suscitent l'intérêt de nombreux néo-agriculteurs. Cela se produit notamment en réponse à une forte demande sociale visant à raccourcir les circuits alimentaires et à écologiser les systèmes agricoles (Lamine, 2017; Navarrete et al., 2012).

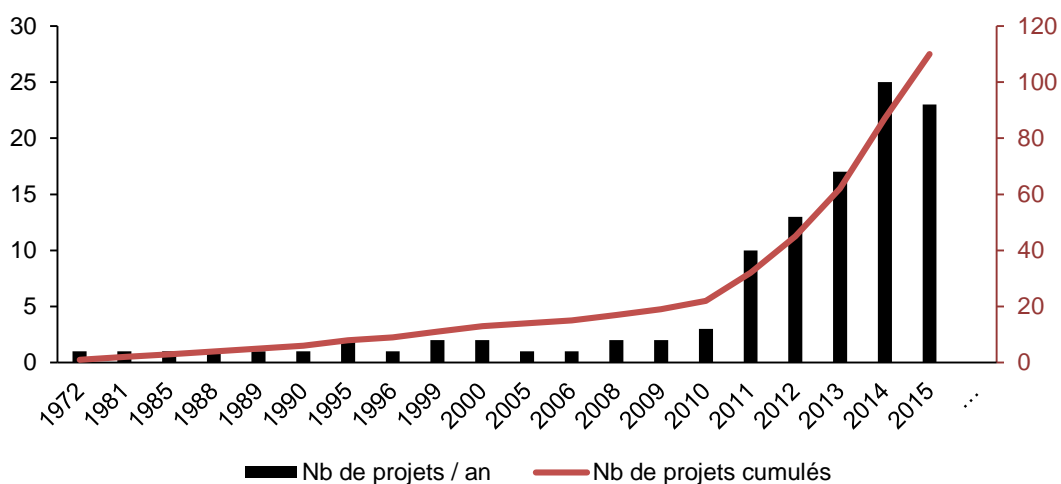


Figure A-2: Nombre de projets verger-maraichers recensés dans le cadre du projet SMART (adapté de Sireyjol 2015)

Pour la première fois en France, le programme CASDAR SMART⁶ a cherché à décrire et caractériser cette forme particulière d'agroforesterie professionnelle. Sur la base de 126 réponses à un questionnaire en ligne, une description de la structure, du fonctionnement et la sociologie de ces fermes a pu être effectuée. Les exploitations sont généralement en agriculture

⁶ SMART : Système Mixtes Agroforestiers : création de Références Techniques & économiques
<https://www.agroforesterie.fr/smart-systemes-maraichers-agroforestiers.php>

biologique, réalisée sur de petites surfaces (63% d'entre elles ont moins de 5 hectares et les parcelles agroforestières représentent 1.3 ha en moyenne). Les agriculteurs combinent une grande variété d'espèces et comptent majoritairement sur des circuits de commercialisation courts (Léger et al., 2019, 2018; Warlop et al., 2017). Ils ne sont majoritairement pas issus du milieu agricole (73%) et possèdent un niveau d'études supérieures relativement haut. En revanche, la grande hétérogénéité des situations et le fait que l'agroforesterie était souvent trop récente sur les fermes enquêtées n'ont pas permis de tirer des enseignements robustes sur les processus biologiques en jeu et les interactions arbres-cultures.

Il existe plusieurs termes pouvant faire référence aux vergers-maraichers, en fonction de l'importance relative du maraichage et de l'arboriculture, mais aussi en fonction du degré d'anthropisation de ces systèmes : potagers-forestiers, jardin-forêt, jardin-multiétagé, vergers-potagers. Dans un contexte d'agriculture professionnelle, une définition du verger-maraicher que nous pouvons retenir est la suivante : **le verger-maraicher est un type d'agroécosystème destiné à la production de fruits et de légumes dans une configuration agroforestière**. Un exemple d'aménagement d'une parcelle en verger-maraicher est présenté en **Figure A-3**.

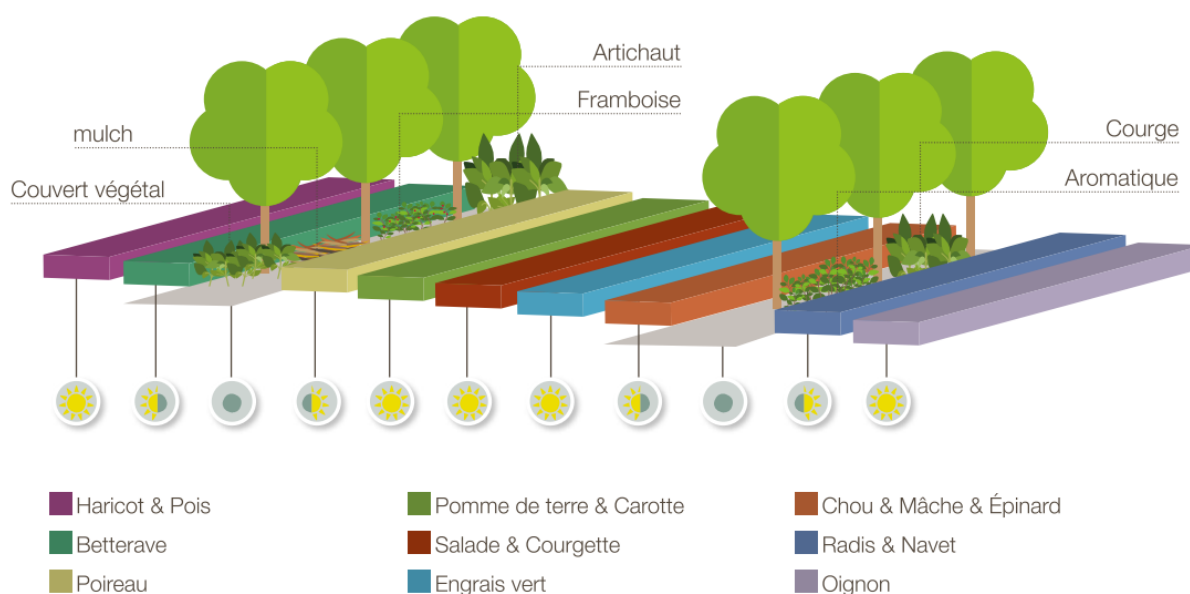


Figure A-3 : Exemple d'aménagement d'un verger-maraicher dans le Nord de la France (Source : Warlop et al. 2017)

2.2.2. Une recherche principalement descriptive : recensement via le projet SMART

Si la recherche commence à se saisir de ce phénomène, c'est principalement par le biais d'études descriptives (Table A-1). La composition, la biodiversité cultivée, les espacements entre lignes d'arbres y sont parfois renseignés. La multiplicité des combinaisons de cultures, le caractère fortement « ancré » et l'âge relativement jeune de ces systèmes rendent l'acquisition de références compliquée avec les cadres d'analyse dont dispose la recherche actuellement. Dans le projet SMART par exemple, même si de nombreux avantages en matière de stratégie de commercialisation ont été notés (Léger et al., 2019), il n'était pas possible d'analyser dans quelle mesure l'agroforesterie avait un impact quantitatif sur les revenus, ni même d'étudier l'impact réel des arbres sur la production maraîchère.

Table A-1. Recensement des recherches sur les systèmes agroforestiers associant fruits et légumes en climats tempérés

Strate arborée	Cultures intercalaires	Localisation	Source
Oliviers	Asperge	Italie	(Rosati et al., 2012)
Orangers	Pois chiches; Pomme de terre	Grèce	(Pantera et al., 2016a)
Oliviers; Figuiers; Raisins de table et Citronniers	Maraîchage (pommes de terre, melons, tomates, haricots, oignons ou fèves) ou PPAM.	Grèce	(Pantera et al., 2016b)
Pommiers et cerisiers	Fraises, laitue, citrouilles, courgettes, haricots.	Suisse	(Petrillo et al., 2016)
Poiriers	Maraîchage	Suisse	(Kaeser et al., 2010)
Vignes complantées de fruitiers	Maraîchage, céréales ou tabac	France (Sud-Ouest)	(Eichhorn et al., 2006; Leterme, 2104)
Oliviers	Maraîchage ou céréales	Bassin méditerranéen	(Dupraz and Liagre, 2008)
Pommiers, Poiriers, Pruniers, Merisiers	Cultures arables, prairies ou pâtures	Europe (climats tempérés)	(Herzog, 1998)
Pêchers	Tomates, courges, fraises, maïs doux	Canada	(Williams and Gordon, 1992)

3. Le Verger-Maraicher : quelles modalités ? Quels intérêts ? Et quels enjeux ?

3.1. Différentes trajectoires et différentes options pour la gestion du cycle productif de l'arbre

Les jeunes arbres fruitiers plantés posent le problème de l'attente d'une récolte. Si les arboriculteurs doivent se résoudre à donner aux arbres le temps nécessaire pour commencer à produire des fruits (par exemple jusqu'à 5-6 ans pour les fruits à pépins), les alternatives offertes par le Verger-Maraicher consistent en une gestion optimale des ressources, du temps et de l'espace, basée sur **deux paradigmes** : les **cultures dites « d'accompagnement »** et **l'agroforesterie (Figure A-4)**.

Dans le premier cas, les cultures d'accompagnement, l'objectif est de maintenir la culture de légumes entre les arbres fruitiers tant que l'ombre des arbres ne les empêche pas de pousser. (**Figure A-4.d**). Les légumes sont ici voués à être retirés sur le long terme, du fait de l'augmentation de la concurrence aérienne et souterraine. La seconde solution consiste à mettre en place un véritable dispositif de cultures intercalaires en limitant volontairement le nombre d'arbres. Les fruitiers sont suffisamment espacés pour permettre une culture intercalaire de légumes sur le long terme. **Il s'agit là du paradigme que nous retiendrons lorsque nous mentionnerons le terme « Verger-Maraicher » dans la suite de ce manuscrit.** Cette configuration peut être la résultante de l'intégration de l'arbre dans une activité maraichère (**Figure A-4.b**) ou conçue *de novo* (**Figure A-4.a**). Cette dernière représente 81% des cas recensés dans le cadre du projet SMART (Cf. supra). Une dernière option consiste à intégrer de manière durable des cultures maraichères dans un verger pré-existant (**Figure A-4.c**).

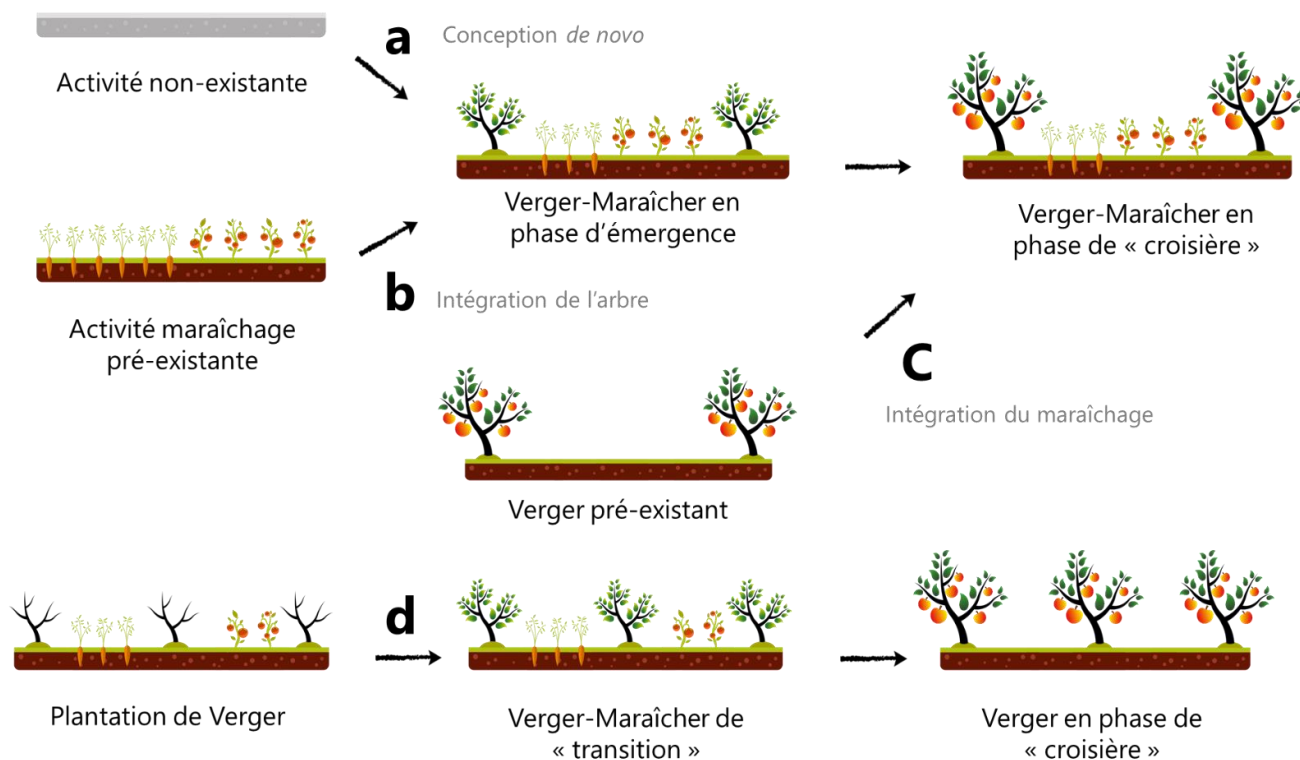


Figure A-4 : Typologie des trajectoires correspondant à différentes options de gestion du cycle productif de l'arbre

3.2. Association de cultures et Agroforesterie, au cœur de ces systèmes

Si le maraîchage (AFAF, n.d.; Agroof, n.d.; Léger et al., 2018) et l'arboriculture (Forey, 2016; Lauri et al., 2016, 2019; Lauri and Simon, 2019) possèdent leurs caractéristiques et leurs comportements propres lorsqu'ils sont en inter-culture, c'est bien l'association spécifique de ces deux productions qui nous intéresse ici et qui soulève de nouvelles problématiques.

Principalement conçus pour optimiser l'utilisation spatiale et temporelle des ressources, en minimisant les interactions négatives tout en maximisant les interactions positives entre les composantes du système (Jose et al., 2004), les vergers-maraîchers multiplient néanmoins les sources d'interactions biologiques possibles. Dans les mélanges plurispécifiques, Justes et al. (2014) distinguent ainsi trois types d'interactions entre espèces : **(i) la compétition** qui se produit lorsqu'une ressource partagée devient limitante ou qu'une espèce génère un environnement défavorable pour l'autre ; **(ii) la facilitation** qui s'opère lorsque l'environnement généré par une espèce est positif pour la seconde ; **(iii) la complémentarité de niche** qui a lieu quand les

différentes espèces utilisent une même ressource de manière décalée dans le temps ou dans l'espace. Nous allons voir ici comment ces trois processus majeurs peuvent se produire dans les systèmes agroforestiers maraichers.

(i) Compétition

Le premier processus que l'on peut discerner quand on parle d'agroforesterie est la compétition : le fait d'associer deux espèces dans un même espace va quasi systématiquement engendrer des concurrences pour un certain nombre de ressources identiques que ces espèces utilisant au même endroit et au même moment. Les exemples d'associations sont nombreux (Dupraz et al., 2005; Dupraz and Liagre, 2008; Fagerholm et al., 2016; Lawson et al., 2019; Lovell et al., 2017b; Shiferaw et al., 2018) et mettent en évidence (à de rares exceptions près) qu'une espèce en association produit moins qu'en monoculture. Cette perte de rendement peut s'expliquer, d'une part, par une densité moins importante des cultures en association par rapport à leur équivalent en monoculture, mais aussi par des compétitions pour les ressources en eau, lumière et les minéraux (García-Barrios and Ong, 2004; Jose et al., 2004; Vandermeer, 1989). Néanmoins, la productivité globale d'une association est généralement supérieure aux cultures pures (Graves et al., 2007; Raseduzzaman and Jensen, 2017; Vandermeer, 1984; Yu et al., 2016), il semblerait donc que certains phénomènes de facilitation et de complémentarités participent à l'élaboration d'un meilleur rendement à l'hectare.

(ii) Facilitation

Une hypothèse centrale dans les systèmes agroforestiers est que la productivité est plus élevée que dans les systèmes de cultures pures en raison d'interactions positives, en surface ou sous terre, pour la capture des ressources (Smith et al., 2013). La présence d'arbres peut modifier l'interception de la lumière et son spectre pour la culture associée, mais aussi son microclimat : température, hygrométrie et vent (Jose et al., 2004; Smith et al., 2013). Cependant, les conséquences de ces modifications diffèrent selon les cycles de développement et les caractéristiques des deux strates. D'une part, les arbres limitent la vitesse du vent et augmentent l'humidité autour d'eux par leur propre transpiration. Elle contribue ainsi à limiter les pics de température et à protéger les cultures sous-jacentes du stress thermique ou du séchage en réduisant leur évapotranspiration (AFAF, n.d.). D'autre part, l'ombre créée par les arbres peut aussi être identifiée comme un facteur de réduction du rendement (Jose et al., 2004). Cette, réponse négative à l'ombrage dépend toutefois de la voie de fixation du carbone de la culture

associée. Contrairement aux espèces C4 comme le maïs ou le sorgho, les espèces C3, comme la plupart des légumes cultivés en climat tempéré, maintiennent un taux constant de photosynthèse entre 50% et 100% d'ensoleillement (Jose et al., 2004). C'est le cas par exemple de certaines variétés de salades qui, en condition d'ombrage à 50%, peuvent conserver un rendement équivalent en raison de sa plasticité physiologique (Marrou et al., 2013). Ainsi, dans les systèmes de vergers-maraichers, les espèces de légumes en C3 profiteront principalement de cette modification microclimatique créée par les arbres. En optimisant l'utilisation des nutriments et en favorisant un bouclage interne des cycles biogéochimiques (les racines des arbres accèdent aux nutriments des couches inférieures du sol et les retournent au sol par la chute des feuilles et les racines mortes), les systèmes mixtes arboricoles semblent également en mesure d'améliorer les niveaux de matière organique et les propriétés physiques du sol et réduisent leur dépendance envers des apports extérieurs. Ainsi, plusieurs études ont enregistré une plus grande diversité microbienne et une activité enzymatique et mycorhizienne accrue dans les systèmes mixtes arboricoles, attribuables à une meilleure qualité et quantité de litière que dans les systèmes de monoculture (Borek and Książniak, 2011; Cannell et al., 1996; Smith et al., 2013; Wartman, 2015).

(iii) Complémentarité de niches

Une autre hypothèse centrale sur le fonctionnement des systèmes mixtes agroforestiers est que l'occupation de différentes strates du sol avec leurs systèmes racinaires respectifs peut conduire à une plus grande efficacité dans l'utilisation des ressources abiotiques (Schroth, 1998). Ce partage de la ressource entre les espèces associées a lieu lorsqu'elles utilisent des formes biogéochimiques différentes d'une même ressource (Bedoussac et al., 2015) ou lorsqu'elles utilisent le même pool de façon différée dans le temps ou dans l'espace (Fridley, 2001). On parle alors de **complémentarités temporelles** ou **spatiales**. Si les arbres et les cultures se développent à différents moments de l'année, il s'agit de complémentarités **temporelles** qui peuvent se traduire par exemple par une efficacité accrue de la photosynthèse à l'échelle du système (Cannell et al., 1996; Eichhorn et al., 2006; Yu et al., 2015). En verger-maraicher particulièrement, les cycles courts des cultures maraichères offrent un niveau de flexibilité supplémentaire pour tirer profit d'un décalage phénologique avec les arbres fruitiers. Elles pourront pousser pendant l'hiver, le printemps ou l'automne, avant ou après le cycle de cultures des arbres, profitant ainsi de tout le rayonnement. Enfin, les complémentarités peuvent aussi être **d'ordre spatial**. Bien que de nombreux travaux aient signalé la plus forte densité de racines d'arbres dans les 30 cm supérieurs du sol, soulignant la concurrence potentielle entre les arbres et les cultures associées,

Schroth (1998) suggère que les plantes elles-mêmes ont tendance à éviter une compétition racinaire excessive par une ségrégation spatiale. Par conséquent, les espèces de plantes associées dans les systèmes mixtes arboricoles développeraient des systèmes racinaires stratifiés verticalement, ce qui conduirait à une complémentarité dans l'utilisation des ressources du sol. Cette situation de systèmes racinaires stratifiés verticalement est susceptible de se produire dans les vergers-maraichers parce que les arbres fruitiers, et en particulier les pommiers, possèdent des systèmes racinaires très plastiques qui réagissent facilement aux changements de leurs conditions de croissance (Schroth, 1998). Pour mieux comprendre ce phénomène Sun et al. (2018) ont récemment conduit une étude visant à explorer la distribution spatiale des racines fines, la différenciation des niches et évaluer la concurrence interspécifique souterraine dans un système agroforestier à base de pommes (de 3, 5 et 7 ans) et de soja. On observe une différenciation spatiale des systèmes racinaires, le pommier occupant des strates plus profondes qu'en monoculture alors que le soja occupait des strates plus superficielles (**Figure A-5**). En revanche, cette capacité à explorer des niches écologiques différentes diminuait progressivement avec l'âge des arbres. Cet exemple montre qu'au-delà de la simple prise en compte des interactions entre espèces, la dynamique propre à chacune de ces espèces (et surtout aux espèces arboricoles) est primordiale.

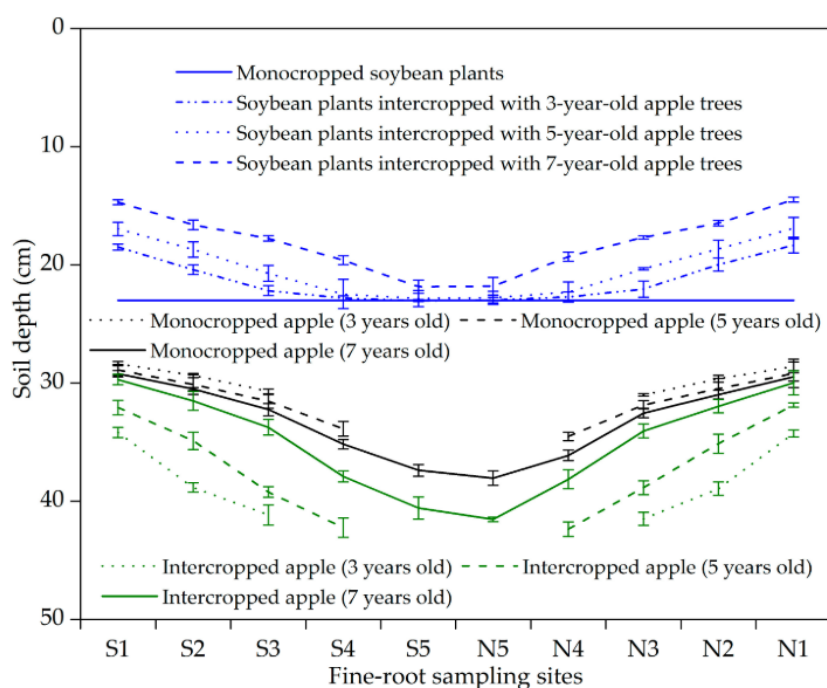


Figure A-5 : Profondeur de l'enracinement du pommier et du soja en fonction de la distance au rang de pommiers et de l'âge des arbres. Sun et al. (2018)

Ces processus (**compétition**, **facilitation** et **complémentarité de niche**) s'appliquent à de nombreux autres facteurs abiotiques dès lors qu'il existe des pools biogéochimiques différents et que les espèces associées utilisent ces pools de manière différée (Justes et al., 2014). Ces interactions restent toutefois très complexes à appréhender en verger-maraicher dans la mesure où elles peuvent se produire de manière **concomitante**, du fait de la grande diversité d'espèces cultivées, et **dynamique**, du fait de la dimension pérenne des arbres fruitiers. L'ensemble de ces processus restent alors à tester dans le cas spécifique du verger-maraicher.

3.3. Enjeux et points de vigilances liés à l'association de ces 2 productions

Après avoir passé en revue les principales caractéristiques des verger-maraichers et les processus biologiques majeurs au sein de ces systèmes, nous allons maintenant nous intéresser aux principaux points de vigilances. Dans notre analyse, ceux-ci sont de plusieurs ordres, et peuvent se résumer en quatre points :

- (i) Approfondir la relation entre diversification des cultures, agroforesterie et résilience du système dans le cas spécifique du verger-maraicher
- (ii) Appréhender une complexité structurelle et organisationnelle accrue
- (iii) Caractériser les changements de pratiques et d'organisation du travail que cette diversité requiert
- (iv) Enfin, mieux discerner les tensions temporelles entre maraichage et arboriculture qui reposent sur les dynamiques très contrastées.

3.3.1. Creuser les liens entre diversité et résilience en contexte horticole

Dans un contexte d'incertitudes croissantes où les moyens de contrôle disponibles pour les agriculteurs sont de moins en moins efficaces, ceux-ci doivent adapter leurs pratiques, et la diversification des cultures est souvent identifiée comme l'un des principaux leviers pour faire face aux risques et aux incertitudes (Cf. Encadré 1) (OECD, 2009; Tilman et al., 2002; Vandermeer et al., 1998). Alors que les vergers-maraichers reposent sur deux piliers agronomiques principaux : la diversification et l'association de cultures, il existe néanmoins

encore peu de littérature sur l'intérêt de ces deux leviers au regard des risques et incertitudes dans le contexte spécifique de l'horticulture.

Encadré 1 : Risques et incertitudes, précision des termes utilisés

Une étude mobilisant la notion de « risque » requiert nécessairement une discussion sur les termes et définitions, pour assurer la cohérence et éviter toute confusion dans la terminologie utilisée. L'Organisation de Coopération et de Développement Economique (OCDE) propose un cadre holistique pour l'analyse des systèmes de gestion des risques agricoles (OECD, 2009). Une première distinction est faite entre le risque et l'incertitude (Knight, 1921) : le **risque** nécessite d'être quantifiable, objectivable en termes numériques ou de probabilités, alors que **l'incertitude** suppose des résultats incertains et des probabilités inconnues. En pratique, cette distinction n'est pas très opérationnelle, car les probabilités sont rarement connues et sont souvent considérées comme subjectives (Moschini and Hennessy, 2001). Certains auteurs font une distinction plus utile entre le risque, considéré comme une exposition à des facteurs externes défavorables et l'incertitude, vue comme une incomplétude des connaissances (Hardaker et al., 2015). En pratique, ces deux concepts sont très liés et sont souvent utilisés de manière substituable.

Dans un contexte agricole, de nombreuses études ont traité de la notion de risque à différentes échelles et selon des critères variables. L'OCDE (OECD, 2000) distingue plusieurs types de risques touchant spécifiquement l'activité agricole: le **risque de production** (conditions météorologiques, maladies et ravageurs, mutations technologiques), les **risques écologiques** (changement climatique, gestion des ressources naturelles telles que l'eau), les **risques de marché** (volatilité des prix de vente, variabilité des coûts des intrants, etc.) et enfin les **risques réglementaires ou institutionnels** (réglementations gouvernementales sur l'agriculture et l'environnement). D'autres auteurs (Hardaker et al., 2015; Huirne et al., 2000) différencient deux grands types de risques en agriculture. En premier lieu, le **risque commercial**, qui comprend les risques de production, de marché, institutionnels et personnels. Si les trois premiers types de risques se retrouvent dans la classification de l'OCDE (Cf. Supra), les risques personnels sont dus à des événements de vie incertains tels que la mort, le divorce ou la maladie. Deuxièmement, le **risque financier**, qui résulte des modalités de financement et des stratégies d'emprunt de l'entreprise agricole.

Notre étude se situe à l'échelle de l'exploitation, nous retiendrons ici la notion de risque sur la production agricole. Plus précisément, **nous considérerons le risque comme la variabilité inter-annuelle de la production.**

De nombreuses études sur les systèmes peu anthropisés suggèrent que les systèmes diversifiés ont tendance à produire des services écosystémiques de manière plus stable (Anderson

et al., 2013; Balvanera et al., 2014; Schindler et al., 2010; Tilman et al., 2006). Ces travaux reconnaissent un effet « portefeuille » à l'œuvre dans les systèmes naturels, qui se traduit par le fait que les communautés à forte diversité donnent une diversité de réponses à une même perturbation environnementale (Elmqvist et al. 2003). Par conséquent lorsqu'elles sont considérées ensemble, ces espèces créent une fonction stabilisatrice qui préserve l'intégrité d'un service écosystémique donné, le service d'approvisionnement par exemple (Cardinale et al., 2007; Tilman et al., 1998; Vandermeer, 1989).

Dans ce contexte de théorie écologique, il serait tentant de faire une analogie avec les systèmes agroforestiers : plusieurs espèces qui poussent ensemble représentent un système plus diversifié que l'une ou l'autre poussant seule. Cependant, la plupart de ces formulations écologiques traitent de situations de grande diversité spécifique, dans des conditions relativement peu anthropisées, et les conclusions qu'elles tirent ne sont pas directement transposables aux systèmes de cultures associés tels que nous les considérons. Dans des situations agricoles où l'impact de l'homme est plus important, il est nécessaire de garder des précautions sur l'applicabilité de ces résultats issus de l'écologie. On peut néanmoins mentionner certaines études tentant de clarifier la relation entre biodiversité (planifiée ou associée) et processus à l'œuvre en horticulture :

- (i) Brown (2012) a comparé les niveaux de biodiversité et leurs effets sur la pression des ravageurs, les rendements et l'utilisation des pesticides entre des parcelles de monoculture (pommiers et pêchers), et des parcelles d'arbres fruitiers en polyculture (pompes, poires, pêches et cerises combinées), avec ou sans plantes compagnes entre les rangs d'arbres. Les résultats montrent que plus d'insectes prédateurs étaient présents dans les parcelles de polyculture et que les traitements les plus diversifiés (polyculture combinée avec des plantes compagnes) avaient la plus grande proportion d'herbivores et de prédateurs. L'auteur conclut que la création d'un verger diversifié peut produire des fruits de haute qualité sans sacrifier le rendement, aucun effet sur la performance des pommiers et des pêchers n'a été observé, tout en réduisant l'utilisation des insecticides.
- (ii) En 2010, Simon et al. ont examiné 30 cas d'études sur les effets de l'augmentation de la diversité végétale dans les vergers (bandes fleuries, couverts végétaux, haies ou même arbres fruitiers intercalaires) sur la lutte contre les ravageurs. L'effet sur la lutte contre les ravageurs était le plus souvent positif (16 cas) ou nul (9), mais aussi négatif

dans certains cas (5). Cette étude souligne le fait que les interventions sur la diversité végétale visaient généralement à favoriser les espèces prédatrices ou parasitoïdes auxiliaires, mais elle constate également des difficultés d'identification des plantes ou mélanges de plantes pour la lutte contre les principaux ravageurs.

- (iii) Plus récemment, une étude (Imbert et al., 2019) s'est attachée à caractériser et comprendre les phénomènes de régulation naturelle dans une parcelle associant Pommiers et Choux. Les résultats de cette étude montrent que la présence de l'arbre induit une plus grande abondance de ravageurs⁷ et une moindre présence d'auxiliaires⁸.

À travers ces quelques exemples, nous voyons que le lien de causalité entre diversité et performances (agronomiques ou environnementales) des systèmes agricoles n'est pas univoque. Plus généralement, il y a un enjeu à clarifier le lien causal dans relation diversité-résilience : le sens de l'effet (positif ou négatif) et le caractère systématique de cette causalité méritent d'être approfondis en contexte agricole (Détang-Dessendre et al., 2018).

3.3.2. Des systèmes « intégrés » et « dynamiques » ?

Un second enjeu lié à l'association de l'arboriculture et du maraichage réside dans le fait que les systèmes qui en résultent sont structurellement complexes. De par l'organisation spatiale et temporelle de plusieurs ateliers, les vergers-maraichers se rapprochent beaucoup de ce que certains auteurs nomment systèmes « dynamiques », « intégrés » ou « synchronisés ». Les cadres d'analyse de systèmes intégrés sont nombreux, notamment dans les systèmes intégrant l'élevage et des polycultures (Bonaudo et al., 2014; Moraine et al., 2016; Ryschawy et al., 2012). Si ces approches diffèrent principalement par les relations entre ateliers et l'échelle considérée elles mettent systématiquement en évidence la nécessité de gérer une complexité structurelle et organisationnelle accrue. Nous allons développer deux cadres d'analyses présentés pour leur valeur générique et leur fonction « d'aide à penser ».

⁷ Sur certains groupes fonctionnels : le puceron *Myzus persicae* Sulzer, les œufs et les chenilles de lépidoptères et les pupes d'aleurodes

⁸ Sur certains groupes fonctionnels également : les chilopodes, les forficules et les fourmis

Hendrickson et al. (2008) ont formalisé la manière dont les agriculteurs combinent un ou plusieurs ateliers avec des stratégies de gestion pour former des systèmes agricoles. Ces systèmes de production peuvent varier en complexité **structurelle** et **organisationnelle** pour former une hiérarchie des systèmes de production. Ces auteurs proposent un cadre d'analyse des systèmes de production les plus courants et leurs implications en termes de complexité de gestion et de durabilité (**Figure A-6**).

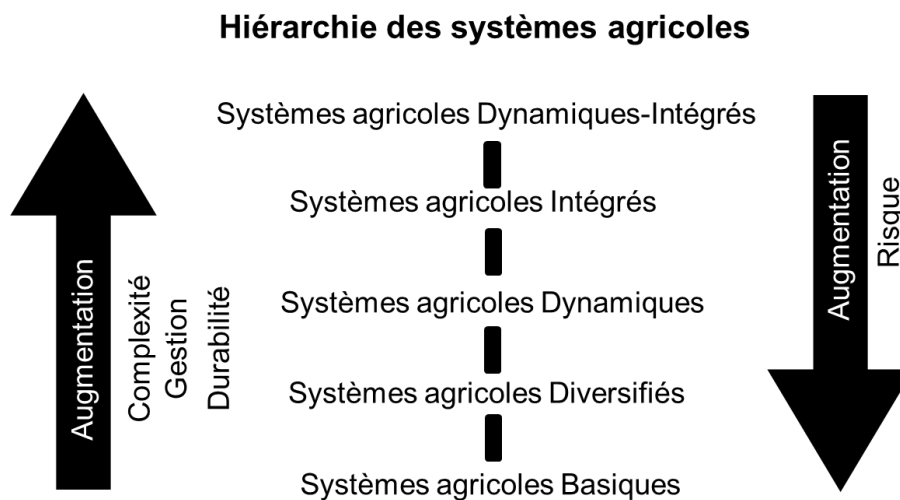


Figure A-6 : Représentation hiérarchique des systèmes agricoles en fonction de leurs caractéristiques dynamiques et de leur degré d'intégration. À mesure que les systèmes agricoles passent de systèmes de production « basiques » à des systèmes « intégrés-dynamiques », la durabilité, la complexité et la gestion du système augmentent, le risque (au sens de résilience face aux aléas) diminue. (adapté de Hendrickson et al. 2008)

Les systèmes « basiques » sont les plus simples et sont fondés sur une monoculture ou une rotation très simple. Les décisions de gestion sont prédéterminées et le système est axé sur la livraison d'un produit uniforme destiné à la transformation alimentaire. À l'inverse, les auteurs décrivent des **systèmes dits « dynamiques-intégrés »**. Il s'agit de systèmes de production avec de multiples ateliers, qui interagissent dans l'espace et/ou dans le temps, et ces interactions se traduisent par un flux de matières entre les ateliers. Bien que les systèmes « intégrés-dynamiques » soient d'une complexité structurelle semblable à celle des systèmes « intégrés », ils exigent un plus haut degré d'efficacité organisationnelle. Les producteurs doivent non seulement comprendre les exigences d'une large gamme de productions, mais ils doivent également tenir compte des potentielles interactions entre les productions afin d'obtenir un maximum de synergies. Une option peut être de modifier la composition du système en fonction de facteurs exogènes ou des contraintes organisationnelles. Par exemple en verger-maraîcher, un producteur peut envisager de modifier l'assolement maraîcher en réponse à un changement des

conditions environnementales induites par la présence des arbres. Pour résumer, l'ajout d'une approche dynamique à un système diversifié augmente les exigences en matière de gestion/organisation parce que les décisions ne sont pas prédéterminées, mais prises en fonction de facteurs multiples. Le système dit « dynamique-intégré » est le système le plus complexe parce qu'il prend en compte plusieurs ateliers et que les interactions entre ces ateliers et les décisions de gestion ne sont pas prédéterminées ou sont évolutives.

Bell et Moore (2012) proposent une lecture proche des systèmes intégrés (**Figure A-7**), en envisageant un ensemble imbriqué de quatre niveaux d'intégration : la **spécialisation** (non intégré sur le plan organisationnel), la **séparation** (intégré sur le plan organisationnel uniquement), la **rotation** (intégré sur le plan organisationnel et spatial, mais non dans le temps) et enfin la **synchronisation** (intégré dans les trois dimensions). Cette classification rejoint les dimensions spatiales et temporelles proposées par Sumberg (2003), auxquelles ce dernier ajoute deux autres dimensions décrites comme étant d'ordre organisationnel plutôt que « physique ». La **dimension propriété** traduit la mesure dans laquelle l'accès et le contrôle des ressources utilisées au sein de plusieurs ateliers sont concentrés entre les mêmes mains. Enfin, la **dimension gestion** de l'intégration traduit l'idée que la gestion des activités des différents ateliers peut être (ou ne pas être) entre les mains de la même personne.

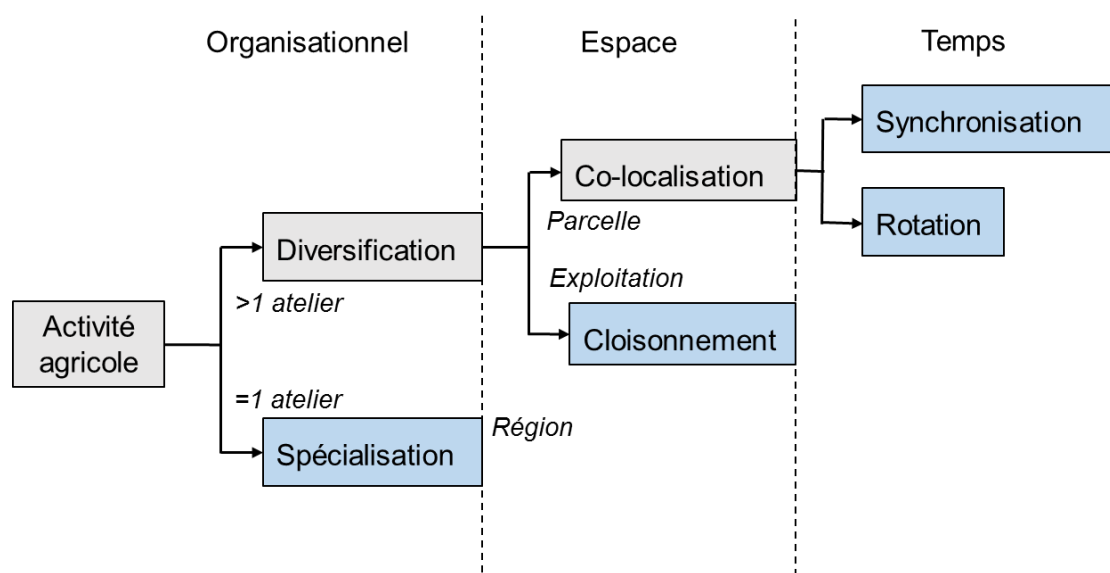


Figure A-7 : Une typologie imbriquée pour décrire les pratiques qui impliquent l'intégration des ateliers de culture et d'élevage au sein des exploitations commerciales. Adapté de Bell et Moore (2012)

3.3.3. Gestion, itinéraires techniques (ITK) et organisation du travail

Du point de vue de l'organisation du travail, les vergers-maraichers présentent deux caractéristiques principales susceptibles de complexifier le fonctionnement de l'exploitation. Premièrement, la présence de deux productions très exigeantes, maraichage et arboriculture, sur la même exploitation suppose a priori la nécessité de faire des adaptations dans la gestion de chaque système afin que ceux-ci soient compatibles en termes organisationnels (Navarrete et al., 2014). Ensuite, l'imbrication de ces ateliers dans une stratégie d'association culturale implique a priori aussi des changements dans la nature des opérations culturales, attribuables au fait que les arbres et les cultures interagissent biologiquement. Les difficultés liées au fait de cultiver une grande diversité de fruits et des légumes au sein d'une même exploitation semblent s'additionner au fait que ces cultures sont agencées dans une logique agroforestière. La question se pose donc de savoir comment cette forme particulière d'agriculture modifie le fonctionnement de l'exploitation.

En maraichage diversifié, Aubry et al. (2011) proposent des clés d'analyse sur les conséquences de la diversification des cultures, couplée à une commercialisation en circuits courts, sur l'organisation du travail et les pratiques culturales qui en résultent. Tout d'abord, la multiplicité des cultures peut induire un regroupement des itinéraires par « lots » de cultures ou de parcelles. Ainsi, les agriculteurs ne raisonnaient plus leurs cultures de manière individuelle, mais opéreraient des regroupements nécessaires pour la simplification de la gestion du système (Marguerie, 2011; Petit et al., 2010). Ensuite, la notion même d'itinéraire technique (au sens de combinaison de pratiques culturales en vue d'un objectif de production) serait considérablement remise en cause dans les systèmes diversifiés, par une homogénéisation et une impossibilité de gérer *n* cultures de manière distincte (Jean, 2011). Certains travaux (Bon et al., 2010; Bressoud, 2006) montrent à ce titre que des opérations de fertilisation peuvent se faire par un apport unique concernant toutes les cultures, indépendamment de leurs besoins individuels. Aussi, certains traitements phytosanitaires peuvent être omis, soit volontairement du fait de la tolérance des circuits courts à des produits de moindre qualité visuelle, soit involontairement du fait des incompatibilités entre certaines plantes ou du respect des délais réglementaires avant récolte (Aubry et al., 2011).

L'ensemble de ces éléments restent valables en condition de verger-maraicher et nous pouvons en formuler 2 complémentaires : (i) l'introduction de l'arbre dans un système maraicher (ou réciproquement) constitue une diversification fonctionnelle, que certains auteurs nomment « diversification horizontale » (Zander, 2008). L'adjonction d'une forme de production supplémentaire et la nécessité d'acquérir des compétences et connaissances sur cette nouvelle production complexifient a priori considérablement plus l'organisation du travail et la gestion du système qu'une simple diversification intra-production (Eksvärd, 2016). On fait l'hypothèse qu'ajouter une culture maraichère à une rotation maraichère déjà diversifiée n'induit pas le même degré de complexité que l'introduction d'une espèce fruitière. (ii) Enfin, la configuration agroforestière (au sens de l'imbrication étroite des productions) peut exacerber des incompatibilités biologiques déjà identifiées en maraichage diversifié, et par conséquent accentuer les modifications des itinéraires techniques qui en résulteraient. Ces hypothèses restent néanmoins à tester.

3.3.4. Le temps « long » de l'arboriculture Vs. Le temps « court » du maraichage

Si l'activité de maraichage diversifié est souvent considérée comme une activité nécessitant peu d'investissement financier comparativement à d'autres types de production, l'arboriculture en revanche demande un investissement conséquent pour mettre en place et faire évoluer l'outil de production. Deux logiques d'investissement et de gestion de l'agrosystème qui renvoient à deux manières de se projeter sur le long terme (Bon et al., 2010). Plus généralement, dans un monde marchand, le fait incontournable que les exploitations doivent investir dans leur avenir si elles veulent en avoir un, peut engendrer des tensions. Comment produire un revenu acceptable à court terme afin de se donner les moyens d'avoir une vision à moyen et long terme ? *Entre-temps*, des objectifs de rentabilité et de viabilité sont à tenir, mais ces objectifs sont mis à mal si, pour tenir une stratégie de long terme, il faut renoncer à un revenu immédiat. Planter des arbres dans une parcelle maraichère, c'est aussi investir dans l'avenir, ce qui est coûteux et incertain. Cela exige que le rendement d'aujourd'hui compense l'investissement financier et le temps de travail que la plantation et la formation des arbres requièrent.

Au-delà de cet aspect purement économique, **une question clé qui doit être abordée est celle de la dynamique de ces systèmes et de la gestion adaptative qui en résulte, pour**

prendre en compte les changements structurels et fonctionnels qu'ils connaissent au court du temps (Léger et al., 2019). Selon Quellier (2004) les associations entre fruitiers et annuelles doivent répondre à l'exigence de gérer au mieux le cycle végétatif d'un arbre qui ne fructifie pas dans ses premières années : *« Nous sommes là en présence d'une des grandes spécificités de l'arboriculture fruitière qui pose, à la communauté rurale, le problème de la gestion d'une culture permanente sur plusieurs décennies, du semis des pépins ou de la plantation de sauvageons à l'abattage de l'arbre »*. Une fois planté, les techniques de formation et d'éclaircissement sont essentielles pour stimuler la croissance et la fructification des arbres, année après année. Ces manipulations de l'architecture des arbres ont deux objectifs : donner une forme à l'arbre pour optimiser l'interception de la lumière par rapport la conception de la plantation et à équilibrer la croissance végétative et la fructification pour assurer la régularité des fruits (Lauri et al., 2016, 2019). En effet, certains arbitrages qui portent sur la prestation immédiate du service de production (dans notre cas, le maraichage) peuvent se faire au détriment d'autres services à l'avenir. Ces compromis dans le temps ont un impact déterminant sur les dynamiques biologiques de l'agrosystème. De nombreux processus naturels, tels que ceux qui impactent la formation de l'arbre, ou la fertilité du sol se produisent à un rythme tel que plusieurs années peuvent passer avant que des effets importants soient perçus par l'agriculteur. Les conséquences de ces arbitrages deviennent alors des externalités supportées avec un décalage temporel. Finalement, la principale caractéristique d'un compromis dans le temps réside dans le fait que les besoins à court terme de l'agriculteur orientent ses décisions de priorisation en ignorant (soit délibérément par manque de temps, soit implicitement par méconnaissance des processus) les conséquences futures de ces arbitrages.

II. Problématique et questions de recherche

1. Enjeux scientifiques et questions de recherche

Comme indiqué précédemment, les vergers-maraichers sont des systèmes mixtes qui visent à optimiser l'utilisation des ressources spatiales, temporelles et physiques en produisant des biens différents sur la même parcelle et de manière concomitante. Cette stratégie d'optimisation peut être la résultante de différents choix stratégiques : valorisation de surfaces limitées disponibles, la recherche de stabilité des revenus notamment via l'atténuation des risques agronomiques, la réponse à la demande des consommateurs de circuits de commercialisation courts, la volonté de diminuer les intrants chimiques ou d'augmenter la biodiversité, etc. Néanmoins, ces systèmes sont par nature complexes, en raison de la grande complexité structurale des systèmes unitaires qui les composent (que sont le maraichage et l'arboriculture), amplifiée par l'association de ces deux systèmes unitaires, mais aussi en raison de leurs dynamiques temporelles très contrastées. Pour être viables, les services rendus doivent être supérieurs aux contraintes liées à ce type de systèmes : nécessité d'acquérir des connaissances et compétences en arboriculture ET en maraichage, contraintes de mécanisation, différentiel dans le démarrage de la production de fruits par rapport aux vergers traditionnels, incertitudes sur les interactions biologiques en jeu, etc.

Dans cette optique, la question de l'identification et/ou de la caractérisation des conditions permettant d'obtenir un compromis entre résilience des performances et complexification du système à gérer, nécessite d'être posée. Nos travaux se concentrent donc autour de la problématique suivante : **Comment se caractérisent les compromis entre les bénéfices attendus de l'agroforesterie maraichère et les difficultés engendrées par la complexité structurelle et organisationnelle de ces systèmes ?**

Sur la base de l'articulation des différentes problématiques citées ci-dessus, les questions de recherche structurant ma thèse sont donc les suivantes :

Q1. La diversification et l'association de cultures sont-elles susceptibles de réduire le risque en horticulture ?

Q2. Comment la diversification et l'association des cultures influencent-elles l'organisation du travail et reconfigurent-elles la nature des pratiques agricoles en verger-maraicher ?

Q3. De quelle manière la différence de dynamique entre les cultures pérennes et annuelles impacte-t-elle la viabilité des systèmes verger-maraichers ?

2. Organisation du manuscrit

Cette thèse est articulée autour de 5 articles : quatre articles pour des revues internationales à comité de lecture (deux publiés, deux en préparation) et un article publié dans les actes d'une conférence internationale. Les questions de recherche mentionnées ci-dessus m'ont amené à développer en parallèle une approche de modélisation et une approche compréhensive qui se nourrissent l'une l'autre. Dans cette section, nous passons brièvement en revue les différents outils mobilisés et leurs apports pour traiter nos questions de recherche.

Dans un premier temps (**Chapitre I**) nous nous saisissons de la théorie du portefeuille ; une théorie économique qui expose comment la diversification des actifs au sein d'un portefeuille d'actifs peut permettre d'en réduire le risque global. Ce chapitre décrit la manière dont nous avons transposé cette théorie à un contexte horticole diversifié, afin de répondre à la première question de recherche (Q1). À partir d'une base de données publique, nous modélisons un très grand nombre de couples de cultures. Cela nous permet d'identifier des stratégies de diversification pertinentes du point de vue de la réduction du risque agronomique pour des assolements relativement simples composés de deux cultures.

Le **Chapitre II** alimente cette première approche en lui apportant deux principaux compléments. D'abord, nous considérons des portefeuilles plus diversifiés permettant de modéliser des assolements allant jusqu'à 22 cultures. Ensuite, nous introduisons un proxy économique pour appréhender la rentabilité économique de l'assolement. Nous montrons

notamment une relation non linéaire entre le nombre de cultures dans le portefeuille et le risque associé. Ainsi, une part significative du risque peut être atténuée jusqu'à 10 cultures.

Le Chapitre III complète notre approche de modélisation de stratégies de diversification, en y intégrant les processus d'interactions entre cultures afin d'apporter d'autres éléments de réponse à la question de recherche (Q1). Les portefeuilles ne sont alors plus considérés comme des ensembles de cultures séparées dans l'espace, mais bien comme des ensembles de cultures en interaction entre elles. Nous proposons donc un cadre conceptuel qui formalise ce que nous appelons les « effets de diversification » et « effets d'association ».

Ces trois premiers chapitres mobilisant fortement la théorie du portefeuille, une description détaillée de cette théorie et de son application en contexte agricole est présentée en **Annexe A**.

Afin de répondre à la deuxième question de recherche (Q2), le **Chapitre IV** examine l'effet du verger-maraicher sur l'organisation du travail et la nature des pratiques agricoles. À partir d'entretiens semi-directifs auprès de 15 agriculteurs, nous décrivons plusieurs typologies de pratiques, qui dépendent du niveau d'intégration entre chaque atelier (arboriculture et maraichage). Il apparaît que l'organisation du travail et les opérations culturales sont altérées à la fois par la diversité fonctionnelle des cultures présentes sur l'exploitation, mais également par la configuration agroforestière de ces cultures.

Concernant la troisième question de recherche (Q3), le **Chapitre V** analyse les relations entre la répartition de la surface cultivée, l'allocation du temps de travail (entre l'arboriculture et le maraichage) et la dynamique biologique de l'agrosystème « verger-maraicher ». Nous avons construit un modèle dynamique à l'échelle de la parcelle. Couplé avec une calibration à dire d'experts, cela nous permet de caractériser la relation entre l'allocation du temps de travail et la dynamique du système, ainsi que d'identifier les dynamiques de gestion satisfaisant les objectifs de l'agriculteur au cours du temps parmi un ensemble des possibles.

Enfin, la **discussion générale** met en perspective l'ensemble des résultats et décrit leurs implications pour d'autres systèmes agricoles, mais aussi pour le développement agricole. Nous proposons des options de gestion pour une bonne articulation entre les bénéfices attendus d'une diversité cultivée accrue et la complexité de gestion qui en résulte.

L'articulation entre les différentes parties de la thèse est présentée en **Figure A-8**.

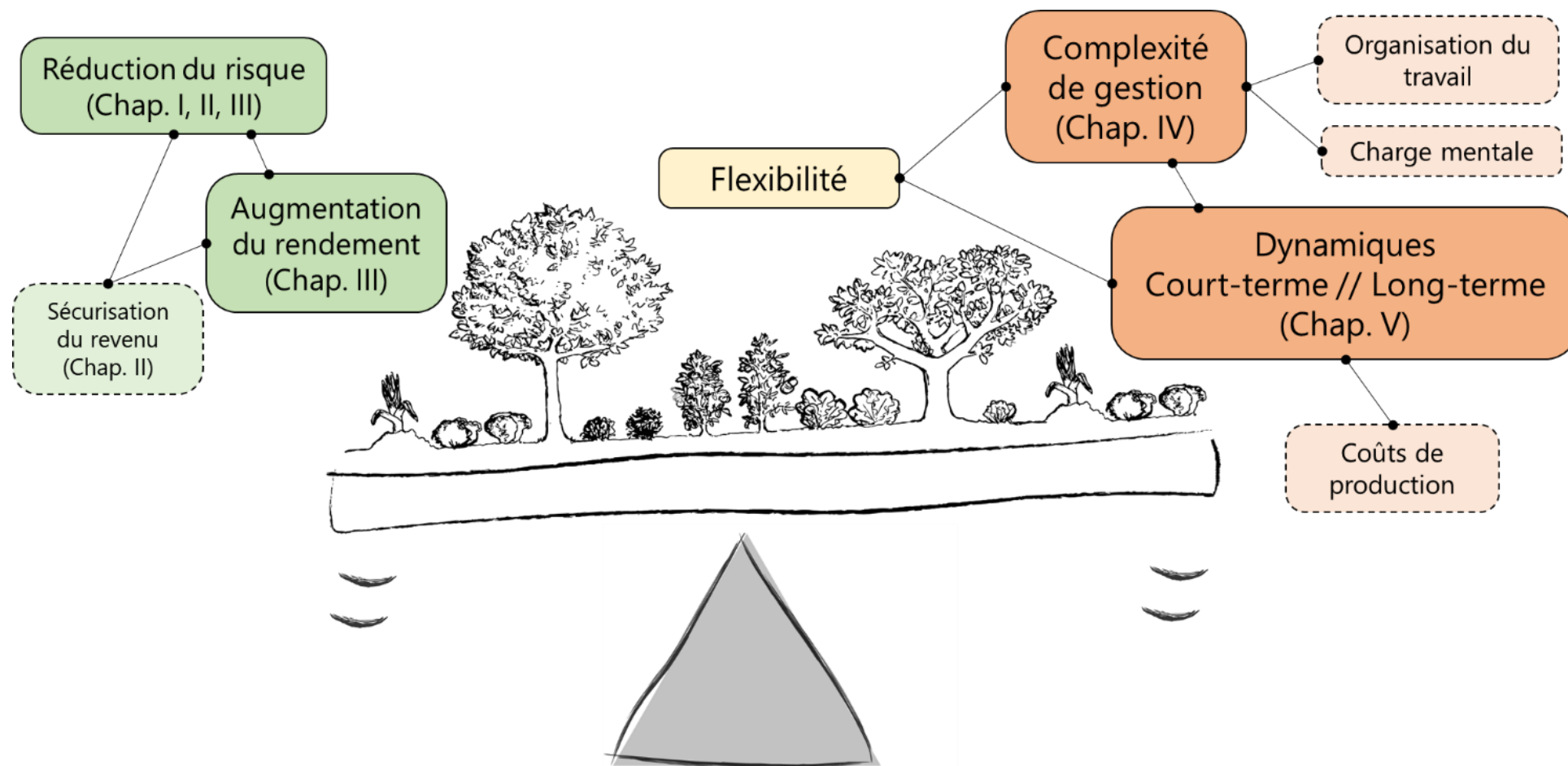
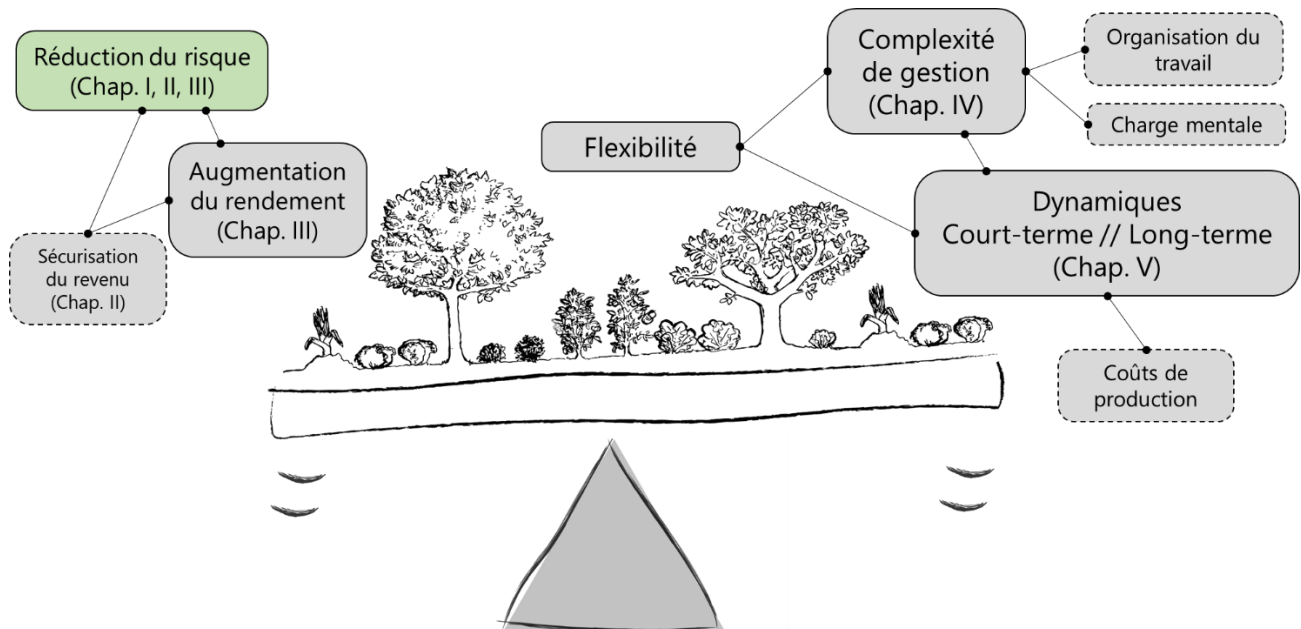


Figure A-8: Résumé graphique de l'organisation du manuscrit.

Partie B. Articles

Chapitre I. Réduction du risque par la diversification des cultures : une application de la théorie du portefeuille aux systèmes horticoles



Par l'association de l'arboriculture et du maraichage diversifié sur une même parcelle, les vergers-maraichers offrent de nombreuses perspectives de recherche. La diversification des cultures est au cœur de ces systèmes. Les agriculteurs qui les mettent en place parient sur les complémentarités entre espèces pour minimiser les risques. Néanmoins, l'adage « **Ne mettez pas tous vos œufs dans le même panier !** » ne précise pas quels paniers doivent être utilisés et comment les œufs qui les composent devraient être distribués. Dans un contexte horticole diversifié, il s'agit de trouver les bonnes combinaisons de cultures en privilégiant des espèces qui se comportent différemment face à un même environnement. Les travaux présentés dans ce chapitre montrent que moins le rendement d'une culture est corrélé à celui d'une autre culture, plus il est avantageux de diversifier la production entre ces cultures.

À partir de l'analyse des rendements de 44 cultures horticoles dans le sud-est de la France, nous avons modélisé toutes les paires possibles de ces cultures afin de déterminer des stratégies de diversification potentiellement intéressantes. En appliquant la **Théorie du Portefeuille** (une théorie économique développée dans les années 50) à la diversification des systèmes horticoles, nous sommes parvenus à quantifier les bénéfices d'une diversification pour ce large éventail de cultures (Figure B-1). Les résultats montrent que (i) la variabilité du rendement attendu des cultures peut être réduite jusqu'à 77% en choisissant la combinaison de cultures appropriée ; (ii) les classifications de cultures les plus courantes telles que la classification botanique ou les types fonctionnels ne permettent pas d'identifier des stratégies de diversification appropriées.

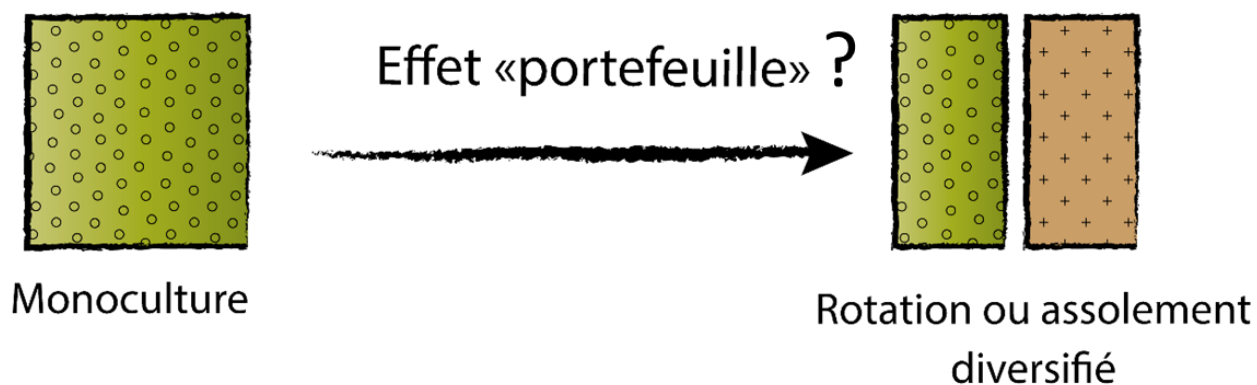


Figure B-1 : Résumé graphique de l'Article I.

Reducing risk through crop diversification: an application of portfolio theory to diversified horticultural systems

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Abstract

In agricultural sciences, it is frequently stated that diversified systems are more likely to cope with risks, but rarely demonstrated in a quantitative way. On the theoretical perspective, risk reduction based on asset diversification is a well-studied mechanism in economics that has been formalized in the Modern Portfolio Theory (MPT). In this paper, we thus explore the opportunities for the application of MPT to quantify the benefits of diversification for risk reduction in a context of highly diversified horticultural systems. Our analysis relies on a model of the effect of crop diversification on risk and expected yield. It is based on a dataset obtained from a range of 44 species and over a period of 10 years. Results show that (i) the variability of expected crop yield can be reduced up to 77% by choosing the appropriate crop combination; (ii) most common crop classifications such as botanical classification or functional types do not make it possible to identify suitable diversification strategies. These results provide insight into

how different horticultural crop combinations may shape the relationship between production and risk in diversified farming systems. Our findings also provide indications on new diversification strategies based on a quantification of risk reduction.

Keywords: Agroecology; agroforestry; variability; fruits; vegetables; Modern Portfolio Theory

1. Introduction

Although current farming systems have achieved to provide sufficient amount of food for a growing demand (IPES-Food, 2016), the increasing variability of weather conditions as well as the growing societal demand for low input agriculture make farming more and more sensitive to risk and uncertainty (OECD, 2011). This phenomenon is also amplified by an increasing price volatility that creates an additional level of risk on farmers' income (Kimura et al., 2010). These issues are particularly harsh in industrial agricultural systems that mainly rely on mono-cropping and high level of synthetic inputs.

In this context of growing uncertainties where means of control are less and less effective, farmers need to adapt their farming practices and land-use diversification is often identified as one of the main levers to cope with risk and uncertainty (OECD, 2009; Tilman et al., 2002; Vandermeer et al., 1998). In the literature, the relationship between biological diversity and risk has mainly been explored through the concepts of ecological stability (Goodman, 1975; Ives and Carpenter, 2007; Tilman, 1999) and agro-ecosystems resilience (Altieri et al., 2015; Holling, 1973; Liebman and Schulte, 2015). The underlying hypothesis, sometimes referred to as “insurance effect”, is that a diversity of species would give a diversity of responses to given soil, climate conditions or environmental disruption, hence contributing to maintain ecosystem functioning (Aerts et al., 2015; Yachi and Loreau, 1999). Therefore, when crops are combined together, they create a stabilizing effect that preserves the integrity of the production service (Isbell et al., 2017; Tilman et al., 1998; Vandermeer, 1989). Although these studies have shown the importance of diversity for risk reduction, few studies have sought to formalize this advantage or to quantify it systematically for agricultural production (Figge, 2001).

Theoretical approaches to the effect of diversification on risk, known as the Modern Portfolio Theory (MPT) have however been developed and widely used in finance (Markowitz,

2010, 1990, 1952). The MPT makes it possible to assess the effect of asset diversification on the global risk of a financial portfolio and to draw the relationship between risk and profit for the range of possible portfolios (Kolm et al., 2014).

The objective of the present study is therefore to quantify the risk reduction enabled by crop diversification in agriculture through the use of the MPT framework. Indeed, similarly to financial agent, a farmer facing an uncertain environment may build a crop portfolio that generates the highest yield for a minimum acceptable risk (Figge, 2004; Fraser et al., 2005). Crops being expected to behave as assets, risk may be significantly reduced by combining different crops in a portfolio. Thus, the diversification of crops within a farming system would be, by analogy, a way to generate an acceptable compromise between risk and expected yield.

A case study on horticultural systems is presented to identify suitable diversification strategies based on optimal portfolio compositions. For this case study, interactions between crops are not taken into account and portfolios should be considered as cropping patterns at the farm scale rather than at the field scale. In horticulture, specifically, crop diversification can be relevant, given that the sector includes a wide range of different crops (fruits, vegetables, berries, tuber crops, medicinal and aromatic crops) and that short cycles of most crops favor numerous crop combinations (Singha et al., 2014; Weinberger and Lumpkin, 2007).

In this paper, we thus explore the opportunities of application of MPT in the field of horticulture. First, we present the theoretical portfolio selection model to minimize risk; we then show the opportunities for application of this theory to a context of diversified horticultural systems.

2. Material and methods

2.1. Application of Modern Portfolio Theory to crop diversification

Markowitz (2010, 1990, 1952) has shown in his Modern Portfolio Theory (MPT) how risk can be reduced when several assets are combined together in a portfolio, and when asset returns are not perfectly correlated. In our case, diversifying the portfolio represents a shift from

monoculture to a combination of crops: the MPT is used to explore different crop mixtures and study their impact on risk and return of the generated portfolios.

According to the MPT, the expected return (or expected yield in our case study) of a portfolio $E(R_p)$ is calculated as the weighted sum of each individual crop in the portfolio:

$$E(R_p) = \sum_i w_i E(R_i) \quad (1)$$

Where:

w_i = Relative weight of crop i (that is, the proportion of the cultivated area of crop “ i ”)

$E(R_i)$ = Expected yield of crop i

$\sum_i w_i = 1$

The agronomic interpretation of Eq. (1) is that the relative weight of crop A and B represents the relative area allocated to each crop. In accordance with portfolio theory, interactions between crops (whether positive or negative) are not taken into account in the calculation of the expected yield which is the weighted sum of monoculture yields. In other words, we consider a situation where crops are not associated within the same plot but grown on different plots of the farm. In addition, the risk of a portfolio is expressed as the standard deviation of the expected portfolio return (σ_p). A portfolio variability depends on the proportion and the variations of each individual crop, but also on the covariance between crops. It is calculated as follows:

$$\sigma_p = \sqrt{\sum_i \sum_j w_i w_j \sigma_{ij}} \quad (2)$$

Where:

w_i = Relative weight of crop i (that is, the proportion of the cultivated area of crop “ i ”)

σ_{ij} = the standard deviation of the yield for crop i when $i = j$, and the covariance of the yields of crops i and j when $i \neq j$.

Following the MPT, standard deviation and correlations are obtained by analyzing the historical variations of asset returns (crop yields in our case study). The yields of two crops may be positively or negatively correlated depending on how their yields have historically varied over

time (Liliehalm and Reeves, 1991). The variance of a crop portfolio can be reduced in two ways, either by favoring crops with low yield variances, or by using specific combinations of crops. Though the first way is straightforward, the second way relies on choosing crops for which yield show correlation close to zero or negative correlation so as to compensate yield fluctuations between crops (Figge, 2004). The MPT can be used to optimize portfolios including a large amount of assets but in order to explore the whole range of possible pairs of crops within the 44 studied, we will focus on portfolios composed of two crops. To do so, Equations (1) and (2) were transcribed into Equations (3) and (4), in the 2-crop diversification case.

$$E(R_p) = w_A E(R_A) + w_B E(R_B) \quad (3)$$

Where:

$$\begin{aligned} w_A, w_B &= \text{Relative weights of crops A and B} \\ E(R_A), E(R_B) &= \text{Expected yields of crops A and B} \\ w_A + w_B &= 1 \end{aligned}$$

$$\sigma_p = \sqrt{w_A^2 \sigma_A^2 + w_B^2 \sigma_B^2 + 2w_A w_B \sigma_A \sigma_B \rho_{A,B}} \quad (4)$$

Where:

$$\begin{aligned} w_A, w_B &= \text{Relative weights of crops A and B} \\ \sigma_A, \sigma_B &= \text{the standard deviation of the yield for crops A and B} \\ \rho_{A,B} &= \text{Correlation coefficient between the yields of crop A and crop B} \end{aligned}$$

Figure B-2, based on Equations (3) and (4) illustrates the theoretical relationship between risk (plotted on the x -axis) and expected return (represented on the y -axis) in a situation where crop A shows a low expected return and a low risk and crop B shows a high expected return and a high risk. The two extreme points of the line labeled A and B represent the yield and risk of monocultures A and B respectively. The curve linking A and B displays the combined yield and standard deviation of every combination of both crops moving from point A ($w_A = 1$; $w_B = 0$) to point B ($w_A = 0$; $w_B = 1$). Portfolio's expected return $E(R_p)$ and its standard deviation can be calculated for any crop combination by changing their respective weights. The straight dotted line represents the risk-return combinations of the portfolio if the two crops were perfectly correlated. Risk reduction enabled by crop diversification is represented by $\Delta\sigma$. The lower the value of the correlation between both crops, the higher the risk reduction of the portfolio.

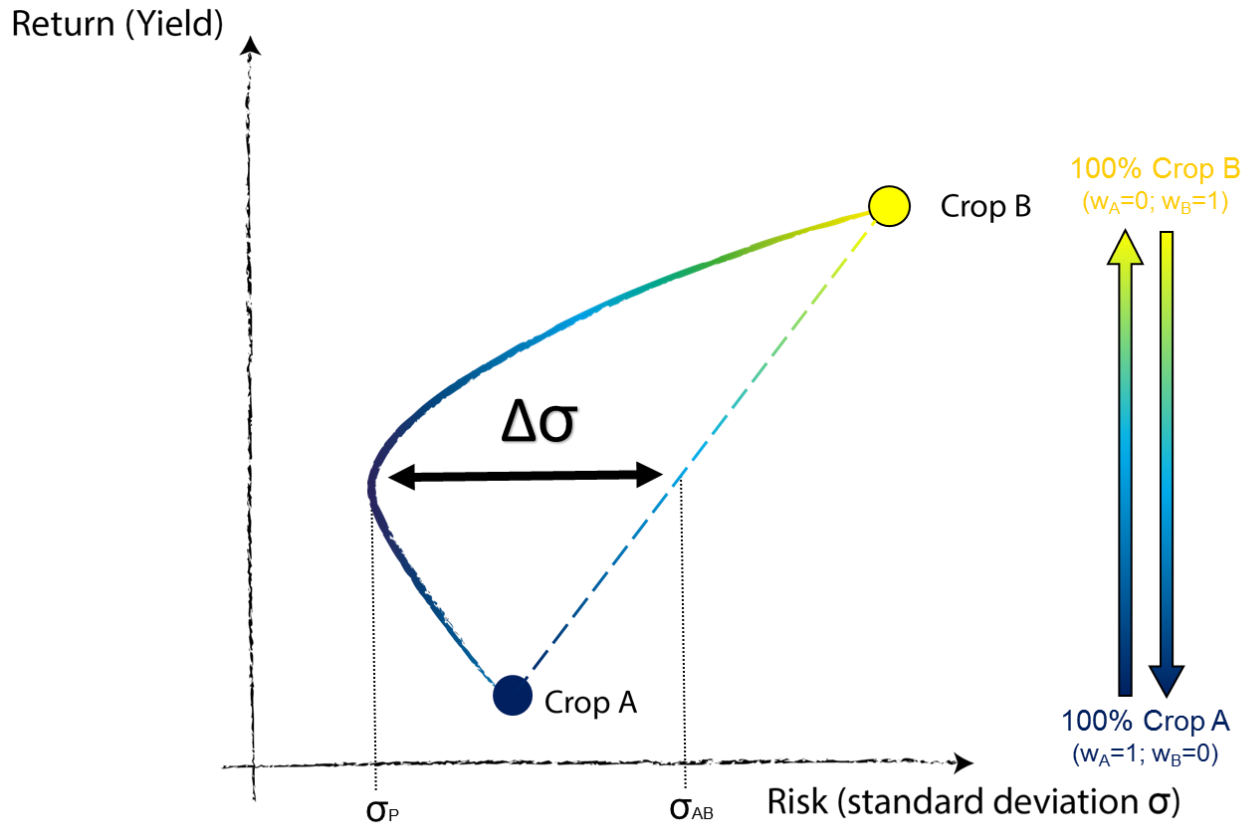


Figure B-2: Risk and return combinations for portfolios composed of crop A and crop B. The dashed line represents the weighted average of a two crops portfolio whereas the solid curve benchmarks the actual risk-return combination for the same portfolio. The "diversification benefit" ($\Delta\sigma$) measures the relative risk reduction between the portfolio standard deviation (σ_P) and the weighted average standard deviation (σ_{AB}).

This diversification benefit ($\Delta\sigma$) is measured by the relative risk reduction calculated with the ratio between the portfolio standard deviation (σ_P) and the weighted average standard deviation (σ_{AB}). It represents the maximum risk reduction allowed by diversification, considering all situations from $w_A = 0$ to $w_A = 1$ (Eq. (5)).

$$\Delta\sigma = \max_{w_A \in \{0;1\}} \left(1 - \frac{\sigma_P}{\sigma_{AB}} \right) \quad (5)$$

2.2. Data collection and simulations

Data were retrieved from the French Interprofessional Technical Center for Fruits and Vegetables (CTIFL) publicly accessible database (<http://www.ctifl.fr/>). We focused our analysis on three close administrative regions (Provence-Alpes-Côte d'Azur, Rhône-Alpes and Languedoc-Roussillon) in order to maintain soil and climate homogeneity. The 44 main horticultural crops cultivated in these regions were selected, 10 fruits, 3 berries and 31 vegetables.

For each crop, the data collected represent the average yield per crop over a ten-year period (2006 to 2015) in each of the three regions. Yield data are collected within the Annual Agricultural Statistics program, which involve all farmers, regardless of their farming system and management practices. Due to inter-regional yield disparities, the region effect was corrected by subtracting the average regional yield of each crop from each yield data. After removing the region effect on yields, standard deviation of each crop was computed. The resulting standard deviation therefore represents the inter-annual variability of crop yields, regardless of the region considered. From these data, every portfolio of two crops was modeled.

We simulated the risk and yield combinations for 100 proportions of crop A and crop B (from $w_A=0$ to $w_A=1$) and deduced the value of the diversification benefit $\Delta\sigma$. To calculate the expected yield for each of the crop portfolios, Eq. 3 was applied, whereas Eq. 4 generated the standard deviation (indicator of the risk) for each crop portfolios. The model was implemented with Python 3.5 (<http://www.python.org/>), statistical analyses and graphical outputs were realized with R 3.5.0 (<https://cran.r-project.org>).

2.3. Linking diversification benefit to naturalist categories of plants

In an attempt to explain trends observed in the diversification effects, we analyzed the results regarding different crop classifications: botanical classification, Pennington and Fisher's typology (2009) and CTIFL functional categorization (See Appendix B.1 for details). For instance, crops from the same botanical family are likely to have common nutrient requirements, water needs or pests and diseases sensitivity (Pennington and Fisher, 2009). Similarly, yields of plants from which the same part is consumed (following the classification of Welbaum (2015)) are likely to be sensitive to similar stresses. Thus, we carried out a one-way analysis of variance to study the link between these classifications systems and the diversification benefit. In addition, Tukey's HSD (Honestly Significant Difference) test was performed to identify crops or classifications that significantly differ from each other.

Finally, following an alternative approach, a new classification system was proposed based on a Hierarchical Cluster Analysis (R package *Agricolae* v.1.2.8) on the diversification benefit metric itself.

3. Results

3.1. Typology of interactions

Among the 946 different crop pairs tested, the risk-return combination curves took four possible functional shapes:

- a. A low yield - low risk crop is combined with a high yield - high risk crop that provides a high diversification benefit (**Figure B-3a**). This shape was observed in 779 out of the 946 pairs tested (82.3 %).
- b. A low yield - low risk crop is combined with a high yield - high risk crop that provides a low diversification benefit (**Figure B-3b**). This shape represents 14 out of the 946 pairs tested (1.5%).
- c. A high yield - low risk crop is combined with a low yield - high risk crop that provides a high diversification benefit (**Figure B-3c**). This shape occurs in 151 out of the 946 pairs tested (16.0 %). It is interesting to notice at this stage that adding a high risk – low yield crop to a high yield – low risk crop (**Figure B-3c**) still provides a benefit in terms of risk reduction.
- d. A high yield - low risk crop is combined with a low yield - high risk crop that provides a low diversification benefit (**Figure B-3d**). This shape appears in only 2 out of the 946 pairs tested (0.2 %).

For the definition of the four functional shapes, the threshold between high and low diversification benefit is set to 10%. A given crop may belong to several types of interactions depending on the second crop with which it is combined.

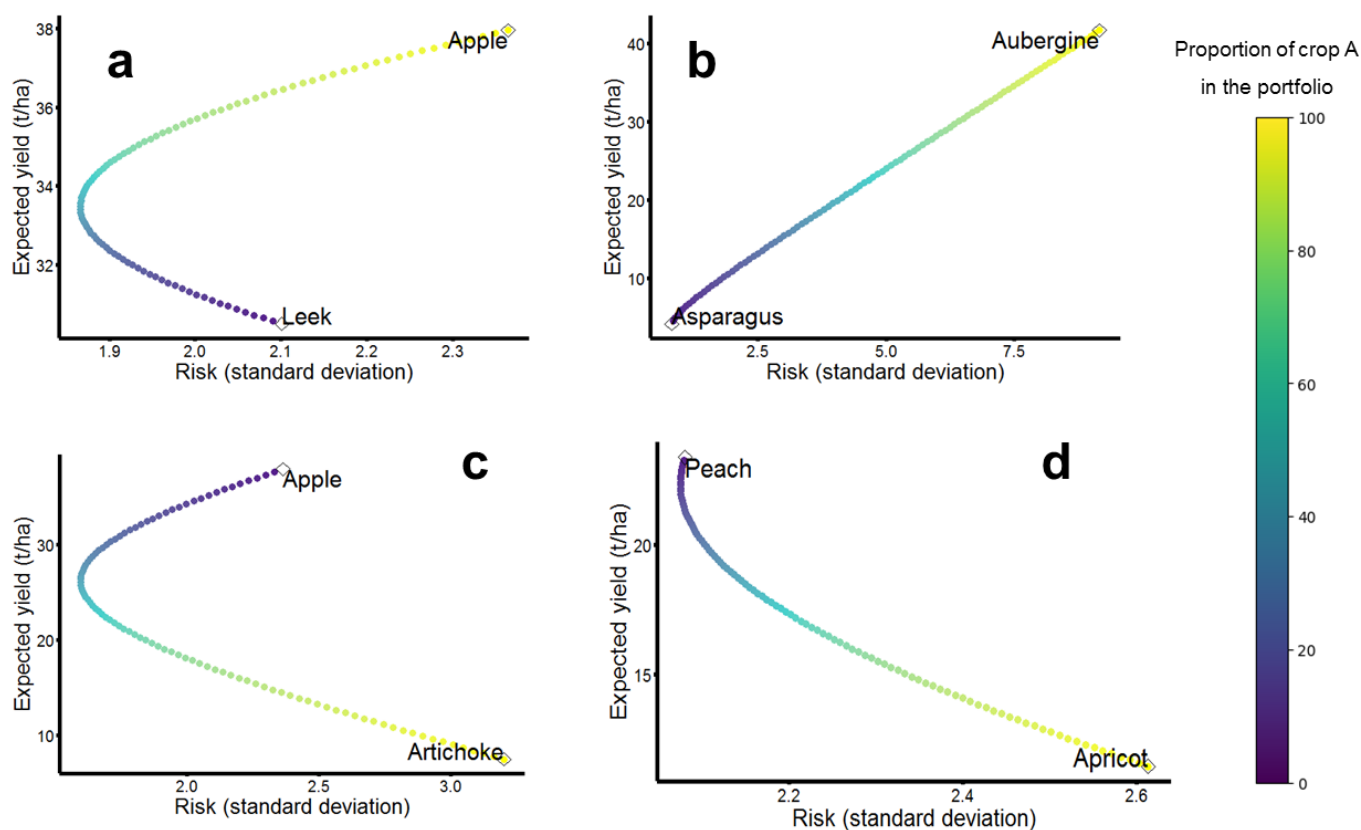


Figure B-3: Risk-return combinations for four different types of interactions. (a) a low yield - low risk crop is combined with a high yield - high risk and provides a high diversification benefit; (b) a low yield - low risk crop is combined with a high yield - high risk and provides a low diversification benefit; (c) a high yield - low risk crop is combined with a low yield - high risk and provides a high diversification benefit; (d) a high yield - low risk crop is combined with a low yield - high risk and provides a low diversification benefit.

3.2. Diversification benefit for the different pairs of crops

The diversification benefit has been calculated for all possible pairs of crops, resulting in a 44×44 matrix (Table B-1). The diversification benefit ranges from 6.5% to 77.1% with an average of 21.5% and a standard deviation of 12.7%. This reflects a high variability of that indicator among crop pairs. The maximum average diversification benefit is achieved for Lamb Lettuce (average of all pairs of crops including Lamb Lettuce = 35.6%) and the minimum average for Apricot (average of all pairs of crops including Apricot = 23.7 %).

The diversification benefit described here gives an indication of the relevance of diversification from one crop to another. However, it does not provide information on the proportion of each crop resulting in the minimum risk. Such information on the optimum ratio of each crop in terms of risk reduction can be found in Appendix B.2.

Table B-1. Matrix of the diversification benefit for each crop combination. The figure at the intersection of rows and columns in the upper triangular part of the matrix represents the diversification benefit that is provided by the combination of two crops in a portfolio (cell shade intensity is proportional to the benefit value). The letter in the lower triangular part represents the type of interaction between both crops (e.g. for a portfolio composed of Apple and Almonds, the risk reduction is 48%, and the type of interaction between both crops is A, according to §3.1).

	Almonds	Apple	Apricot	Artichoke	Asparagus	Aubergine	Beetroot	Blackcurrant	Broccoli	Brussels sprouts	Carrot	Cauliflower	Celeriac (Stor.)	Celery	Chard	Cherry	Cucumber	Fig	French bean	Garlic	Gooseberry	Kiwi
Almonds		48%	21%	24%	23%	30%	16%	25%	46%	32%	37%	22%	19%	26%	26%	27%	29%	49%	25%	19%	30%	27%
Apple	A		25%	41%	22%	19%	49%	42%	17%	15%	25%	29%	31%	33%	19%	18%	20%	21%	28%	44%	28%	34%
Apricot	A	C		23%	26%	17%	19%	28%	18%	24%	20%	33%	25%	31%	25%	15%	21%	27%	18%	33%	27%	15%
Artichoke	A	C	C		30%	31%	20%	13%	28%	32%	24%	29%	28%	24%	24%	35%	21%	30%	24%	35%	31%	30%
Asparagus	A	A	A	A		17%	44%	32%	37%	25%	23%	19%	12%	43%	9%	33%	32%	28%	33%	29%	36%	26%
Aubergine	A	A	A	A	A		25%	36%	18%	26%	22%	31%	15%	36%	7%	23%	32%	22%	33%	36%	33%	24%
Beetroot	A	A	C	C	A	A		21%	27%	40%	27%	37%	30%	25%	36%	24%	29%	39%	20%	26%	34%	26%
Blackcurrant	C	A	A	A	A	A	A		45%	38%	48%	29%	23%	19%	29%	23%	26%	35%	24%	17%	15%	21%
Broccoli	A	A	A	C	A	A	A	A		22%	10%	32%	46%	38%	28%	28%	22%	17%	28%	55%	43%	33%
Brussels sprouts	A	C	A	C	A	A	C	A	A		30%	28%	28%	19%	24%	26%	12%	23%	13%	43%	32%	30%
Carrot	A	A	A	A	A	A	A	A	B	A		28%	34%	55%	29%	41%	28%	21%	29%	47%	49%	34%
Cauliflower	A	A	C	C	A	A	A	A	A	C	A		20%	30%	18%	45%	21%	29%	27%	25%	30%	25%
Celeriac (Stor.)	A	C	A	A	A	A	A	A	A	C	A	A		30%	16%	31%	37%	29%	28%	18%	25%	18%
Celery	A	A	A	A	A	C	A	A	A	A	C	A	C		30%	24%	22%	34%	20%	30%	20%	27%
Chard	A	C	A	C	B	B	A	A	A	A	A	C	A	A		31%	25%	30%	37%	37%	36%	32%
Cherry	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		28%	29%	21%	24%	15%	17%
Cucumber	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		31%	17%	44%	31%	37%
Fig	A	A	A	A	A	A	A	A	C	A	A	A	A	A	A	A	A		19%	41%	25%	20%
French bean	C	A	A	C	C	A	A	C	A	A	A	A	A	A	A	C	A	C		30%	22%	15%
Garlic	A	A	A	C	C	A	A	A	A	A	A	A	A	A	A	C	A	C	C		11%	15%
Gooseberry	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	C	A		11%
Kiwi	A	A	C	C	A	A	A	A	A	C	A	A	A	A	A	A	A	A	A	A	A	
Lamb lettuce	A	A	A	C	A	A	A	A	C	A	A	A	A	A	A	A	A	A	A	A	A	C
Leek	A	A	C	C	A	B	C	A	A	C	A	A	C	A	A	A	A	A	A	A	A	A
Lettuce	A	A	C	C	A	A	C	A	A	C	A	A	C	A	A	A	A	A	A	A	A	A
Melon	A	A	C	C	B	A	A	A	A	C	A	C	A	A	A	A	A	A	A	A	A	C
Nectarines	A	C	A	A	A	A	A	A	A	A	A	A	B	C	C	A	A	A	A	A	A	A
Onion	A	C	A	A	A	A	A	A	A	A	A	A	C	C	C	A	A	A	A	A	A	A
Pea	C	A	A	A	C	A	A	C	A	A	A	A	A	A	A	C	A	A	C	A	C	A
Peach	A	A	D	C	A	A	A	A	A	C	A	A	A	A	A	A	A	A	A	A	A	A
Pear	A	C	A	C	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Plum	A	A	C	C	A	A	A	A	A	C	A	C	A	A	A	A	A	A	A	A	A	C
Radish	A	C	A	C	A	A	C	A	A	A	B	C	A	A	A	A	A	A	A	A	A	A
Raspberry	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	D	A	A	C	C	A	A
Shallot	A	A	C	C	A	A	A	A	A	C	A	A	A	A	A	A	A	A	A	A	A	C
Spinach	A	A	C	C	A	A	A	A	C	C	A	A	A	B	A	A	A	C	A	A	A	C
Squash	A	C	A	A	A	A	A	A	A	C	A	A	C	C	A	A	A	A	A	A	A	A
Strawberry	A	A	C	C	A	A	A	A	A	C	A	A	A	A	A	A	A	A	A	A	A	C
Sweet corn	A	A	A	C	A	A	A	A	C	A	A	A	A	A	A	A	A	C	A	A	A	A
Sweet pepper	A	C	A	A	A	A	A	A	A	C	A	C	C	C	C	A	B	A	A	A	A	A
Tomato	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	C	A	A	A	A	A
Turnip	A	A	C	C	A	B	A	A	A	C	A	A	A	A	B	A	A	A	A	A	A	A
Watermelon	A	A	A	A	A	C	A	A	A	C	A	C	C	A	A	A	A	A	A	A	A	A
Zucchini	A	A	A	A	B	C	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A	A

Table B-1(*suite*)

	Lamb lettuce	Leek	Lettuce	Melon	Nectarines	Onion	Pea	Peach	Pear	Plum	Radish	Raspberry	Shallot	Spinach	Squash	Strawberry	Sweet corn	Sweet pepper	Tomato	Turnip	Watermelon	Zucchini
Almonds	30%	28%	23%	17%	12%	29%	37%	25%	24%	38%	27%	46%	24%	25%	37%	25%	34%	25%	18%	28%	14%	25%
Apple	37%	16%	37%	33%	39%	33%	24%	22%	20%	22%	25%	12%	41%	39%	16%	19%	24%	18%	35%	17%	49%	18%
Apricot	39%	14%	25%	16%	19%	35%	24%	7%	24%	19%	24%	16%	34%	31%	23%	16%	31%	19%	39%	16%	33%	23%
Artichoke	32%	29%	36%	20%	32%	20%	25%	36%	28%	28%	29%	27%	33%	26%	40%	37%	19%	30%	33%	32%	39%	31%
Asparagus	45%	11%	28%	9%	16%	23%	26%	17%	22%	38%	15%	29%	33%	65%	23%	16%	26%	27%	17%	16%	27%	8%
Aubergine	77%	8%	41%	13%	29%	56%	32%	12%	30%	30%	11%	14%	41%	43%	45%	16%	33%	23%	31%	8%	44%	20%
Beetroot	29%	31%	23%	22%	27%	40%	40%	27%	29%	27%	31%	33%	28%	19%	47%	33%	43%	25%	35%	34%	27%	43%
Blackcurrant	30%	41%	39%	33%	22%	27%	29%	35%	25%	28%	39%	24%	25%	21%	34%	33%	19%	32%	32%	29%	22%	36%
Broccoli	36%	19%	24%	26%	48%	37%	20%	21%	30%	25%	19%	18%	48%	32%	29%	24%	38%	24%	55%	29%	58%	31%
Brussels sprouts	28%	24%	30%	31%	32%	32%	27%	30%	30%	26%	27%	23%	28%	28%	24%	19%	29%	14%	35%	21%	47%	12%
Carrot	34%	17%	14%	18%	33%	24%	23%	17%	33%	29%	9%	28%	51%	49%	24%	24%	36%	25%	37%	36%	41%	24%
Cauliflower	37%	34%	21%	23%	19%	26%	27%	29%	25%	40%	26%	42%	36%	34%	27%	25%	27%	32%	24%	24%	21%	18%
Celeriac (Stor.)	51%	19%	30%	13%	7%	30%	43%	17%	29%	36%	24%	35%	20%	44%	34%	30%	25%	37%	18%	13%	18%	17%
Celery	23%	46%	46%	38%	33%	33%	33%	48%	34%	26%	53%	29%	16%	10%	40%	32%	31%	27%	31%	24%	29%	31%
Chard	66%	14%	42%	12%	28%	45%	30%	20%	27%	36%	15%	21%	40%	44%	42%	11%	26%	23%	24%	9%	37%	9%
Cherry	32%	21%	41%	32%	28%	34%	21%	19%	14%	22%	34%	9%	24%	27%	17%	23%	32%	20%	35%	23%	39%	35%
Cucumber	26%	32%	19%	39%	36%	40%	29%	30%	32%	26%	30%	25%	43%	20%	26%	20%	22%	7%	42%	24%	38%	18%
Fig	40%	24%	33%	28%	42%	32%	11%	27%	41%	34%	20%	15%	36%	47%	24%	37%	27%	35%	48%	21%	42%	30%
French bean	25%	34%	25%	27%	26%	25%	20%	29%	28%	31%	31%	22%	25%	27%	21%	26%	33%	19%	35%	29%	35%	25%
Garlic	27%	38%	34%	32%	11%	24%	35%	26%	20%	35%	39%	36%	19%	25%	25%	38%	30%	37%	16%	32%	13%	42%
Gooseberry	31%	38%	46%	42%	23%	32%	20%	29%	24%	27%	38%	16%	23%	22%	21%	33%	24%	29%	23%	23%	25%	41%
Kiwi	37%	23%	32%	20%	13%	27%	20%	16%	18%	29%	30%	19%	23%	33%	22%	25%	32%	33%	24%	19%	27%	32%
Lamb lettuce		51%	18%	50%	32%	13%	31%	50%	27%	26%	56%	47%	21%	16%	18%	45%	35%	29%	31%	61%	21%	41%
Leek	A		27%	13%	23%	36%	31%	7%	19%	29%	14%	17%	40%	55%	28%	15%	25%	22%	29%	11%	42%	16%
Lettuce	A	A		29%	19%	23%	35%	21%	31%	33%	26%	51%	32%	34%	22%	32%	31%	26%	32%	40%	23%	24%
Melon	C	A	A		17%	26%	27%	15%	25%	38%	15%	30%	32%	52%	34%	18%	37%	33%	22%	19%	27%	16%
Nectarines	A	C	C	A		20%	41%	14%	19%	31%	29%	43%	19%	36%	23%	27%	28%	36%	16%	23%	12%	20%
Onion	A	A	A	A	A		23%	35%	20%	28%	35%	41%	21%	38%	11%	39%	26%	45%	21%	51%	21%	30%
Pea	A	A	A	A	A	A		30%	27%	35%	22%	14%	35%	39%	16%	24%	35%	27%	34%	33%	43%	31%
Peach	A	B	C	A	A	A	A		21%	25%	16%	19%	36%	46%	22%	16%	25%	25%	28%	13%	31%	19%
Pear	A	C	C	A	C	A	A	A		26%	32%	24%	33%	33%	15%	21%	30%	25%	20%	29%	33%	26%
Plum	A	A	A	C	A	A	A	A	A		33%	22%	25%	24%	23%	25%	25%	29%	33%	27%	32%	31%
Radish	A	C	C	C	A	A	A	C	A	A		21%	50%	57%	33%	16%	31%	24%	27%	24%	41%	17%
Raspberry	A	A	A	A	A	A	C	A	A	A	A		41%	35%	23%	17%	25%	18%	41%	17%	56%	30%
Shallot	C	A	A	C	A	A	A	A	A	C	A	A		24%	28%	42%	29%	50%	21%	34%	23%	34%
Spinach	C	A	A	A	A	A	A	A	A	C	A	A	A		42%	34%	34%	23%	33%	36%	25%	46%
Squash	A	C	C	A	A	C	A	A	A	A	A	A	A	A		29%	26%	27%	29%	37%	30%	25%
Strawberry	C	A	A	A	A	A	A	A	A	C	C	A	C	A	A		30%	14%	19%	16%	41%	11%
Sweet corn	C	A	A	A	A	A	A	A	A	A	A	A	A	C	A	A		35%	29%	20%	27%	24%
Sweet pepper	A	A	A	A	A	C	A	A	A	A	A	A	A	A	A	A	A		33%	24%	42%	21%
Tomato	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		28%	19%	20%
Turnip	A	A	A	A	A	A	A	A	A	A	C	A	A	A	A	A	A	A	A		32%	14%
Watermelon	A	A	A	A	C	C	A	A	A	A	A	A	A	A	C	A	A	C	A	A		34%
Zucchini	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	

3.3. Diversification benefits cannot be deduced from naturalist categories

Based on the diversification matrix (Table B-1) the diversification benefit was tested against common crop classification systems. Pairwise comparison was performed using Tukey's Honestly Significant Difference test ($P=0.05$) to compare the means of each classification system. We can observe that some grouping systems enable to identify levers for potential diversification schemes (Figure B-4).

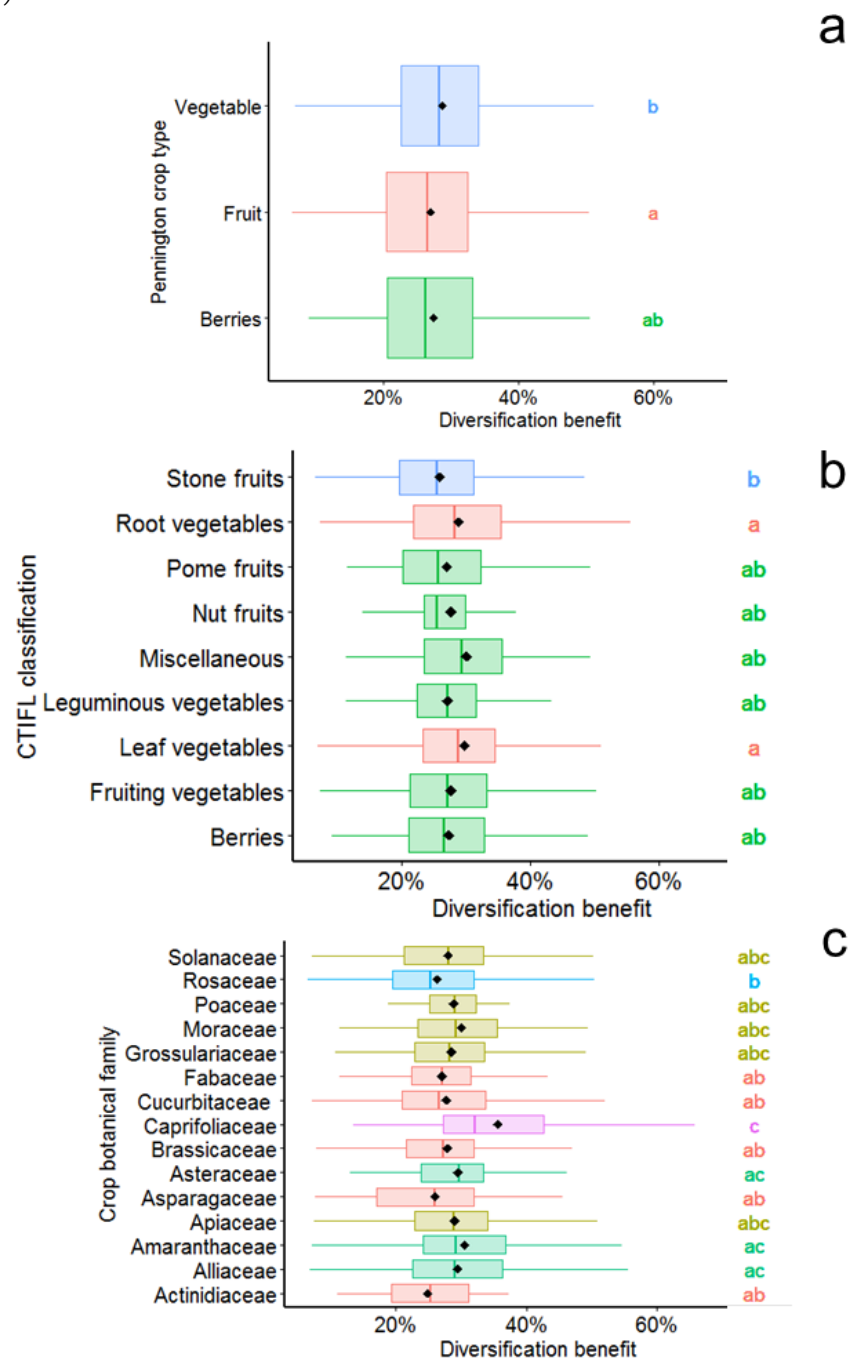


Figure B-4: Relations between diversification benefit and (a) Pennington's crop type, (b) CTIFL crop functional classification and (c) crop botanical family. Groups displayed with the same letters did not show significant differences according to Tukey's Honestly Significant Difference ($P \leq 0.05$).

The explanatory value of the different crop classifications was also tested in their interactions (see Appendix B.3 for details). However, neither the categories themselves nor their interactions provided substantial information to define diversification strategies based on these categorization systems.

3.4. Towards new classifications based on diversification benefit

Based on a cluster analysis using the diversification benefit as criteria, the 44 crops were categorized into five clusters. The groups obtained correspond to homogeneous groups of crops considering their behavior in diversification strategies (**Figure B-5**). Results indicate that clusters do not match with classical horticultural categories. As we can see on the lower triangle part of the matrix, diversification is more interesting when crops are selected among different clusters rather than within clusters. It is noticeable that the highest diversification benefits are obtained by diversifying group 5 crops with group 3 crops.

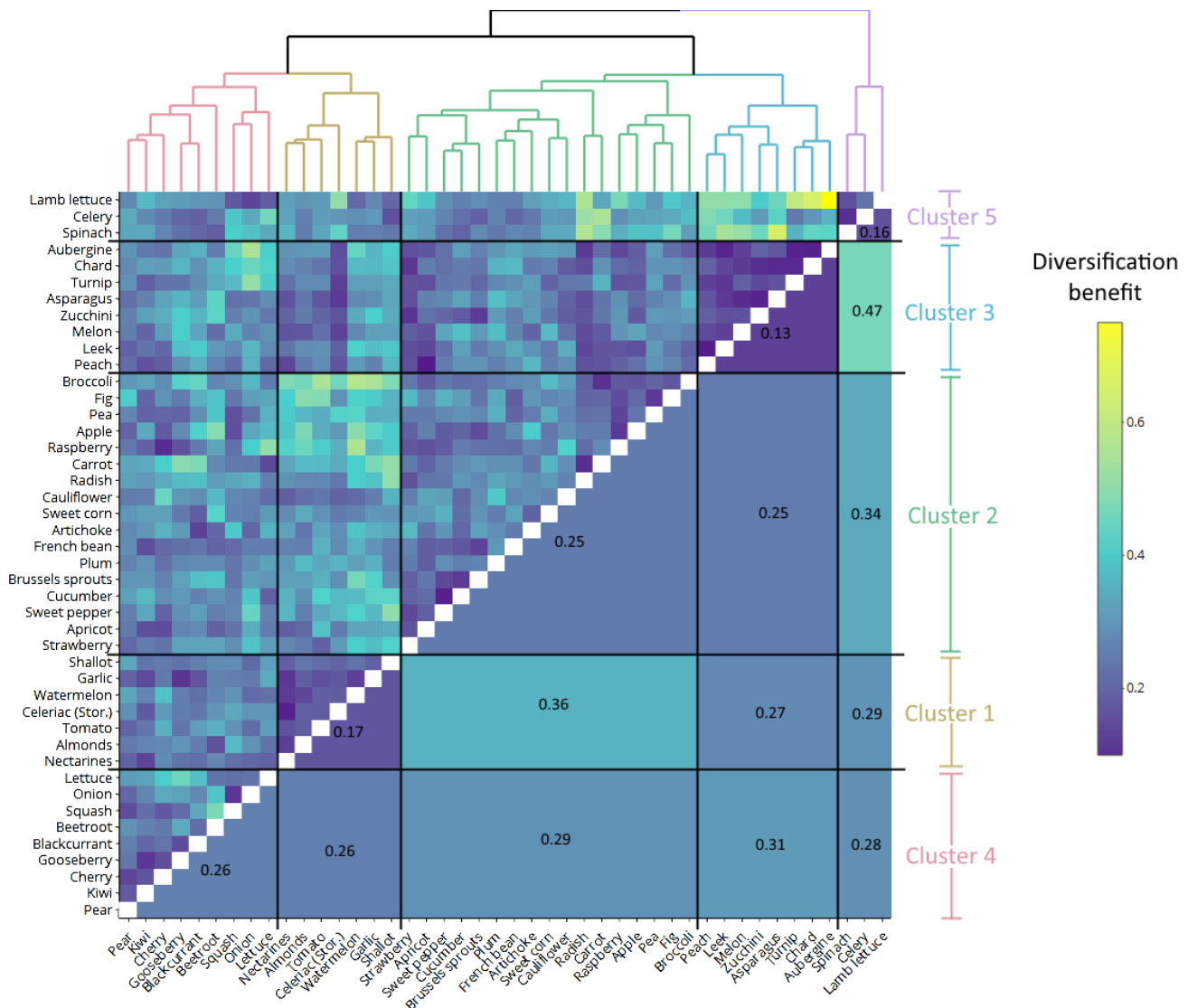


Figure B-5 : Matrix of diversification clustering. The upper triangular part of the matrix represents the diversification benefit that is provided by the combination of two crops in the portfolio. The lower triangular part represents the average diversification benefits when crops from one cluster are mixed with crops from the other corresponding cluster.

4. Discussion

4.1. Diversifying under uncertainty

While most of the literature linking agriculture and biodiversity has acknowledged that diversified agro-systems are better able to cope with perturbations, little information is available on a quantitative assessment of this comparative advantage. In this study we introduced and linked the notions of risk and returns, through the Modern Portfolio Theory, as a basis for the assessment of diversified horticultural systems.

Based on the MPT framework, we showed that it is possible to highlight the relationship between return and risk of diversified crop portfolios. Portfolio theory formalizes the information that farmers require to handle their crop portfolio efficiently. The two dimensions (risk and return) representation makes it possible to define the appropriate level of crop diversification as a function of the risk aversion profile of each farmer (Hardaker et al., 2015) and of what they are willing to lose in expected yield to earn as a unit of risk. Results suggested that the overall risk is likely to be decreased through crop diversification and that this risk reduction is quantifiable through the *diversification benefit* metric. One of our main results is that risk, defined as the standard deviation of crops yield, can be reduced up to 77% by choosing the proper association of crops. These results corroborate the recommendations reported in forestry (Crowe and Parker, 2008; Knoke et al., 2005), fishery (DuFour et al., 2015) or water resource management (Aerts et al., 2015; Beuhler, 2006) highlighting the relevance of MPT approach to define optimum diversification strategies. Specifically, in horticulture, there may be a special interest in combining crop species whose yields behave in an opposite manner depending on the cropping conditions, the weather or the presence of pests and diseases (Nalley and Barkley, 2010).

However, diversification strategies relying on botanical aspects (as proposed by Figge 2004) do not show identifiable patterns in our particular case study and were therefore not useful to capture complementarities in crop behavior. This leads us to believe that other factors than classical naturalist classifications would be more suited to explain crop behavior in a diversification strategy. Indeed fruit and vegetables categories can be insufficient to explain the range of functional diversity provided by a large crop portfolio (Wood et al., 2015). Several authors (Pennington and Fisher, 2009; Song et al., 2014) suggested other classification systems, such as functional response traits, that may be relevant because they rely on physiological characteristics of plant development, growth and structure. Functional response types are groups of plant species that behave similarly to abiotic and biotic conditions, such as climatic conditions or fertilization regime (Diaz and Cabido, 2001). The greater variation of different response traits could then enhance the maintenance of agroecosystem functions (Lavorel and Garnier, 2002). Further studies on the processes underlying crop variability for a wide range of crops are, however, still needed to develop this approach.

4.2. Limits and perspectives

A major limitation of the present study lies in the use of an agronomic criterion, crop productivity, instead of an economic criterion, the price that would be a closer estimate of the farmer's objectives. We made this choice to remain close to the biological processes at stake in an attempt to look for the biological drivers underlying the diversification benefit. Indeed, comparing economic profitability would lead to different interpretation, since crop profitability does not directly reflect the biological processes at stake but a complex interaction between agronomic and economic processes. Furthermore, a profitability analysis would require additional information on crop prices and crop production costs (Castro et al., 2015) in the particular context of highly diversified systems. This type of data being particularly difficult to obtain, such an enhancement of our approach would lead to significantly reduce the pool of crops that we could consider (Knoke et al., 2015). Preliminary work has already been undertaken to deal with this particular issue (Raphaël Paut et al., 2018) but further developments are still required.

Portfolios of two crops on a wide range of crops enabled an exhaustive exploration of all possible combinations. However, in diversified horticultural systems, high numbers of species and complex rotations are often implemented (Morel et al., 2017). Due to simulations constraints, it was not possible to explore all possible combinations for larger portfolios. Nevertheless, a development of our model has been carried out on larger amount of crops as a preliminary approach (Raphaël Paut et al., 2018) and the results observed in the present study remain consistent. This multi-crop portfolio study, moreover, showed that increasing the number of crops within the portfolio was an efficient mean to overcome the trade-off between risk and expected return.

In addition, models simulating the impact of diversification practices on farm performances need to be put into perspective with farmers' technical, commercial and environmental constraints (Fernandez et al., 2013). In other words, not all crop portfolios are comparable for farmers once economic or commercial dimensions (e.g. community supported agriculture) are taken into account. Crop rotations may also greatly influence the definition of the respective share of crops in a portfolio, based in particular on the principles of agroecology. Some portfolio compositions theoretically pertinent in terms of risk reduction may turn to be irrelevant in an agronomic approach. Considering the growing attention given to environmental, social and immaterial dimensions in diversified horticultural systems (Morel and Léger, 2016), a strictly

return-based analysis is not sufficient and revised criteria have to be developed. Meynard et al. (2013) showed in this respect that crop diversification is not only steered by production risk management factors, but also by market opportunities and the development of supply chains enhancing land use diversification. Such an in-depth analysis of crop portfolios profitability, feasibility and interest to the farmer was beyond the scope of this study but would be an important step forward toward the use of our results as a support decision tool with the farmers.

Finally, in the current study, we focused our analysis on the diversification effect of multi-cropping. In a context of highly diversified horticultural systems, it has, however, been noticed that farmers frequently associate species in intercropping or agroforestry designs in which crops interact with each other (Lauri et al., 2016; Warlop, 2016). They therefore benefit from both the diversification effect that we considered in this study and from an association effect, also called “species interaction effect” (Lhomme and Winkel, 2002), resulting from biological interactions between crops. In this sense, intercropping agricultural systems differ from other forms of portfolios since interaction between crops can no longer be neglected (Vandermeer, 1989). Preliminary work in this direction showed that intercropping could lead to both risk reduction and yield increase since most crop association led to an overall increase in production (Raphael Paut et al., 2018).

5. Conclusion

By applying the Modern Portfolio Theory to the diversification of horticultural systems, we managed to quantify the diversification benefits associated with a wide range of crop portfolios. In this respect, the portfolio theory makes it possible to better understand the trade-offs between risk and expected production in diversified systems. It also enables to identify relevant crop diversification strategies based on risk reduction. It is expected that this approach could be used as a tool to optimize portfolios including larger amount of crops. Besides, the results presented here illustrate the specific case of horticultural systems. However, the model remains valid for most agricultural systems. Indeed, the method developed in this study only requires crops’ yield and variance, which are widely available and used data, relevant for most cropping systems. In this sense, our method and findings may have wider implications for other farming systems such as field crops or crop-livestock farming systems.

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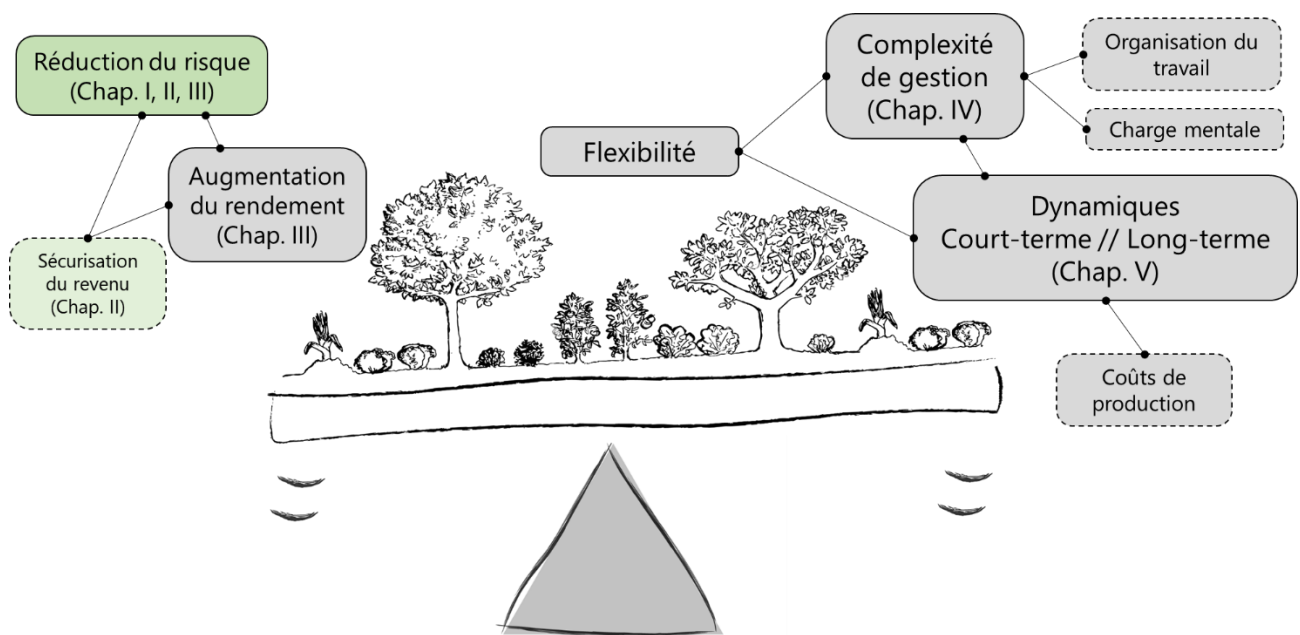
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Chapitre II. Vers des assolements plus diversifiés



Dans le premier chapitre, nous avons mobilisé la théorie du portefeuille pour étudier un grand nombre de paires de cultures. Nous avons également introduit le « bénéfice de diversification », métrique qui permet de quantifier l'intérêt d'une stratégie de diversification en termes de réduction du risque. La théorie du portefeuille permet ainsi de mieux comprendre les compromis rendement-risque dans des systèmes diversifiés et d'identifier des stratégies de diversification pertinentes du point de vue de la réduction des risques agronomiques. Néanmoins, dans la pratique les agriculteurs en verger-maraicher constituent des portefeuilles (ou assolements) combinant plusieurs dizaines d'espèces fruitières et maraichères en rotation. Cela augmente le nombre de combinaisons de cultures possibles et complexifie leur étude.

L'objectif du chapitre suivant est donc d'explorer des stratégies de diversification en considérant des portefeuilles plus diversifiés (jusqu'à 22 espèces de fruits et légumes), cela de deux manières distinctes. Tout d'abord, nous augmentons le nombre d'espèces dans l'assolement et explorons toutes les combinaisons possibles de ces espèces. Ensuite, nous définissons trois types de portefeuilles : les portefeuilles uniquement composés de légumes, ceux uniquement composés de fruits, et d'autres portefeuilles mixtes. Les résultats montrent que (i) l'augmentation du nombre de cultures dans le portefeuille améliore progressivement le compromis rendement-risque ; (ii) une grande proportion du risque peut être réduite jusqu'à 10 cultures ; (iii) les classifications *classiques* de fruits et légumes ne montrent pas de tendances claires permettant de conclure sur l'intérêt d'une diversification basée sur ces aspects botaniques.

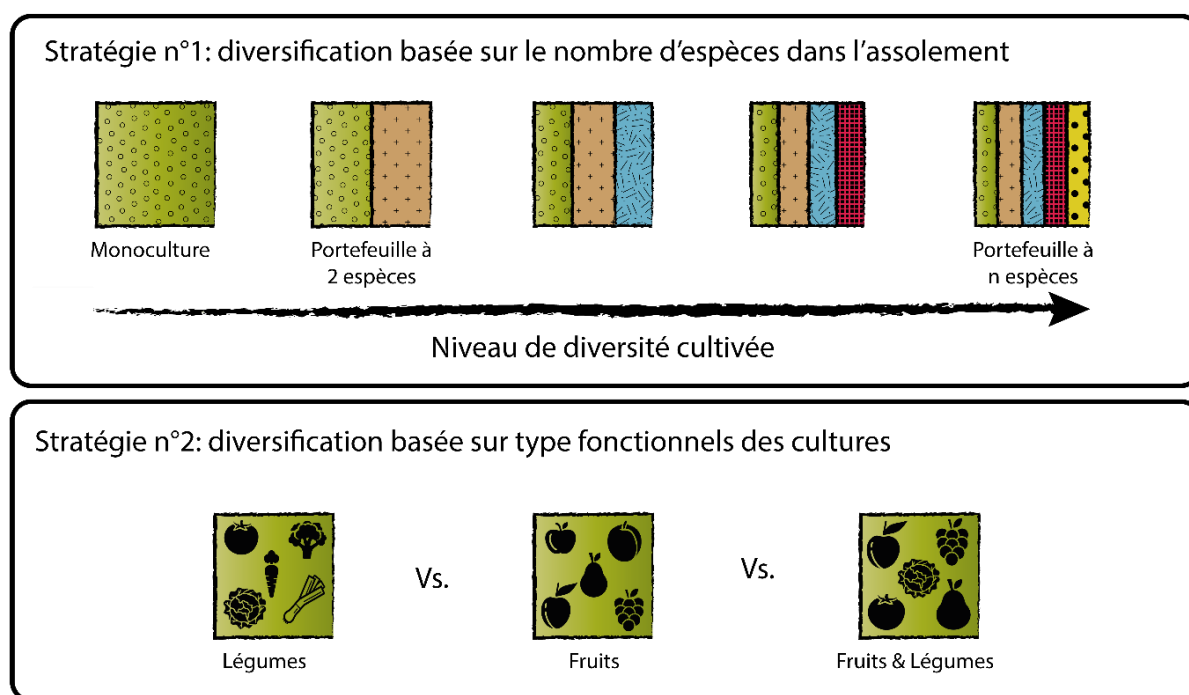


Figure B-6 : Résumé graphique de l'Article II

Benefits of diversified horticultural systems: assessment with the modern portfolio theory

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Abstract:

In a context of a redefinition of farming systems, innovative cropping systems have arisen in the recent decades. Among them, diversified horticultural systems show a growing interest in Europe, especially among new entrants into farming. One of the main motivations for farmers to grow simultaneously a variety of vegetables and fruits is to reduce the overall risk on production through a diversification effect. On the theoretical point of view, risk reduction based on diversification of assets is a well-studied mechanism in economics that has been formalized in the Modern Portfolio Theory (MPT). In practice, farmers tend to build crop portfolios that generate the highest yield while minimizing the risk on the overall crop production. The objective of this study was to understand how different fruit-vegetable combinations shape the relationship between production and risk in a diversified farming system. Based on the MPT framework, we explored all possible crop portfolios composed of 1 to 5 crops chosen in a list of 22 commonly grown fruits and vegetables. Results showed that (i) increasing portfolio compositions from 1 to 5 crops progressively improves the production-risk trade-off that farmers have to face; (ii) fruit

and vegetables classification does not show clear trends to conclude on the interest of diversification based on botanical aspects. These results led us to identify suitable diversification strategies for fruits and vegetables production that make it possible to reduce the overall risk on crop production while maintaining the same level of production.

Keywords: Horticulture, diversification, risk, Modern Portfolio Theory, yield, variability

1. Introduction

The last decades have been marked by a growing interest in sustainable farming systems, with a fast-acting progress in its achievement (Warlop, 2016; Wezel et al., 2014). Within this general dynamic, farming strategies developed by innovative growers are highly diverse (Morel et al., 2017) but a common objective followed by these systems is the reduction of risk through an increased cultivated diversity.

In the literature, the relationship between agricultural diversity and risk has been explored from the point of view of ecological stability (Ives and Carpenter, 2007; Tilman et al., 2006) and agricultural systems resilience (Isbell et al., 2017; Liebman and Schulte, 2015). The underlying hypothesis is that an increased diversity of crops creates a stabilizing effect that preserves the production services and reduces crop failure risk (Altieri and Nicholls, 2004; Vandermeer and Schultz, 1990). In parallel to these ecological studies, a widely used approach in economic sciences to evaluate the risk reduction obtained through diversification is the Modern Portfolio Theory (MPT) (Markowitz, 1952, 1959). This theory provides a mathematical framework for the analysis of diversified portfolios in order to minimize risk and maximize returns (Kolm et al., 2014).

In the present study, the effect of crop diversification is assessed within the MPT framework by the relationship between risk and the number of crops in the portfolio. Crops are expected to behave as assets, thus risk may be significantly reduced by combining several crops in a portfolio. By analogy, farmers would tend to build crop portfolios that generate the highest yield for a minimum acceptable risk (Figge, 2004; Fraser et al., 2005).

First, we present the theoretical portfolio selection model to minimize risk; we then explore the opportunities for the application of this theory to a context of diversified horticultural systems.

2. Material and methods

2.1. Application of the Modern Portfolio Theory

The Modern Portfolio Theory (Markowitz, 2010, 1952) formalizes the notion of risk reduction in economics, through an efficient diversification of assets within a portfolio. The general idea behind this theory is that when assets are combined in a portfolio and when asset returns are not perfectly correlated, the portfolio risk is reduced compared to single asset portfolios. Applying this theory to an agricultural context, a crop portfolio can be considered as a combination of N crops within a farm, with the returns R_n , ($n = 1, 2 \dots N$). The **expected return** of a portfolio P is the weighted sum of the return of each individual crop in the portfolio:

$$E(R_P) = \sum_i w_i E(R_i) \quad (6)$$

where w_i the relative weight of crop i (that is, the proportion of crop “ i ” in the portfolio) and $E(R_i)$ the expected return of crop i .

In addition, we assimilate the **risk** (σ_p) of a portfolio to the standard deviation of the crop returns. It is calculated as follows:

$$\sigma_P^2 = \sum_i \sum_j w_i w_j \sigma_{ij} \quad (7)$$

where σ_{ij} the standard deviation of the return for crop i when $i = j$, and the covariance of the return of crops i and j when $i \neq j$.

A portfolio is optimal on the risk dimension if, for a given expected return $E(R_p)$, the portfolio has the lowest risk σ_p . The variance of a portfolio can be reduced in two ways, either by favoring crops with low return variances, or by using specific combinations of crops. Although the first way is intuitive, the second way relies on choosing crops for which yield variability shows little correlation so as to compensate yield fluctuations between crops (Figge, 2004).

Equations (6) and (7) allow to build **Figure B-7**. The expected return $E(R_p)$ of portfolios is represented on the y-axis. The risk is plotted on the x-axis as the standard deviation of $E(R_p)$. The coordinates for all possible portfolios are represented by the point cloud. The optimal portfolios (in the sense of Pareto) are located on the curve linking points A and B, known as *efficient frontier*. All portfolios below this curve have a lower expected return or a greater risk. For instance, Portfolio 2 will be preferentially chosen over Portfolio 3 because it offers a higher expected return for the same level of risk. Likewise, Portfolio 1 will be favored over Portfolio 3 because it offers the same expected return for a lower risk.

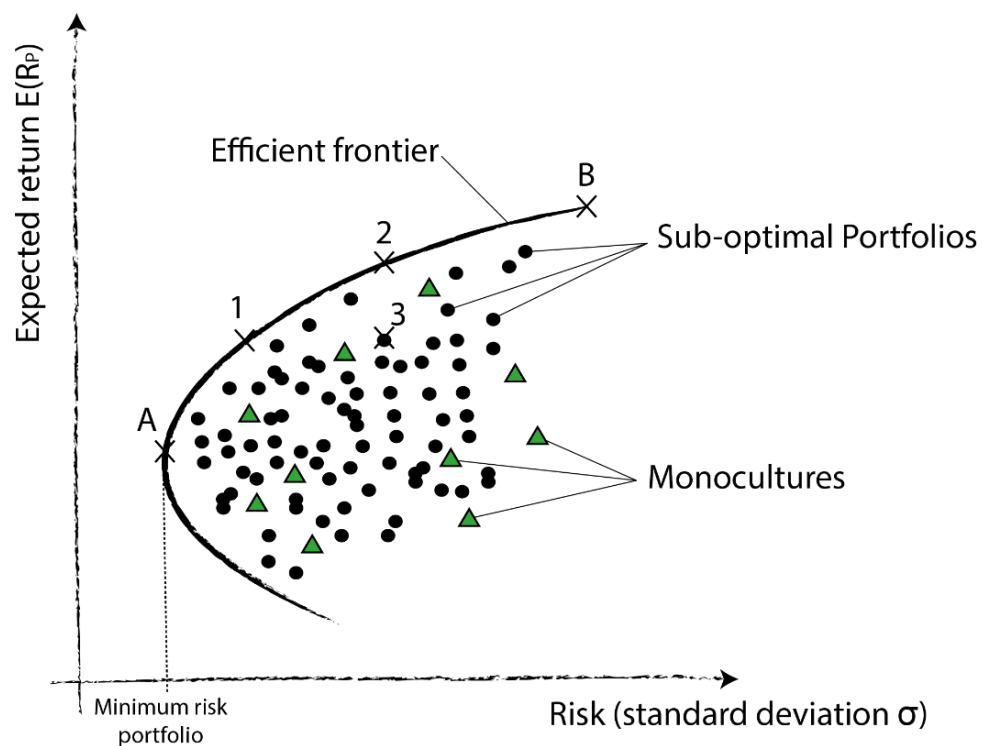


Figure B-7 : Risk-return relationship for hypothetical large portfolios

2.2. Systematic and unsystematic risk

Combining crops in a portfolio may reduce the risk of portfolio returns, as long as their correlation coefficient is less than 1. The part of the risk that can be reduced by diversification is known as *unsystematic risk* (or diversifiable risk). However, regardless of the level of diversification, there is always some risk that cannot be reduced, owing to the fact that crops are somehow correlated to each other. This part is referred to as *systematic risk* (or non-diversifiable risk). These features are illustrated in **Figure B-8**, where the curve asymptotically approaches a minimum risk that cannot be crossed, when the portfolio is extended (Figge, 2001). This figure shows that

beyond a given number of crops, the unsystematic risk reduction becomes negligible. The remaining variability of such portfolio will depend on external factors that are not specific to a crop or another (Turvey et al., 1988).

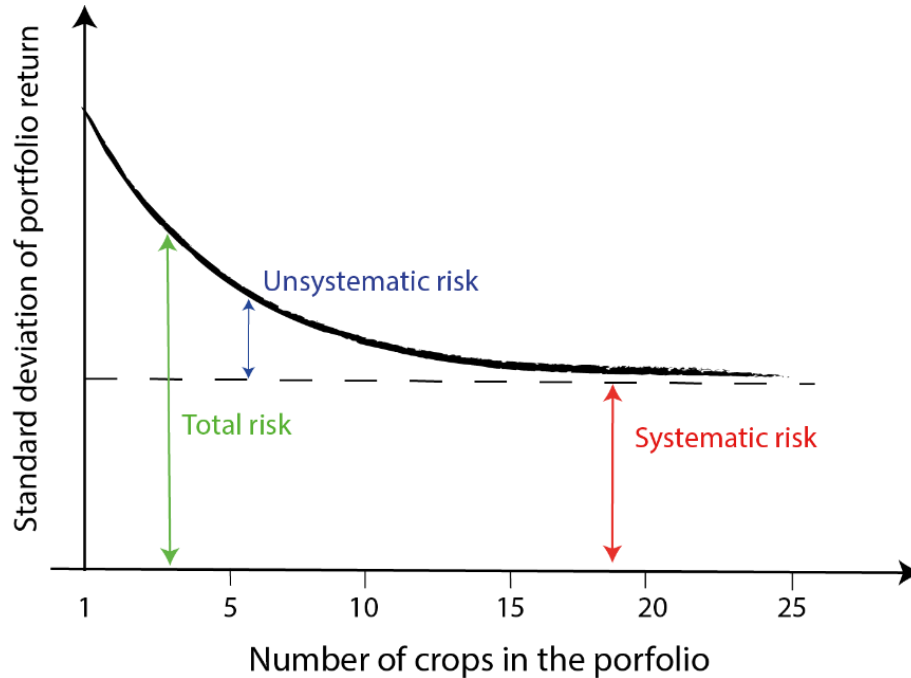


Figure B-8 : Systematic and non-systematic risk as a function of the number of crops in the portfolio

2.3. Data collection

In this study, data was collected from the French Interprofessional Technical Center for Fruits and Vegetables (Ctifl), which gathers information from the following sources: Agreste (National Agricultural Statistics), Eurostat and French Customs. We selected the three administrative regions of the South-East of France according to their relative soil and climate homogeneity. We selected 22 horticultural crops cultivated in these regions, 10 fruits and 12 vegetables, according to Pennington classification (Pennington and Fisher, 2009). For each crop, agronomic yield data was available for a range of 10 years (2006 to 2015 included). An estimation of the expected return for each crop has been made by multiplying the agronomic yield with the consumer price index (CPI) of the national statistical office (INSEE).

2.4. Generating portfolios of N crops

From the 22 horticultural crops selected, we generated every possible combination of portfolios from one to five crops (that is, the number of k -multicombination Γ_k^n). This led to 65,780 different unique portfolios. Risk and return combination has been calculated for each generated portfolio. Then we analyzed the generated portfolio according to two diversification strategies: first, based on the level of cultivated diversity from one to five crops (**Figure B-9a**); second, based on the functional type of crops (**Figure B-9b**).

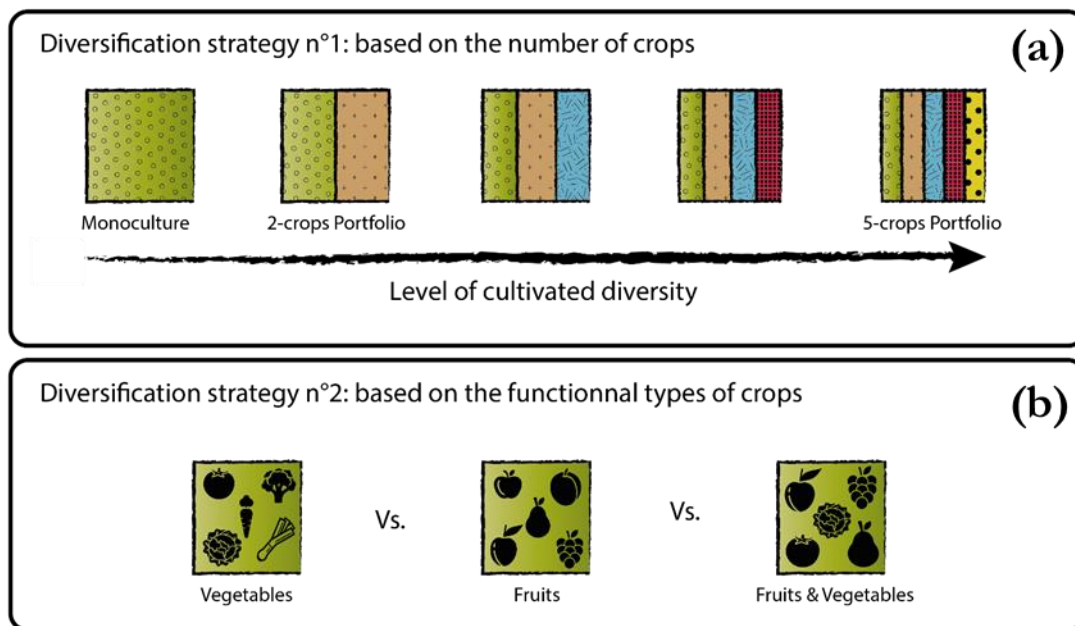


Figure B-9 : Representation of diversification strategies as alternatives to monocultures

Due to the large number of possible portfolios, we could explore both diversification strategies for all portfolios composed of up to 5 crops. For simulation purposes, we only simulated a subset of the portfolios up to 22 crops. These remaining portfolios were generated for combinations of crops up to 22, that is, the number of k -combination C_k^n .

3. Results

3.1. Diversification strategy n°1: which level of cultivated diversity is suitable?

Combinations of crops within our sample led to 22 portfolios composed of sole crops, 924 portfolios composed of 2 crops, 9240 portfolios composed of 3 crops, 29260 portfolios composed of 4 crops and 26334 portfolios composed of 5 crops (Figure B-10).

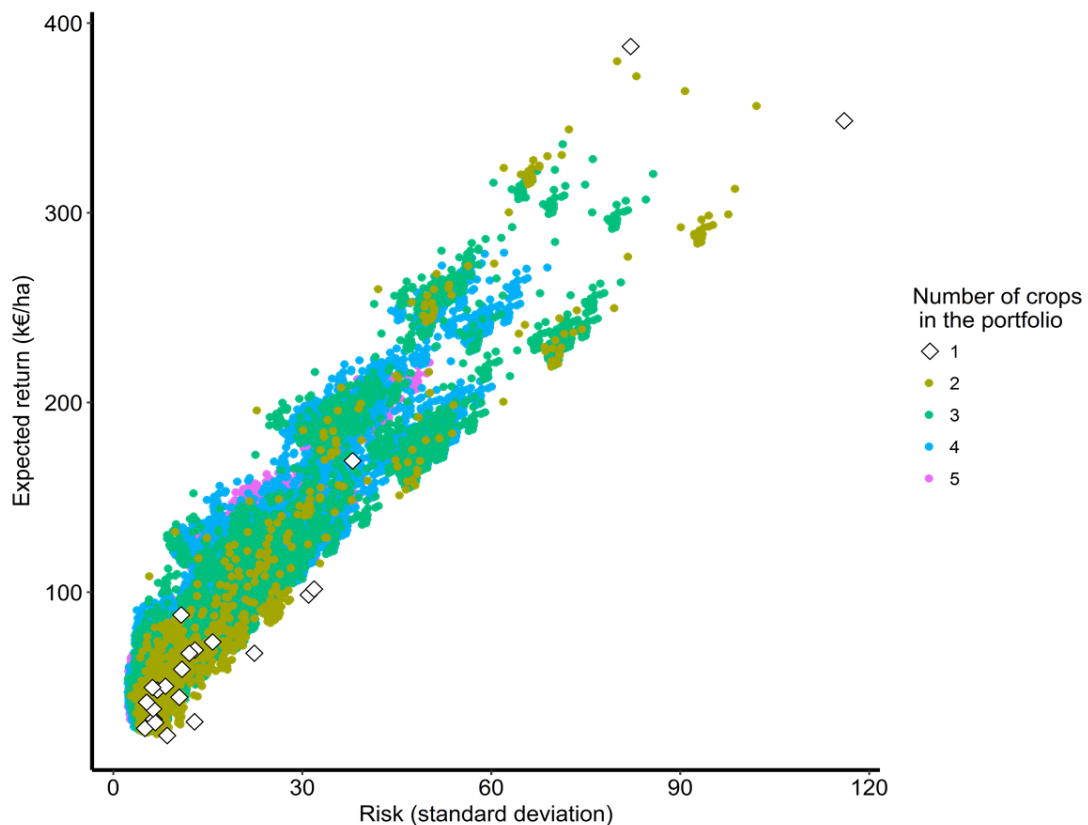


Figure B-10 : Risk and return combinations for portfolios composed of 1 to 5 crops

The linear regression on each level of diversity shows that an increasing number of crops in a portfolio leads to a better risk and return combination ($p < 0.05$, Table B-2). Indeed, the slope of the regression increases with the diversification level. Our data also indicate that the range of risk and return values decreases as the number of crops in the portfolio increases. The interest is that the maximum risk is reduced, but it goes together with a lower maximum expected return.

Table B-2. Linear regression parameters for each level of crop diversity

Number of crops in the portfolio	Slope	Intercept	Risk (portfolio standard deviation)
1	3.35 ^{abc}	17.6 ^a	21.2 ^a
2	3.41 ^b	25.2 ^b	18.7 ^b
3	3.46 ^c	29.7 ^c	17.1 ^c
4	3.51 ^d	32.9 ^d	15.9 ^d
5	3.58 ^e	34.6 ^e	15.1 ^{de}

^a Means followed by the same letter within a column did not show significant differences according to Tukey's Honestly Significant Difference ($P \leq 0.05$).

3.2. Systematic and non-systematic risk

The risk and return combinations were then calculated for all portfolios combining different crops. If we keep on adding crops to the portfolio, from 1 to 22 crops, the average standard deviation of portfolios drops from 21.2 to 13.9 respectively (**Figure B-11**). For the same average return, 34% of the risk could be eliminated due to diversification. This part of the risk is called unsystematic risk. Furthermore, we can observe that the risk curve tends towards a threshold that represents the systematic risk and that seem incompressible even if the portfolio is enlarged. This observed saturation effect can be illustrated by the fact that two third of the unsystematic risk was eliminated with 10 crops.

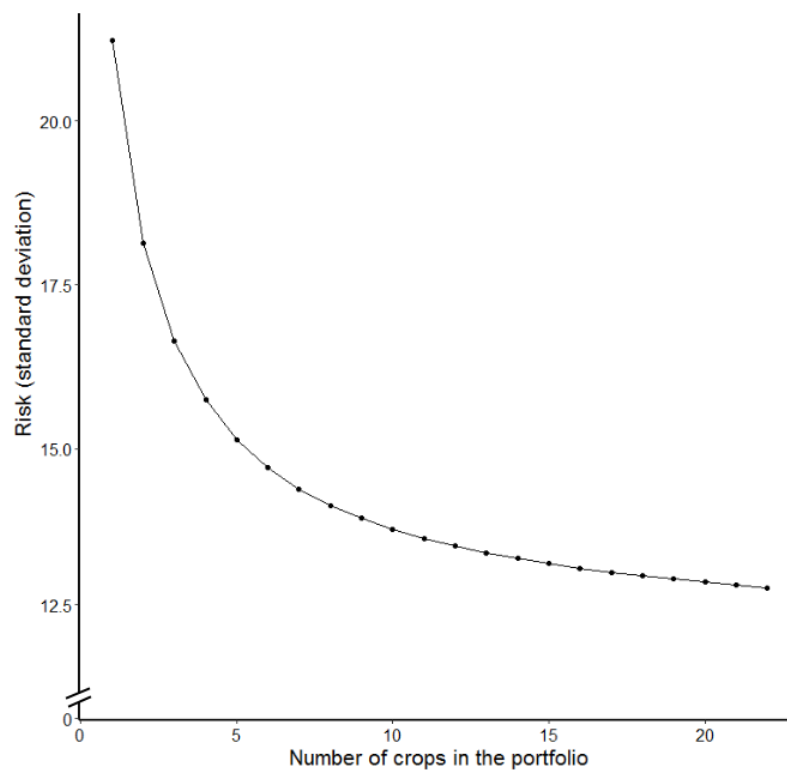


Figure B-11 : Effect of increasing portfolio compositions from 1 to 22 crops on the portfolio’s standard deviation.

3.3. Diversification strategy n°2: Portfolios mixing fruit and vegetable production

The second diversification strategy tested led to 4368 unique portfolios composed of vegetables, 2002 portfolios composed of fruits and 59410 portfolios composed of both fruits and vegetables. Fruit and vegetable sorting do not show clear trends to conclude on the interest of diversification based on botanical aspects. The “fruit only” strategy is the one that is the least interesting because it offers less risk/return compromises than either of the other two strategies (Table B-3). In addition, fruits and vegetables or sole vegetables seem slightly interchangeable. Therefore, we will have to look for other criteria to choose, especially in services provided by diversification that do not impact the production.

Table B-3. Linear regression parameters for the different portfolio types

Type of crops composing the portfolio	Slope	Intercept	Risk (portfolio standard deviation)	Expected return (k€)
Vegetables only	3.50 ^{ab}	31.7 ^b	21.4 ^a	106.5 ^a
Fruits & Vegetables	3.51 ^b	33.5 ^c	15.6 ^b	88.2 ^b
Fruits only	3.84 ^c	29.5 ^a	9.9 ^c	67.7 ^c

^a Means followed by the same letter within a column did not show significant differences according to Tukey's Honestly Significant Difference ($P \leq 0.05$).

4. Discussion and conclusion

Literature in the research domains of agriculture and biodiversity has acknowledged that diversified systems are better able to cope with future risks. However, they do not assess this risk in a quantitative way. Our aim was therefore to apply the MPT framework as a basis for the assessment of new farming arrangements based on a large cultivated diversity.

Results revealed that it is possible to highlight the relationship between return and risk of diversified crop portfolios. Based on the MPT framework, we showed that it is possible to reduce the overall risk through crop diversification, and to quantify it. One of our main results is that risk can be reduced by increasing the cultivated diversity (that is, by increasing the number of crops in our portfolio). These results are consistent with those reported for forestry (Crowe and Parker, 2008; Knoke et al., 2005), fishery (DuFour et al., 2015) or water resource management

(Aerts et al., 2015; Beuhler, 2006). Specifically, there might be a particular interest in combining crop species whose yields behave inversely according to the cropping conditions, the weather or the presence of pests and diseases (Nalley and Barkley, 2010). Besides, portfolio theory formalizes the information that portfolio managers require to handle their crop portfolio efficiently. The two dimensions (risk and return) representation allows defining the appropriate level of crop diversification as a function of the risk aversion profile of each farmer.

Moreover, a diversification strategy based on botanical aspects (as suggested by Figge 2004) does not show identifiable patterns in our particular case study. This leads us to believe that other factors than a fruit/vegetable classification would be more suited to explain crop behavior in a diversification strategy. Indeed fruit and vegetables categories can be limited to explain the range of functional diversity provided by a large crop portfolio (Wood et al., 2015). As suggested by several authors (Pennington and Fisher, 2009; Song et al., 2014) other classification systems, such as botanic classification or functional response traits, may be relevant because they are based on physiological characteristics of plant development, growth and structure. Functional response types are groups of plant species that behave similarly to abiotic and biotic conditions, such as climatic conditions or fertilization regime (Diaz and Cabido, 2001). The greater variation of different response traits could then enhance the maintenance of agroecosystem functions (Lavorel and Garnier, 2002). It is also suitable for growers because plants within a functional group have similar cultivation requirements or pests and diseases sensitivity.

Finally, to further develop and improve our model, we identified three main questions that remain to be answered in future investigation. First, the expected return used in the present study does not reflect the effective profitability of crops. Additional information on crop production costs (Better, 1988; Current et al., 1979) particularly in diversified systems would be needed. However, due to the scarcity of data, such an improvement of our approach would be likely to significantly reduce the pool of crops that we could consider. Secondly, in a perspective of highly diversified horticultural systems, it has been observed that new farming arrangements often mix species within intercropping or agroforestry design, where crops interact together (Lauri et al., 2016; Warlop, 2016). Taking into account interactions between crops in the risk and return evaluation of such systems could be relevant (Blandon, 2004). Lastly, models simulating the impact of diversification practices on farm performances must account for farmers' objectives, aspirations and farming context (Fernandez et al., 2013; Morel and Léger, 2016). In

other words, not all crop portfolios are equivalent to the farmer once agronomic or commercial dimensions are taken into account. Given the increasing value attributed to environmental, social and immaterial dimensions, a strictly income-based analysis is not sufficient and revised criteria have to be developed.

Acknowledgments

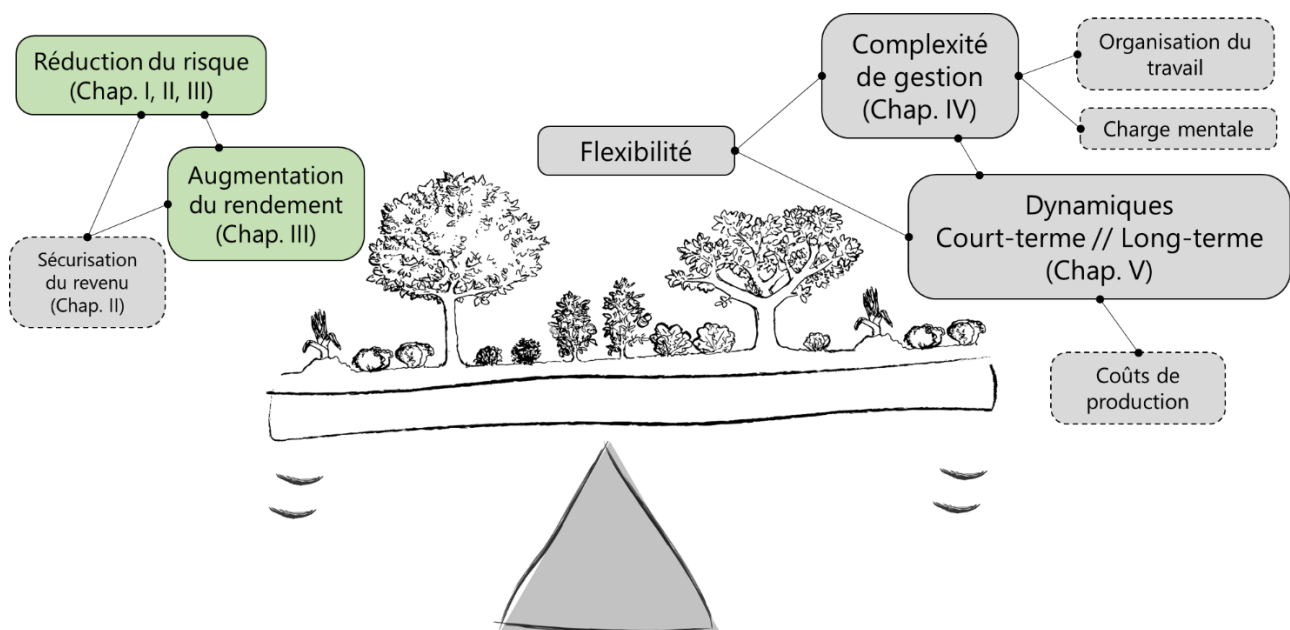
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Chapitre III. Modélisation des effets de « diversification » et « d'association » dans les systèmes agricoles



Dans un premier temps, nous avons modélisé l'intérêt de la diversification pour la gestion du risque agronomique, en faisant un parallèle avec la Théorie du Portefeuille. Chaque culture est un actif, caractérisé par un gain (le rendement) et un risque (la variabilité de ce rendement). L'originalité de notre approche vient de son application aux sciences agronomiques, jusqu'alors assez peu répandue. Elle constitue un outil permettant de mieux appréhender une stratégie de diversification en horticulture, basée sur la réduction de la variabilité du rendement. Cependant ces travaux (Chapitres 1 & 2) s'intéressent uniquement à la diversification vue comme un accroissement de la diversité cultivée sans prendre en compte les interactions biologiques entre les espèces. Or, les vergers-maraichers sont conçus dans une logique agroforestière, les interactions et complémentarités entre cultures sont recherchées afin de maximiser ce que nous appellerons « **l'effet d'association** » entre cultures (Figure B-12). Les éléments du système interagissent entre eux et diffèrent en cela des actifs classiquement étudiés en économie.

Les travaux de recherche ont jusqu'alors souvent porté sur la comparaison des configurations agroforestières avec des cultures pures, mais l'agroforesterie a rarement été mise en perspective avec d'autres formes de diversification de l'utilisation des terres, y compris une simple diversification en « mosaïque⁹ » au sein de l'exploitation. L'objectif de ce chapitre est d'élaborer une approche de modélisation pour comparer la performance des stratégies de diversification agroforestière et de diversification en mosaïque sur le rendement et le risque, en tenant compte des effets des interactions entre cultures, qu'il s'agisse de pérennes ou d'annuelles. Pour cela, nous combinons la Théorie du Portefeuille (qui formalise l'effet de diversification) avec le concept de Surface Equivalente Assolée¹⁰ (qui formalise l'effet de l'association) dans un cadre d'analyse unifié.

L'application de cadre à un corpus de publications scientifiques montre que les systèmes associés sont généralement plus performants qu'une approche en mosaïque, à la fois en termes de rendement et de risque. Ainsi les cultures associées, outre leur intérêt productif, peuvent avoir des rendements plus stables au cours du temps et servir de stratégie complémentaire à une simple diversification pour l'atténuation des risques.

⁹ Diversification en mosaïque : forme de diversification qui consiste à cultiver différentes espèces sur des parcelles distinctes et séparées spatialement, au sein d'une même exploitation.

¹⁰ Surface Equivalente Assolée, ou Land Equivalent Ratio (LER) en anglais. Ce ratio permet de comparer la performance d'une association de cultures à celle des mêmes cultures cultivées séparément.

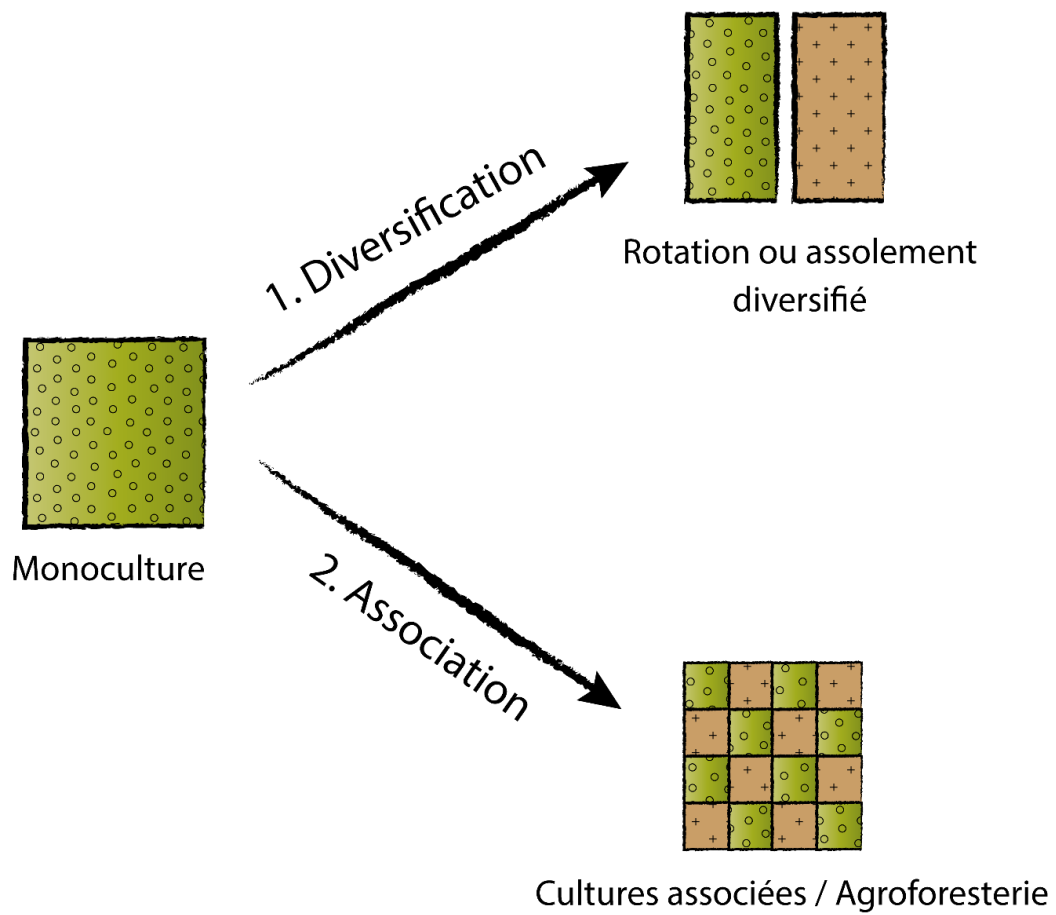


Figure B-12 : Résumé graphique du Chapitre III

Modelling crop diversification and association effects in agricultural systems

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Abstract

The need to redesign more sustainable agricultural systems able of producing more, especially through intercropping or agroforestry, cannot be achieved without taking into account the essential aspect of production variability. Yet, although many studies have focused on the effect of intercropping on overall production, the particular issue of production variability in such systems remains relatively unstudied. The approach we propose, for a shift towards a sustainable intensification of agricultural systems, considers the dual dimensions of yield and risk in a combined framework for the assessment and the comparison of two diversification strategies: (i) a simple diversification strategy (SDS) considered as an increasing number of crops grown on separate plots within a farm and (ii) an intercropping strategy (IC) considered as a within-plot increased diversity, where more than one species is grown at the same time and place. The two perspectives examined here were Modern Portfolio Theory and Land Equivalent Ratio. The former quantifies the effect of diversification on risk, the latter measures the effect of association on production. This research merges both approaches in a combined framework in order to assess intercropping system performances. By applying our framework to cases selected from the literature, we explored and compared the potential benefits of these two strategies in terms of yield and risk. Results showed that intercropping, in addition to being interesting with regard to yield, can have an additional risk reduction effect compared to a simple diversification strategy. Conversely, some crop mixtures maintained or even increased yield variability. Our work

contributes to a better understanding of the possible impacts of diversification strategies on trade-offs between yield and risk, but also underlines the importance of taking yield variability into account in further studies.

Keywords: intercropping; agroforestry; diversification; Land Equivalent Ratio; LER; Modern Portfolio Theory; agroecology

1. Introduction

Agricultural systems are facing a productive challenge, the necessity to ensure a sufficient quantity of goods for a growing population (Fischer et al., 2014; Tilman et al., 2011; Tscharrntke et al., 2012). However, this productivity issue cannot be decoupled, even more so today, from the necessity of stability of this provision service (Hardaker et al., 2015; OECD, 2011). Indeed, weather and climate being significant drivers of agricultural production systems, food security seems doomed to deteriorate on a global scale, despite advances in technology and other fronts (Matiu et al., 2017; Osborne and Wheeler, 2013; Ray et al., 2015). In addition, the ecologization of agriculture limits the pool of management options available for farmers or their efficacy to control system variability, indicating the importance of finding farm-level responses (HLPE, 2019; Reidsma et al., 2010).

The dual productivity-stability issue therefore seems essential for designing and evaluating sustainable agricultural systems in a situation of increasing uncertainties (Muller et al., 2017; Urruty et al., 2016). Production stability depends on scale in nested systems. Although greater stability through crop diversity can be achieved at a national level (Renard and Tilman, 2019) it seems that farm scale is a crucial level to achieve this property (Reidsma et al., 2007). In this context, new farming organizations have emerged in the last decades, creating diversified systems based on the agroecological paradigm (Krebs and Bach, 2018; Wezel et al., 2014, 2009). Among these diversified systems, we can identify two diversification pathways. The first one, called Simple Diversification Strategy (SDS) corresponds to an increased cultivated diversity, that is to say, an increased number of species grown within a farm (Malézieux et al., 2009; Ratnadass et al., 2012). Because different crops are grown in different fields (i.e., spatial diversification) biological interactions between crops do not occur. The other diversification strategy is called intercropping (IC) and refers to the spatial association of crops on the same plot and involves a

diversity of ecological interactions between crops (Lovell et al., 2017a; Torquebiau, 2000; Vandermeer, 1989). In the case of tree-crop interactions, this system is also referred to as agroforestry.

In contrast to monocultures, both strategies lead to a more diversified production system, but while SDS relies on diversification to reduce risks, IC also relies on spatial association to benefits from the biological interactions between crops. Therefore, these two diversification strategies rely on two stacked paradigms in managing the balance between risk and yield, and a comparison of both approaches regarding risk-yield trade-offs is still lacking.

A relevant tool to address this issue is the Modern Portfolio Theory (MPT). The MPT has been initially developed in finance (Markowitz, 2010, 1952) and recently used in agricultural sciences to select relevant crop combinations in a portfolio under uncertainty (Barkley and Peterson, 2010; Fraser et al., 2005; Nalley and Barkley, 2010; Paut et al., 2019; Van Noordwijk et al., 1994). The central point of this theory is based on the fact that if productions of the two crops are not perfectly correlated with each other, combining these crops in a portfolio, which corresponds to a diversified land use, makes it possible to reduce the risk associated with crop production. Specifically, there may be large potential gains from combining varieties or species that are characterized by inverse yield responses to environmental fluctuations such as droughts, pests or diseases.

Applied to agricultural sciences, MPT makes it possible to define the best crop combinations when the expected yields, the individual risks of each crop, as well as the correlations between crops are known (Knoke et al., 2015; Paut et al., 2019). Although other definitions of risk exist in agricultural studies, the MPT considers risk as the unpredictability of yields (*i.e.* standard deviation of yield) rather than the probability of not reaching a stated goal (Van Noordwijk and Van Andel, 1988; Van Winsen et al., 2013). Thus the overall yield and risk of a crop portfolio, considered as a group of physically separated plots, can be assessed (Castro et al., 2015; Fraser et al., 2005). This approach therefore seems to be more appropriate for a simple diversification strategy (SDS) rather than for the selection of intercropping systems (IC), where interactions between crops are sought and can lead to a non-linear effect on yields (Paul et al., 2017).

Besides, intercropping (IC) is another form of diversification in which interactions between crops are prevalent. Crop interactions that may lead to an increasing productivity are

often assessed by the so-called Land Equivalent Ratio (LER) (Willey, 1979a). The LER compares the land-use efficiency of crops grown in intercropping systems with sole crops. It is a widespread and useful indicator to assess the benefits of intercropping in terms of production, but it is generally used in a way that does not consider a possible decrease of the yield variability that could result from intercropping (Fukai, 1993; Lithourgidis et al., 2011; Rao and Willey, 1980).

Yet, from a biological perspective, it seems that mixed systems are better able to buffer environmental variations. Beyond the diversification effect above-mentioned, ecological interactions can generate a combination of stabilizing mechanisms such as complementarity in resource use, i.e. the ability of one component to use resources not needed by another one, which leads to a compensation in the ecosystem functions they provide and promotes stability (Bedoussac et al., 2015; Grman et al., 2010; Tilman, 1999). Facilitation mechanism can also occur when certain species mitigate harsh environmental conditions or provide resources for others (Hooper et al., 2005; Mulder et al., 2001; Vandermeer, 1989). Such mechanisms obviously cannot occur if the crops are grown separately. However, even though biological diversity has been reported to be important in yield stability, there is still limited experimental evidence of this relationship in the specific case of crops interacting with each other (Blandon, 2004; Francis, 1989; Willey, 1979b) and some conflicting reports. The early research on intercropping suggested that these systems are likely to be more stable (Rao and Singh, 1990; Vandermeer and Schultz, 1990) but there is still little quantitative information on the extent or the operational significance of this improved performance. In some cases, intercropping systems can have more stable yields over time and can serve as a risk mitigation strategy due to the relative sensitivity of their component crops to temperature fluctuations, drought or pests and diseases (Francis, 1989). Inversely, the production variability can increase due to the existence of shared pests and diseases, e.g. polyphagous insects, fungal diseases (Schroth et al., 2000) or the microclimate created by one plant on the other (Jose et al., 2004; Monteith et al., 1991). In the end, in many situations it remains unclear whether increased stability can be achieved effectively and whether this stability is due to the diversification effect or to biological interactions between crops (Blandon, 2004, 1985; Paul et al., 2017; Rao and Singh, 1990; Rao and Willey, 1980).

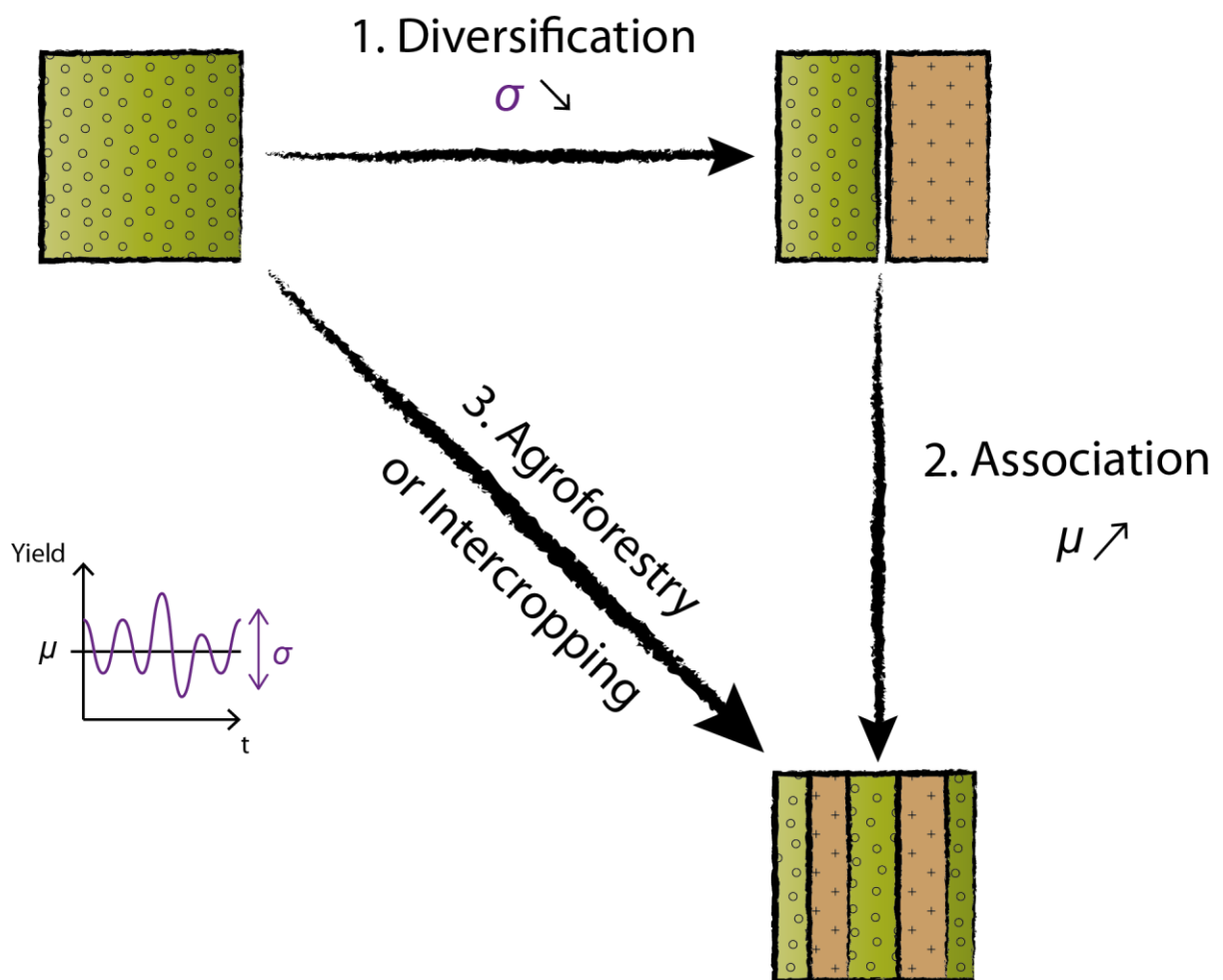


Figure B-13 : Graphical summary of the approach, with μ standing for mean crop production and σ its standard deviation.

To summarize, Modern Portfolio Theory and Land Equivalent Ratio are relevant frameworks to analyze different mechanisms associated with diversified cropping systems. MPT makes it possible to formalize the risk reduction effect of crop diversification, but does not, in its standard application, consider ecological interactions between crops neither spatially nor temporally. LER provides a standardized basis to assess mean production of intercropping systems, but does not account for the risk-reduction effect of such diversification (although it could also be applied to any parameter of a statistical distribution rather than the mean, e.g. to an X% percentile). The aim of the present study is therefore to combine these two theoretical approaches in a unified framework to formalize the effect of intercropping on both production and risk (**Figure B-13**).

We will then apply our framework to horticultural systems, for which the issue of diversification and association is of great relevance. Horticulture, indeed, makes it possible to

combine a large number of crops with a wide range of functional traits in both diversification and association configurations. Moreover, there has been a strong development of diversified horticultural systems in recent years, combining an increasing crop diversity (Morel et al., 2017; Morel and Léger, 2016; Navarrete et al., 2014) with intercropping and agroforestry configurations (Léger et al., 2018, 2019; Sieffert et al., 2014). This creates a fertile ground for the application of our conceptual framework to an applied issue relevant to a growing number of farmers. For the application of our conceptual framework, we conducted a literature review from which we extracted the data necessary for the application of this model.

2. Material and methods

2.1. Formalizing the diversification effect through the Modern Portfolio Theory

Markowitz (2010, 1990, 1952) first introduced the so-called Modern portfolio Theory (MPT) in finance in order to analyze how diversified portfolios of assets could provide a risk-reducing effect, as long as assets return are not perfectly correlated. He defined risk as the portfolio standard deviation. In our case, a portfolio diversification consists in moving from a monoculture to a more diversified agrosystem. According to the MPT, the expected yield of a portfolio P is the weighted sum of each individual asset in the portfolio:

$$E(Y_P) = \sum_i w_i E(Y_i) = w_A E(Y_A) + w_B E(Y_B) \quad (8)$$

where w_i is the weight of crop i (that is, the proportion of the cultivated area of crop i), $E(Y_i)$ is the expected yield of crop i and the sum of w_A and w_B is equal to 1. Notice that in this view, the yield associated with each asset is independent from the composition of the portfolio.

Furthermore, the risk of a portfolio is measured by its standard deviation. The risk of the system composed of two crops (Crop A and Crop B), σ_P , is defined as follows:

$$\sigma_P = \sqrt{\sum_j \sum_j w_i w_j \sigma_{ij}} = \sqrt{w_A^2 \sigma_A^2 + w_B^2 \sigma_B^2 + 2w_A w_B \sigma_A \sigma_B \rho_{AB}} \quad (9)$$

where σ_i is the standard deviation of yield for crop i , ρ_{AB} is the correlation coefficient of crop A and crop B. Eq. (9) shows that the standard deviation of the portfolio (σ_P) is the sum of two components: a variance term and a covariance term. It follows that the variability of a portfolio can be reduced in two ways, either by favoring crops with low yield variances, or by choosing crops with a low coefficient of correlation ρ . The effect of different values of ρ is illustrated in **Figure B-14**.

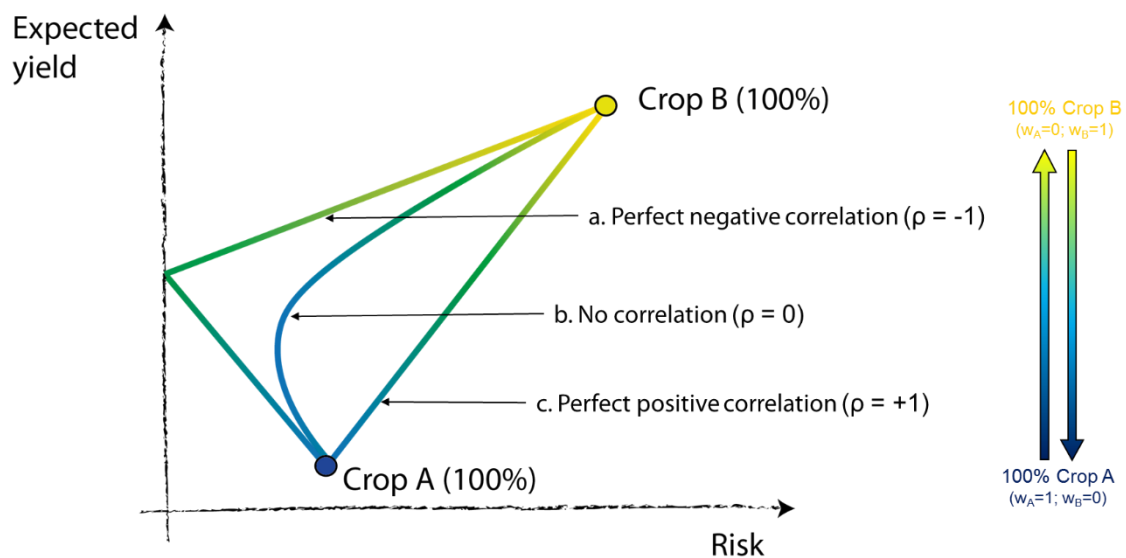


Figure B-14 : Possible yield and risk combinations for a two-crops portfolio when: (a) crop yields are perfectly negatively correlated ($\rho_{AB} = -1$); (b) crop yields are not correlated ($\rho_{AB} = 0$) and (c) crop yields are perfectly correlated ($\rho_{AB} = +1$).

2.2. Formalizing the association effect through the Land Equivalent Ratio

When two crops are cultivated simultaneously on the same plot, interactions between these two crops may lead to an overall production different from the weighted sum of the production of each crop cultivated in monoculture. This association effect is classically assessed in the literature by the so-called Land Equivalent Ratio (LER) (Bedoussac and Justes, 2011; Mead and Willey, 1980; Vandermeer, 1989; Willey, 1979a). LER represents the relative area needed for sole crops to produce the same yields as those obtained by an intercropping design. For a given proportion (k) of crop A in the association with crop B, the value of the LER $_k$ is calculated as the yields of each individual crop in relation to their yield as sole crops (Equation (10)).

$$LER_k = LER_A^k + LER_B^{1-k} = \frac{Y_A^k}{S_A} + \frac{Y_B^{1-k}}{S_B} \quad (10)$$

Where Y_i^k is the yield of crop i when grown as an intercrop at the proportion of k , S_i is the yield of crop i when grown as a sole crop. An LER greater than 1 means that the intercropping system mixing crop A and crop B produces more than its respective monoculture for the same cultivated area. The value 1 is the critical threshold, above which the intercrop is to be favored, and below which the monocultures may be preferred. Following Vandermeer (1989), we consider only three situations where the LER continuum might be convex (competition), concave (facilitation) or linear (no interaction), presented in **Figure B-15** : Examples of three qualitatively distinct forms of the Land Equivalent Ratio distribution. The solid curve represents a situation of facilitation (LER=1.5); the dotted line represents a situation of independence (LER=1) and the dashed line represents a situation of competition (LER=0.5). **Figure B-15**.

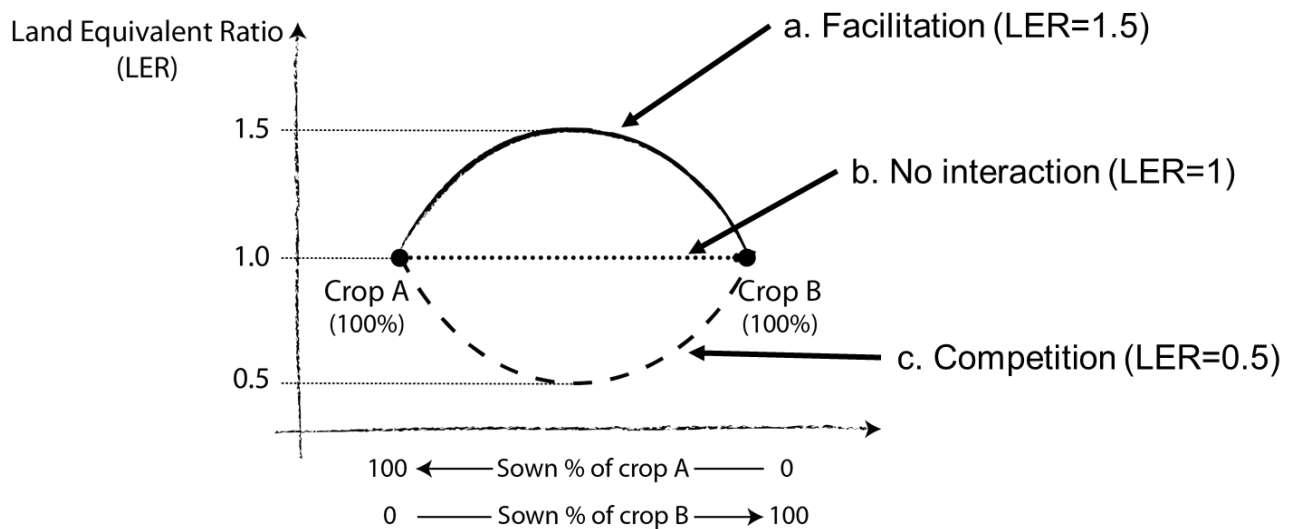


Figure B-15 : Examples of three qualitatively distinct forms of the Land Equivalent Ratio distribution. The solid curve represents a situation of facilitation (LER=1.5); the dotted line represents a situation of independence (LER=1) and the dashed line represents a situation of competition (LER=0.5).

2.3. Proposition of a new conceptual framework

As discussed above, despite an emerging consensus on the fact that intercropping can decrease the overall yield variability, this effect has rarely been quantified and no study clearly disentangled diversification effect from association effect on individual crop variability in horticulture (but see Van Noordwijk et al., 1994 for other crops). For the application of our new

conceptual framework, this leads us to recompose Eq.(8) and Eq.(9) into Eq.(11) and Eq.(12) respectively. Thus, the intercropping portfolio yield $E(Y_{AB})$ is considered as the weighted average of each crop yield multiplied by its relative yield in intercropping design:

$$E(Y_{AB})^k = LER_A^k w_A E(Y_A) + LER_B^{1-k} w_B E(Y_B) \quad (11)$$

where $E(Y_i)^k$ is the expected yield of crop i and LER_A^k is the partial LER of crop A at the proportion of k in the portfolio.

Besides, the risk of the intercropping portfolio is defined by Eq.(12) as the risk of a two crop portfolio multiplied by two factors. First, as for the yield (Eq. (11)), yield variability is subject to an affine transformation and is multiplied by the LER corresponding coefficient at the proportion of k in the intercropping design. Then, we introduce the coefficient β for the specific effect of intercropping on risk:

$$\begin{aligned} \sigma_{P(A,B)}^k & \\ &= \sqrt{w_A^2 (\beta_A LER_A^k \sigma_A)^2 + w_B^2 (\beta_B LER_B^k \sigma_B)^2 + 2w_A w_B \beta_A LER_A^k \sigma_A \beta_B LER_B^k \sigma_B \rho_{AB}} \end{aligned} \quad (12)$$

β_A and β_B are the partial coefficient of crop A and B respectively, that represent the effect of intercropping on yield variability. Due to the lack of sufficiently accurate data in literature to evaluate β_A and β_B , we will consider β_A and β_B being equal in the present application, but different values of β_i are explored in 228Appendix C.1. Beta being strictly positive, we can factorize into Eq. (12)bis.

$$\begin{aligned} \sigma_{P(A,B)}^k & \\ &= \beta \sqrt{w_A^2 (LER_A^k \sigma_A)^2 + w_B^2 (LER_B^k \sigma_B)^2 + 2w_A w_B LER_A^k \sigma_A LER_B^k \sigma_B \rho_{AB}} \end{aligned} \quad (12)\text{bis}$$

2.3.1. Considering different effects of intercropping on risk: three hypotheses

Yield variability of each crop may be affected by the intercropping design, positively or negatively depending on the choice of intercrops and their interactions. In this study, we will successively consider three contrasted hypotheses representing different effects (β values) of

intercropping on yield variability. First, the intercropping design decreases the variability of crop yields (i.e. when $\beta < 1$) compared to a simple diversification strategy (SDS), the portfolio standard deviation σ_P is reduced. This hypothesis integrates an additional risk reduction effect of crop association, compared to SDS. The second hypothesis states that the variability of each crop remains unchanged in intercropping compared to that of SDS. In other words, we assume that there is no biological effect of IC on yield variability of each crop. In this case, the β coefficient is therefore set at 1. Third, the intercropping design has a negative impact on crop yield stability (i.e. when $\beta > 1$), the portfolio standard deviation σ_P would be increased.

2.3.2. Exploration of contrasted scenarios considering our hypotheses

In order to screen different configurations, we developed scenarios that illustrate possible patterns in a contrasting way. Within each scenario, we considered the combination of three effects: (i) the effect of crop diversification on risk (ρ_{AB}); (ii) the effect of crop association on productivity (LER) and (iii) the effect of crop association on risk (β). Depending on how crops interact with each other, the LER can take any positive value, but in most cases, it lies between 0.5 and 1.5. To show contrasting situations, we selected three LER values that represent three distinct biological interactions: competition (LER=0.5), independence (LER=1) and complementarities (LER=1.5). Similarly, the correlation coefficient between crop A and crop B can take any value between -1 and 1. As an extreme situation, if yields are perfectly correlated, ρ_{AB} will be equal to 1. At the other extreme will be a situation where ρ_{AB} is equal to -1, between these two bounds will be a continuum of cases where the yields of the two crops are more or less closely related. In agroforestry systems it may be a common situation where the yields of crops and trees are not correlated (Blandon, 1985), in this case ρ_{AB} will be zero. Finally, considering our working hypotheses (Cf. supra), the association effect on risk (β) was set at 0.5, 1 and 1.5, reflecting a decrease of individual crop variability ($\beta=0.5$), no effect ($\beta=1$) or an increase of individual crop variability ($\beta=1.5$). The combination of these three effects, each taking three distinct values, generated 27 scenarios presented in **Figure B-16**.

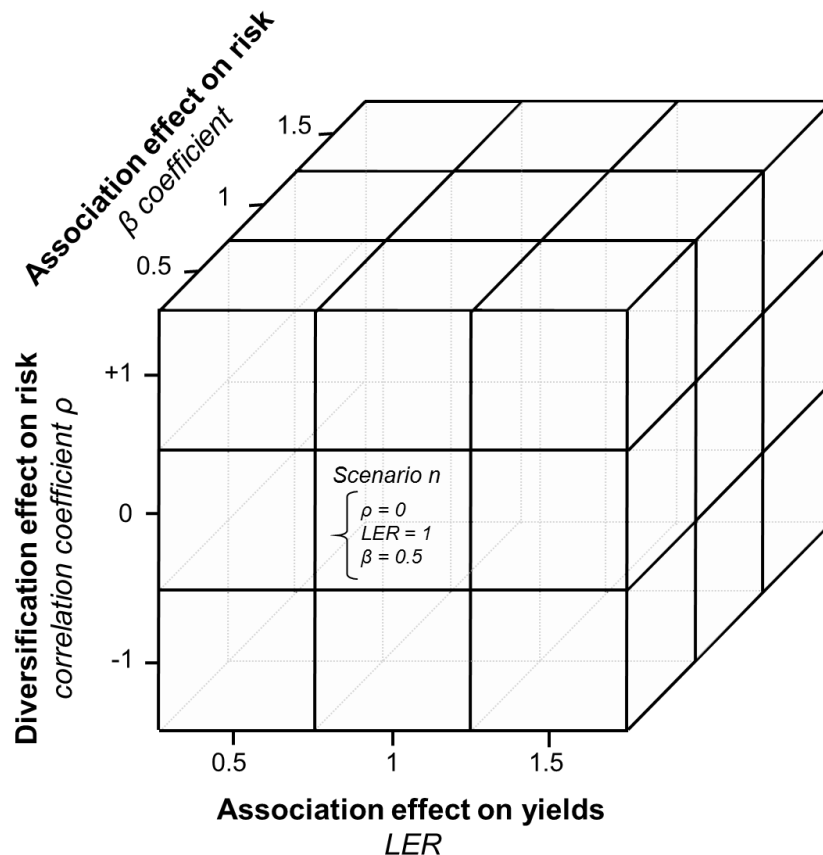


Figure B-16 : Parameter values for the development of the 27 contrasted scenarios

2.4. Mini review on intercropping systems based on fruits and/or vegetables to identify promising intercropping systems for the design of mixed horticultural systems

2.4.1. Data collection

In order to illustrate our approach, we applied our framework to real situations of intercropping. A literature review was carried out on horticultural intercropping systems. Studies were identified from a search in the Institute for Scientific Information Web of Knowledge and Google Scholar databases. We searched for the following terms: (*intercrop** OR *agroforestry* OR *mixed crop**) AND (*fruit** OR *orchard* OR *vegetable** OR *market gardening*). Among the 1,387 publications that came out of this query, we selected 74 studies that provided the data necessary to compute LER values. The reviewed papers involved vegetables and/or fruits in intercropping or agroforestry designs. It resulted in 534 experiments (an experiment is defined by a unique crop

combination in site and year) from which 449 were complete, meaning that both crop yields as sole crops and intercrops were available. From each experiment, we also extracted and coded crop species, relative crop density, LER, location and other useful information from each treatment. The list of reviewed papers is provided in Appendix C.2.

2.4.2. Simulations

Among the 74 studies reviewed for LER values, our model combining MPT and LER approaches was applied to all studies for which there were inter-annual repetitions of yield measurements. This resulted in 41 studies for which sufficient data were available: the yield of each crop $E(Y_i)$ is the mean yield of inter-annual repetitions; the standard deviation of each crop σ_i is calculated as the inter-annual variability of yields; the Land Equivalent Ratio LER_i^k is the LER of crop i at the proportion k ; the weight of each crop in the portfolio w_k is the proportion of crops in the intercropping design and the correlation coefficient ρ_{AB} is the correlation between crop yields through time.

Once $E(Y_i)$ and σ_i were computed for each intercropping design, we simulated the yield and risk combinations for 100 proportions of crop A and crop B (from $w_A=0$ to $w_A=1$) considering our two hypotheses. First, assuming intercropping had no effect on risk, Eq. (4) and Eq. (5) were applied to calculate yield and risk respectively. Second, assuming intercropping had an effect on risk, we used raw data from the paper to obtain the coefficient β by solving Eq. (5bis). Finally, intercropping systems were clustered using a k-means clustering on the three model output parameters (LER, β , ρ). Clusters were projected on the three dimensions and a Tukey's HSD was used to identify differences in cluster parameters. The model was implemented and graphical outputs were realized with R software 3.5.0 (<https://cran.r-project.org>).

3. Results

3.1. Yield and risk trade-offs: comparing SDS and IC

For the 27 possible combinations of Land Equivalent Ratio (LER), beta coefficient (β) and correlation coefficient (ρ), the yield-risk relationship curves were plotted, based on Equations (4) and (6). Points named Crop A and Crop B represent the yield and risk of sole crops ($w_A=1$

and $w_B=1$ respectively). The transition from Crop A to Crop B corresponds to the consideration of systems with an increasing area of crop B.

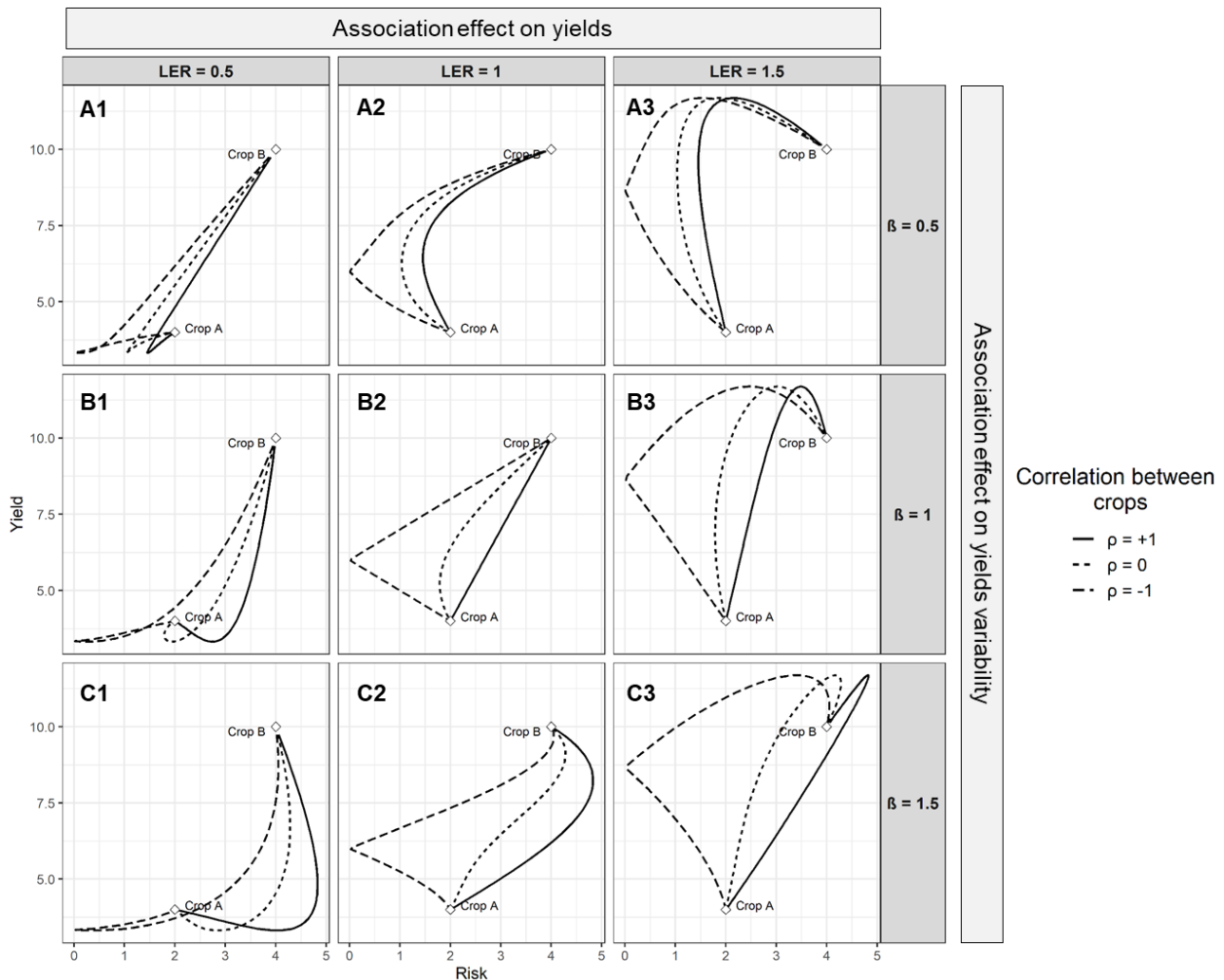


Figure B-17 : Yield and risk trade-offs among 27 contrasting scenarios of land-use options. Each curve represents a unique combination of LER, β and ρ coefficients. Moving from crop A to crop B corresponds to the consideration of systems with an increasing area allocated to crop B.

Figure B-17 shows the possible scenarios for 27 alternative cropping systems. Moving from scenarios 1 to 3 corresponds to an increasing association effect on yield, whereas moving from A to C corresponds to taking the different hypotheses of intercropping effect on risk into account. Notice that the line joining crop A to crop B in the scenario B2 also represents the weighted average of crop yields and risks. It can serve as a basis for the assessment of land-use alternatives on yield and risk dimensions. In confronting the different diversification alternatives, we can observe that some options perform better than sole crops on both dimensions (A3, B3). Some other options are only of interest in one of the two dimensions (A1, A2, B2, C2 and C3), which illustrate that intercropping can lead a trade-off between the different expected benefits.

Finally, some combinations perform poorly compared to the weighted average on both dimensions (B1 and C1). These portfolios, in addition to being in a competitive situation, exhibit greater variability than their pure crop equivalents.

In addition, the combination of crops are presented considering a low risk – low yield crop combined with a high yield – high risk crop. This type of combination is very common in agriculture. However, other functional forms may be obtained when a high yield - low risk crop is combined with a low yield - high risk crop as shown by Paut et al. (2019). Interestingly, this functional form adding a high-risk crop to a low-risk monoculture is still beneficial in terms of risk reduction. We do not detail these situations in this result section but we observed the same diversity of patterns. The reader may find them in Appendix C.3.

3.2. Application of our framework to selected cases from the literature

3.2.1. Characteristics of fruits and/or vegetables intercropping systems in the literature

The analysis of LER values among these observations found an average 38% increase in yield in intercropping designs compared to their monoculture components (*t*-test, $p < 0.001$). Overall, intercropping was more efficient than monocropping, since 405 out of the 449 calculated LER values were larger than 1 (**Figure B-18a**) but still 44 situations showed a LER < 1 corresponding to a lower yield in association than in sole crops. Moreover, the standard deviation on LER was 0.36, suggesting a high variability in LERs depending on crop species, treatments and experimental designs (**Figure B-18b**).

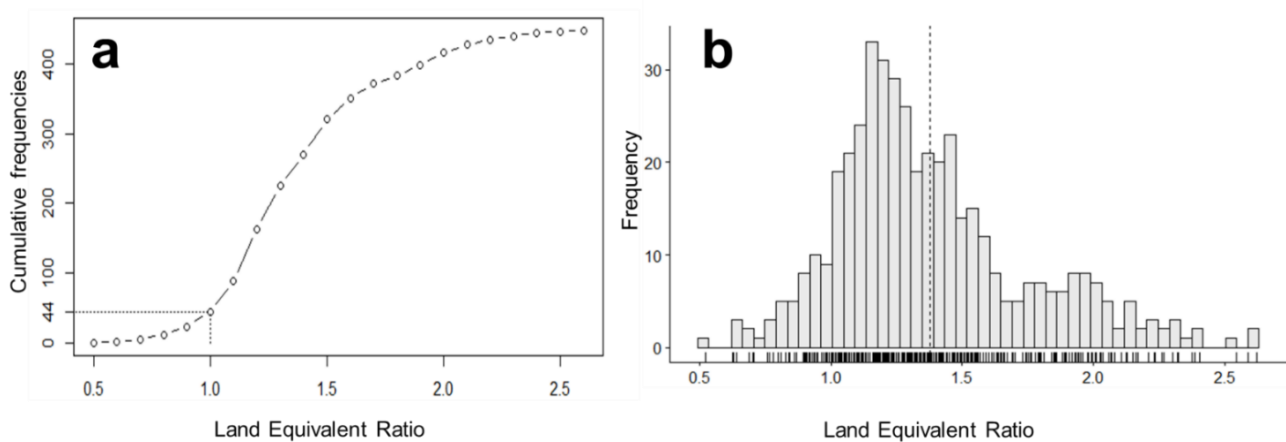


Figure B-18 : Cumulative frequencies (a) and frequency distribution (b) of Land Equivalent Ratios (LER) for the reviewed fruits and vegetables intercropping designs.

3.2.2. Modelling diversification and association effect on selected cases from the literature

Our model combining MPT and LER approaches was run on 41 studies for which sufficient data was available. From the reviewed papers, we could also extract the β value, which gives an indication of the relevance of the intercropping (in a given pedoclimatic context) with regard to yield variability. For illustrative purposes, two contrasting case studies have been selected among a large variety of cases, but the full set of intercropping systems is described in Appendix C.4.

In the first example given here (lettuce-radish intercropping, **Figure B-19a**, Cecílio Filho et al., 2007), diversification led to a strong reduction in risk and association made it possible to reach the lowest level of risk for a yield similar to the one obtained with lettuce only. In this case, there is a supplementary risk reduction effect due to the intercropping design ($\beta < 1$). Thus, in addition to having a positive effect on yield (LER=1.48), the intercropping has an additional risk-related advantage over a simple diversification.

Another interesting example of agroforestry system for which we found sufficient data in the literature is Apricot-Peanut intercropping (**Figure B-19b**, Bai et al., 2016) and it corresponds to the C3 functional form (Cf. **Figure B-17**). In this particular example, crop yields are strongly positively correlated, meaning that there is little effect on risk due to diversification. The yield improvement is important (LER=1.35) but we can observe a strong increasing effect

of intercropping on yields variability ($\beta=1.67$). In this example, there is no effect of diversification on risk, but additionally, the intercropping increases yield variability.

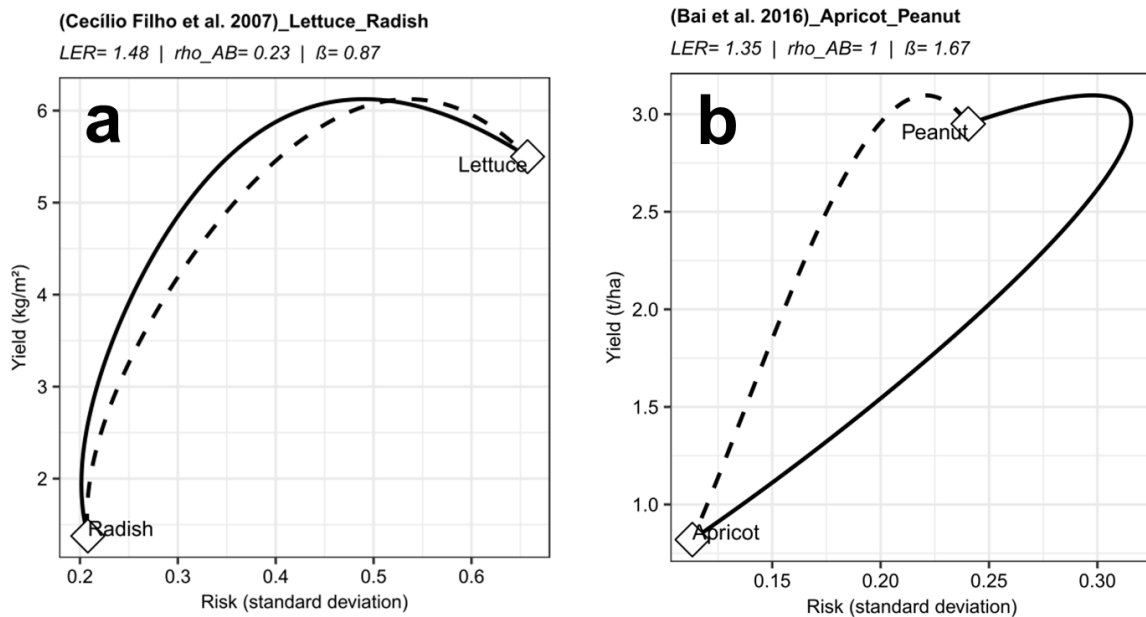


Figure B-19 : Risk-yields combinations considering our two hypotheses for two crop couples: (a) Lettuce-Radish and (b) Apricot-Peanut. The dashed curve represents the baseline hypothesis (H1) in the case where intercropping is assumed to have no effect on risk ($\beta=1$). The solid curve represents the alternative hypothesis (H2) in the case where intercropping effect on risk is considered ($\beta=0.87$ Fig. 7a; $\beta=1.67$ Fig. 7b). Moving from crop A to crop B implies an increasing proportion of crop B in the intercropping design.

From the reviewed papers, we observed an average positive correlation between crop yields; the average correlation coefficient was 0.25. The findings also indicate a strong positive effect of intercropping on yields, the average Land Equivalent Ratio was 1.40. We also extracted the β value, which gives an indication of the relevance of the intercropping with regard to yield variability. This coefficient provides information on whether the intercropping is profitable in terms of risk reduction, compared to a simple diversification strategy (in a given pedoclimatic context). The average value of β was 0.79. The statistical analysis (t -test) of β showed that it was significantly below 1 ($p < 0.001$) meaning that on average intercropping reduced individual crop variability.

3.2.3. Distinction in intercropping types

On the basis of a cluster analysis (k-means) the 41 selected experimentations were categorized into four clusters with different patterns in the dimensions LER, β and ρ (**Figure B-20**).

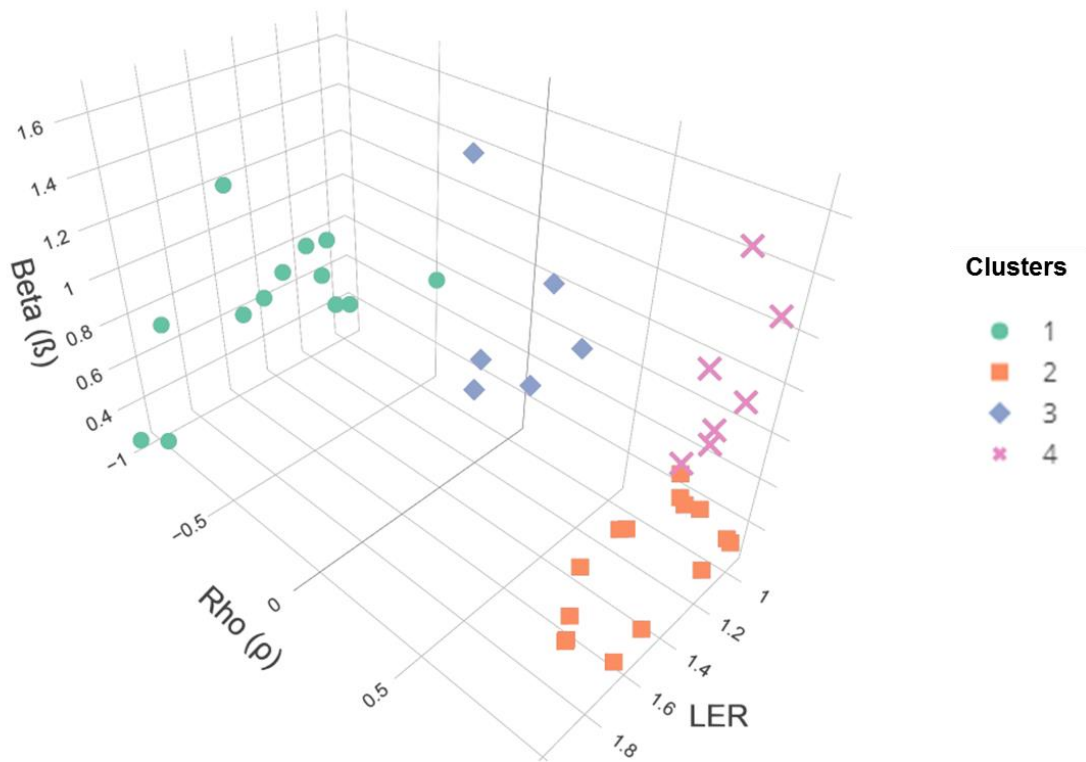


Figure B-20 : Representation of the studies reviewed as a function of the three dimensions (LER, β , ρ) considered in our model. K-means clustering on the three dimensions distinguished four types of intercropping systems.

The different intercropping clusters showed important variations in their structural parameters, except from the Land Equivalent Ratio, which remained relatively similar between clusters. Cluster 1 is characterized by a low correlation coefficient (-1) and a low β (0.63). Cluster 2 shows a similar β but can be distinguished from the first cluster by a correlation coefficient equal to 1. Clusters 3 and 4 differ from the first two ones on parameter β , which is close to one (0.94 and 1.06 respectively). They differ from each other on the parameter ρ (0.18 and 1.00 respectively). Overall, the clusters are characterized by different combinations of β and ρ values. This reflects a variety of diversification and association effects on yield variability. The details of the cluster analysis and further statistical analysis are presented in Appendix C.5.

4. Discussion

4.1. A framework to compare Simple Diversification Strategy and Intercropping

The two perspectives examined here were Modern Portfolio Theory and Land Equivalent Ratio. The former quantifies the effect of diversification on risk, the latter measures the effect of association on production. This research has merged both approaches in a combined framework in order to assess intercropping and agroforestry system performances. By applying this framework to real cases from the literature, our work contributes to a better understanding of the possible impacts of diversification strategies on the trade-offs between productivity and risk. The present model is not straightforward for deciders, but it requires some minor adaptations to serve as a decision-making tool. By formalizing the model to make it accessible and to facilitate the interpretation of its results for application purposes, it may therefore facilitate the choice of farm portfolios that results in the best agronomic performances associated with the lowest variability. The advantage of a bi-dimensional assessment (yield-risk) of portfolios is that it does not offer a unique better option, but rather provides a wide range of choices among which each option results in a combination of association and diversification effects.

4.2. Segregate or associate crops? Necessary trade-offs

Some authors reported that mixed cropping (Kjær et al., 2009; Reiss and Drinkwater, 2018) or intercropping (Raseduzzaman and Jensen, 2017) might be sustainable strategies for increasing agroecosystems performances, by enhancing mean yield and yield stability, associated with a lower environmental impact. Our findings seem to indicate that this is indeed the case in horticulture. By comparing different diversification alternatives (Cf. **Figure B-17**) we can observe that some intercropping options give better results than sole crops in both dimensions (A3 and B3, **Figure B-17**). Those are the intercropping designs that might be encouraged without requiring compromises. Some other options are only of interest in one of the two dimensions. They will have to be the subject of trade-offs according to the production objectives of each farmer and his/her risk aversion. From the application of our framework to existing literature, we could quantify these trade-offs for a range of crop couples. First, the high average LER (1.40) indicates that intercropping is advisable in terms of yield improvements as compared to monocultures. Second, we observed a positive correlation between crop yields (average $\rho=0.25$;

median=0.83). This might be due to the low number of inter-annual repetitions that tend to result in extreme correlation values. Nevertheless, this indicates that in intercropping, diversification has a minor effect on reducing yield variability in the reviewed papers. Finally, the mean β was 0.79, suggesting that in our sample, intercropping has overall an additional risk reducing effect as compared to Simple Diversification Systems.

By disentangling the effect of diversification and association on yield variability, our findings indicate that beyond the well-known effect of intercropping on yield, intercropping is also likely to be beneficial in terms of yield variability (or stability) and this beyond the simple diversification effect. However, the scarcity of long-term data leads us to be cautious about the numerical conclusions provided here. Moreover, our cluster analysis shows that risk reduction from intercropping is highly reliant on crop combinations. Rao and Singh (1990) highlighted this specific issue and pointed out that intercropping stability also depends a lot on crop cultivars and agronomic management. In a wider sense, it is interesting to note that a shift toward more agroecological practices can in some cases lead to increased variability in yields. Knapp and van der Heijden (2018) showed that organic agriculture has, per yield unit, a higher variability compared to conventional agriculture. Similar results were reported in horticulture by Lesur-Dumoulin et al. (2017). More generally, although agroecological systems (such as intercropping or organic agriculture) may be more environmentally friendly, further attention should be paid to reducing the variability of their yields.

Finally, trade-offs also occur in practice. Whether to integrate or segregate crops is still debated (Sida et al., 2018; van Noordwijk et al., 2012) and it is often a matter of balancing the benefits expected from the association with the complexity generated. A farmer intercropping multiple crops has to integrate other types of knowledge than that required by monocropping practices (e.g. coordinate plant growth, water requirements, pests and diseases management, harvest, etc.). This increased management complexity is even more critical when intercropping is integrated into highly mechanized agricultural systems (Bybee-Finley and Ryan, 2018). Nevertheless, in temperate areas, this is part of an ongoing 'path dependency' rather than an insurmountable challenge, as shown by research on mechanized agroforestry in Europe (Dupraz et al., 2005; Eichhorn et al., 2006).

4.3. Perspectives for the model improvement

In the present study, risk was assessed by the standard deviation of yields. It is the definition of risk which is brought by the portfolio theory. Standard deviation (or variance) is also a widespread metric for risk assessment in agricultural sciences (Ben-Ari and Makowski, 2014; Zhong et al., 2016). However, other useful approaches of risk were suggested and assumed to be suitable for intercropping systems. Rao and Willey (1980) suggested evaluating risk by calculating the probability of crop 'failure' to produce a specific income in comparison with single crops. The estimate of the probability of crop 'failure' can be meaningful because it provides a more consistent reflection of farmers' attitudes towards stability. It would also allow any tradeoff between mean increase and variance reduction to be assessed quantitatively (Van Noordwijk et al., 1994). Integrating this alternative notion of risk in our model would make it clearer whether SDS or IC can be chosen over pure crops.

Besides the issue of measuring risk, a further limitation of our application is that we limited our analysis to crop production, which does not directly reflect profitability *stricto sensu*. The issue of economic efficiency of agroforestry systems in a context of uncertainty has already been discussed (Bandon, 2004, 1985; Ramírez et al., 2001; Reeves and Lilieholm, 1993) but the lack of knowledge on biological interactions between crops and economics of such systems has made it difficult to develop a systemic model for the comparison of diversification schemes (SDS vs. IC) in relation to risk (Paul et al., 2017). Thus to refine our model, more information on production costs and returns (especially in the context of intercropping systems) for a wide variety of crops would be necessary (Pande et al., 2018). The issue of incorporating economic valuation in the model also lies in knowing the relationship between crop yields and prices. However, while the introduction of economic data can affect crop profitability, it would not generate new relationship typologies (as presented in **Figure B-17**). It also would have an equal impact on SDS and IC, then would not modify the relative performance of both strategies (Paul et al., 2017). In line with the issue of profitability being a suitable indicator for the assessment of such systems, we assume that alternative indicators could be integrated in the comparison between diversification strategies (Convertino and Valverde, 2013). Following Groot et al. (2012), multi-criteria approaches may be useful for the further development of our model taking into account the multiple agriculture ecosystems services. Each service can be treated separately or as proposed by van Noordwijk et al. (2018), as a whole multifunctionality indicator.

The illustrative applications of our framework to real situations were limited due to the scarcity of literature data. Further evaluations of yield and associated standard deviations in a wide range of systems are now needed to determine the conditions in which SDS or IC would be more efficient. In-depth understanding of the biological interactions between crops, between trees and crops, pests and environmental conditions is still lacking, while it is often presented as a basis for farmers to design new mixtures and new ways to organize compatible crops in the field space (Francis, 1989). Understanding ecological functioning is indeed important and often highlighted in studies dealing with intercropping, but our data driven approach offers a complementary point of view that makes it possible to overcome the lack of knowledge on ecological processes.

Finally, the diversification approaches in this study were limited to portfolios composed of two species. Yet, considering the growing interest of farmers in combining a large number of species within complex rotations (Galluzzi et al., 2010; Hoang et al., 2014; Morel et al., 2017), it would be especially interesting to extend our approach to more diversified systems. From the theoretical point of view, extension of the framework to situations with more than two crops is straightforward and does not present any mathematical difficulty (Raphaël Paut et al., 2018; Van Noordwijk et al., 1994). The issue once again lies in the availability of data, since data requirement increases rapidly with the number of crops. To our knowledge, very little research has evaluated yield and standard deviations of more than two crops in associations compared to monocultures.

5. Conclusion

Taking risk into account in decision-making for the definition of sustainable crop rotation strategies has become essential. Our approach provides an analytical framework that can help farmers or land-use planners in the comparison of simple diversification strategies with more integrated ones such as intercropping or agroforestry. By disentangling the effects of association and diversification on risk and production, we propose an approach that makes it possible to decompose the interests and limits of each of these strategies. We show that there are trade-offs between the increase in yield generated by intercropping, the reduction of risk resulting from diversification, but also the specific effect of intercropping on risk. Taking into account the resultant of these three elements is therefore crucial for the definition of diversification strategies.

Long-term field experiments will be needed to better understand biological processes that underlie these interrelationships. The example applications presented in this study illustrate the particular case of horticultural systems. Nevertheless, the approach developed here remains applicable to most agricultural systems. Indeed, our model only requires farm components (crops or animal products) yield and variance, which are commonly available data, relevant for most farming systems. In this perspective, our method and findings may have wider implications for other farming systems such as field crops or mixed crop-livestock farming systems.

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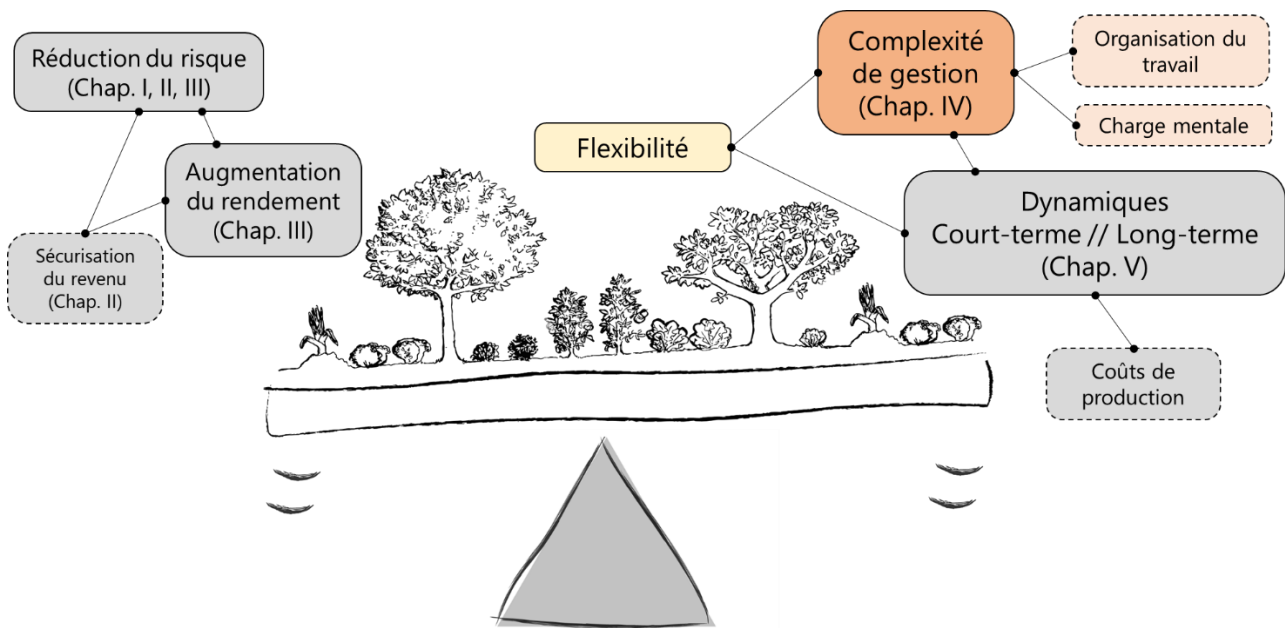
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Chapitre IV. Impact de l'agroforesterie horticole sur l'organisation du travail et les pratiques de gestion



Dans les trois précédents chapitres, nous avons construit des cadres d'analyses mobilisant et combinant successivement (i) la Théorie du Portefeuille, en l'adaptant au contexte agricole de cultures conduites en association, et (ii) le concept agronomique de Surface Equivalente Assolée, utilisé pour évaluer la plus-value des interactions entre cultures différentes plantées sur une même parcelle. Ces travaux permettent de distinguer formellement les effets de diversification (plusieurs cultures sur des parcelles différentes) des effets d'association (plusieurs cultures en interaction biologique au sein d'une même parcelle) que ce soit sur le rendement ou sur le risque.

D'un point de vue théorique, la diversification et l'association de cultures semblent donc des leviers pertinents pour concilier hauts niveaux de rendements et faibles risques en horticulture. Néanmoins dans la pratique, ces systèmes très diversifiés ont une complexité structurelle et organisationnelle accrue, qui induit une forte difficulté de gestion. Dans ce chapitre, nous caractérisons les changements de pratiques et d'organisation du travail qui interviennent en systèmes verger-maraicher. Cette section donne à voir la diversité des systèmes observés et propose un modèle conceptuel du niveau d'intégration de ces systèmes. Ce travail s'appuie sur des entretiens auprès de quinze agriculteurs. Il permet de définir les entités élémentaires pertinentes pour les agriculteurs en contexte verger-maraicher, appelées « **Entités de Gestion** », et de les qualifier en termes d'organisation du travail. Une analyse de la nature de ces entités de gestion et de leurs répartitions au sein des fermes étudiées offre la possibilité de mieux comprendre les réorganisations du travail, induites d'une part, par le fait de cultiver des fruits et des légumes sur la même ferme, et d'autre part de les cultiver dans une logique agroforestière (**Figure B-21**).

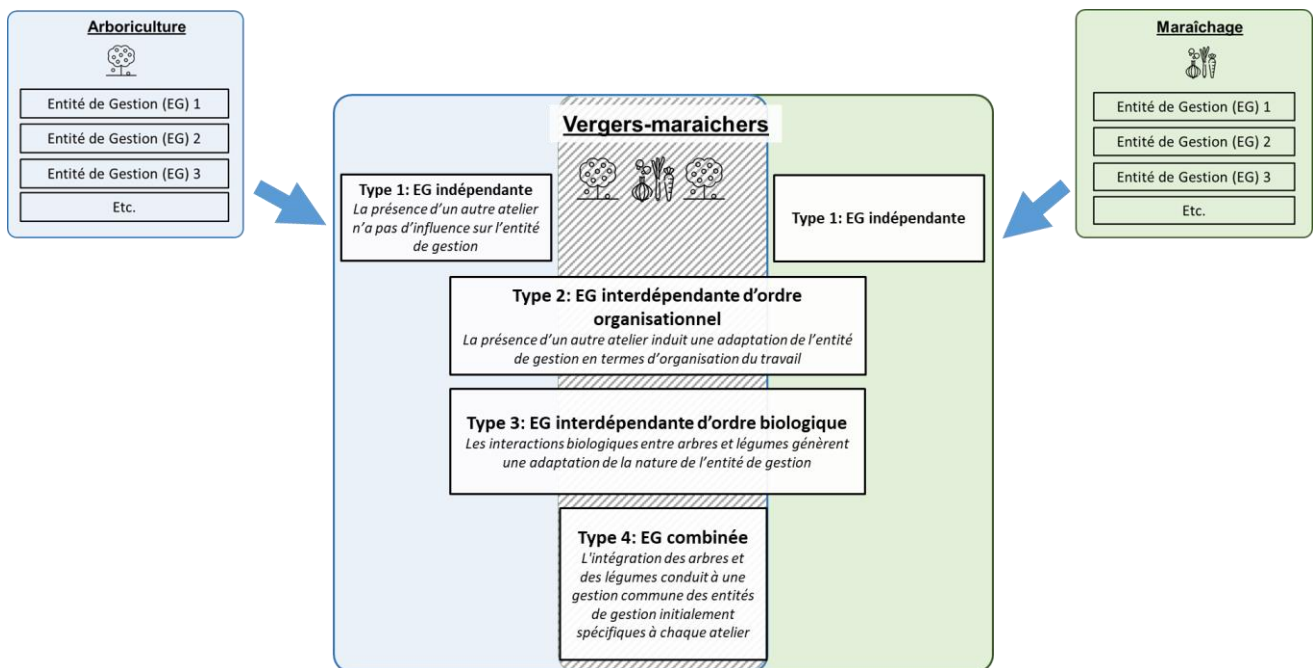


Figure B-21 : Résumé graphique du chapitre IV. Représentation graphique des types d'entités de gestion (EG) d'un système verger-maraîcher. Les EG peuvent être de quatre types différents : Indépendantes (type 1) ; Interdépendantes sur le plan organisationnel (type 2), Interdépendantes sur le plan biologique (type 3) ; Combinées (type 4). La zone de chevauchement entre les deux ateliers représente leur niveau d'intégration.

Trade-offs between diversity and complexity in mixed horticultural systems: a theoretical and empirical investigation

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Abstract

The integration of orchards and market gardening into mixed horticultural systems (MHS) is a promising way to address the dual productive and environmental challenge facing agriculture today. However, the management of these systems is particularly challenging for two main reasons. (i) the first is related to their structural complexity, since they add the intrinsic difficulties of two very demanding systems, fruit tree growing and market gardening, to which are added the difficulties related to the interactions between the two systems. Even more than for single-enterprise farms, the management of MHS integrates the need to prioritize and arbitrate between conflicting objectives and constraints; (ii) the second limitation is linked to the high level of uncertainty on these systems, related to their agro-ecological nature which mobilizes fundamentally uncertain biological processes, but also related to the incomplete knowledge on how the dynamics interact with system steering actions. In practice, this two-sided complexity implies a reconfiguration of the management practices of both orchard and market gardening. In order to better understand how these changes occur, the work proposed here follows both a comprehensive and a modelling approach. First, we explore the theoretical consequences of an increase in cultivated diversity on labor organization. Second, we develop an analytical framework to describe the reorganization of management practices induced by the level of integration between the two components: orchard and market gardening. This framework is built based on the interview of fifteen farmers in the south-east of France. From a theoretical point of view, our

model highlights the trade-offs between the level of cultivated diversity and labor organization complexity. From an empirical point of view, our results provide a better understanding of the impact of MHS on the nature of management practices and labor organization.

Keywords : Agroforestry; intercropping; market gardening; orchards; horticulture; integration.

1. Introduction

Since the 1950s, temperate agriculture has been guided by the objective of increasing food production. The availability of low-cost inputs (mineral fertilizers, synthetic pesticides) has made it possible to introduce the logic of economies of scale. The resulting intensification of farming systems has led to the specialization of farms in most regions, leading to dramatic environmental consequences: water pollution due to excess fertilization, soil degradation, depletion of natural resources, loss of biodiversity and reduced resistance to climate change (EIP-AGRI Focus Group, 2017). The modernization of agriculture has also led to the exclusion of trees from cultivated areas. This exclusion has progressively developed in a technical environment of landscape homogenization, making it difficult for farmers to adopt more complex systems (Eichhorn et al., 2006).

However, noteworthy attempts to address the problems raised by specialized systems are the integration of several enterprises within farms (Bell and Moore, 2012; Bonaudo et al., 2014; Ryschawy et al., 2012). In particular, facing the limits of the simplification paradigm, agroforestry systems combine perennial and annual crops on the same plot (Malézieux et al., 2009). Among these systems whose two strata are cultivated, Mixed Horticultural Systems (MHS), where fruit trees and vegetables are intercropped have recently regained importance in temperate areas (Léger et al., 2019; Sieffert et al., 2014). This distinctive form of professional agroforestry is mostly found in organic agriculture, on small areas. Farmers often combine a large variety of vegetables with fruit shrubs and/or fruit trees (**Figure B-22**) and they rely mainly on short food supply chains (Léger et al., 2018; Warlop, 2016). Due to their highly agro-ecological nature, these systems seem to be able to address many specific challenges of developed European regions: (*i*) their efficiency is an asset in the competition for land use in a context of increasing urbanization; (*ii*) their diversified production is particularly adapted to the needs of urban populations while facilitating the creation of social links since it allows short food supply chains

(farm shops, community-supported agriculture, markets, etc.); *(iii)* finally, because of their strong agro-ecological properties, these systems seem consistent with the process of limiting the negative externalities of agricultural systems while maintaining a high level of agricultural production per surface unit.

Despite these many advantages, Mixed Horticultural Systems in temperate zones have been very little studied and many references are missing for their design and especially their management. Recent studies consist of detailed descriptive analyses of system components and its agrobiodiversity (Wezel and Bender, 2003) or analyze how MHS can improve nutrients or water cycle efficiency and thus reduce environmental impacts (Abid Karray et al., 2008; Ali and Mattsson, 2017), but few studies have focused on implementation conditions and therefore their social acceptability. These gaps are all the more disabling as there is a growing demand for references from the agricultural profession (census carried out in France in the CASDAR SMART project (Castel et al., 2019; Léger et al., 2019)).

From the point of view of technical management and labor organization, diversified cropping systems appear highly complex because of the great diversity of tasks faced by farmers (Salmona, 1994). Indeed, the increasing ecologization of agricultural systems is known to complicate their management by increasing the number and diversity of elements and interactions to be managed (Hendrickson et al., 2008; Moraine et al., 2012). With regard to MHS, one can identify two main sources of complexity. First, there is a high uncertainty on biological processes: while tree-crop ecological interactions are becoming well known for timber based agroforestry (Dupraz et al., 2019; Jose et al., 2004; Lovell et al., 2017c), the specific intercropping of fruit trees and vegetables remains relatively unstudied (Imbert et al., 2019; Jamar et al., 2016). This complicates the predictability of the consequences of farmers' operations on the system dynamics. Second, the combination of two very demanding systems (orchards and vegetables) may lead to an increase in the knowledge, skills and know-how required. It is therefore necessary for farmers to implement appropriate management, coordination and learning arrangements. In the case of market gardening, most vegetables – unlike field crops – have short infra-annual cycles which multiplies the difficulties associated with building crop planning; a given vegetable can be grown several times in a season. Moreover, there are many technical operations required for each crop before marketing, growers must manage seedlings, plantations, irrigation, fertilization, treatments, harvests and packaging for each of their crops (Bon et al., 2010; Navarrete et al.,

2014). Mixed horticultural systems have an even greater degree of structural complexity than diversified market gardening systems due to the integration of perennial species.

All these elements draw a complex relationship between crop diversity, labor organization and the corresponding management practices. Following Aubry et al. (2011) we assume the existence of changes in management practices, by grouping or simplifying operations related to working time and organizational constraints within the farm. We also hypothesize that these changes occur under strong constraints on labor time. The objective of the present work is to better understand how increased diversity impacts labor organization. To do so, the approach proposed here follows both a modelling and a comprehensive method. First, we will explore the consequences of an increasing cultivated diversity on working time using a computational approach. To deepen the analysis, we will present a conceptual framework to analyze how this increasing cultivated diversity impacts the reconfiguration of farmers' practices. We will finally apply this framework to the analysis of a pool of MHS farms to demonstrate how its application enabled the description and characterization of the reconfiguration of management practices in a production context.

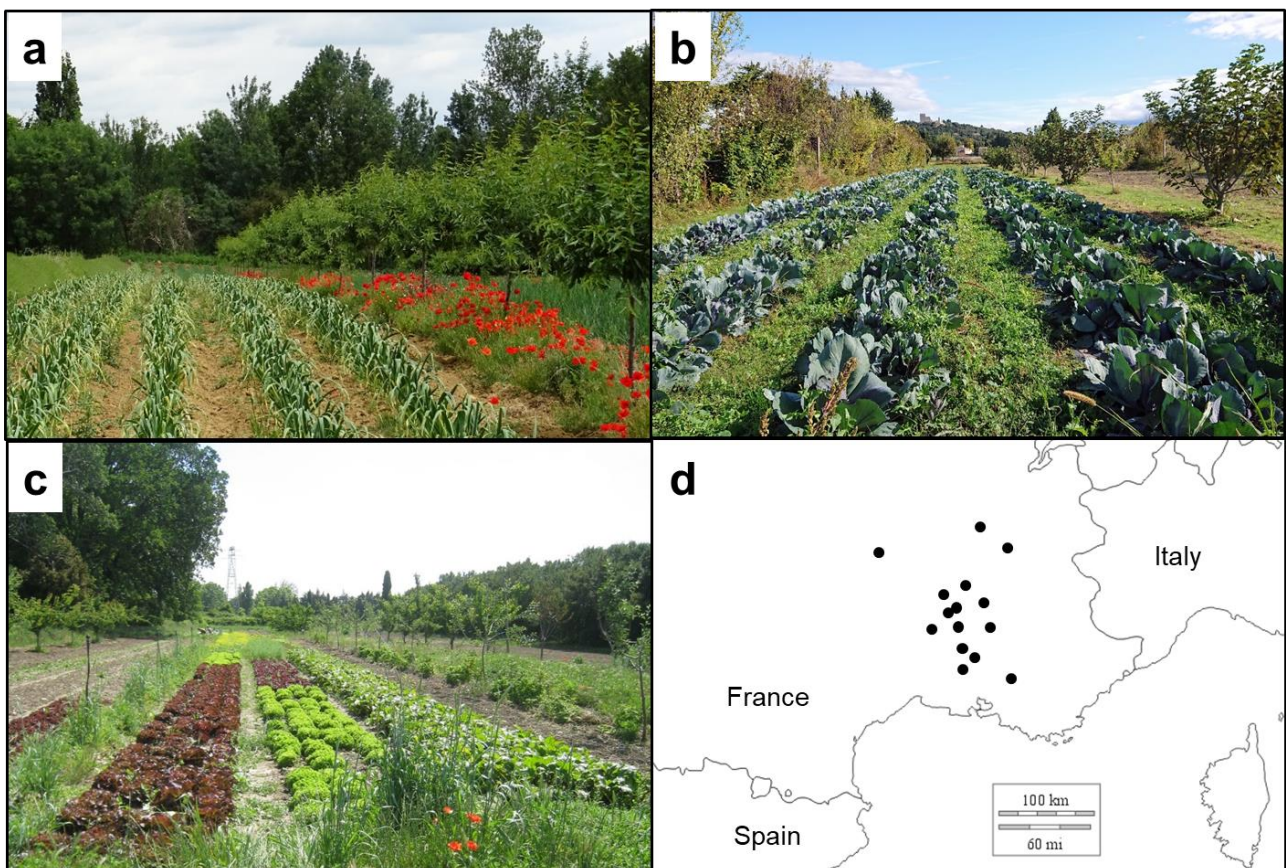


Figure B-22. Three mixed horticultural systems: a) onion-almonds intercropping; b) prune-cabbage-fig intercropping; c) lettuce-pear intercropping and d) map of the interviewed farmers

2. Material and method

2.1. Computational approach to identify “sticking points”

To study the impact of crop diversification on labor organization we consider a shift from a monoculture towards a more diversified system of n crops. For each level of cultivated diversity (k), we simulated the annual workload distribution curves of all possible crop portfolios. A crop portfolio is defined as an evenly distributed rotation of k among n crops over 1 hectare. Each crop requires a certain amount of working hours per hectare per time step. The resulting annual distribution of working hours according to the crop rotation influences the annual work schedule, as presented in **Figure B-23**. For each time step (the month in our case), the total workload (WL_m) is the weighted monthly workload of each crop i composing the crop rotation (Eq. (13)). At this stage, we make the hypothesis of the independence and additivity of workload between crops.

$$WL_m = \frac{1}{n} \sum_{i=1}^n WL_i \quad (13)$$

where WL_i is the monthly workload requirement of crop “ i ” and n is the number of crops in the crop rotation.

From Eq. (13), it is possible to define the notion of *sticking points*. The combination of crops in a rotation may induce spikes in working time. A sticking point occurs when for a given month, the total working time is higher than a defined threshold. The sticking point, if any, is also quantifiable in terms of time exceeding the given threshold. In the specific case of small-scale diversified farms, the viability threshold concerning working time has been found very variable and subjective (Morel and Léger, 2016; Petit et al., 2010). We therefore consider several alternative threshold values from 35h to 55h per hectare per week.

From the set of possible portfolios, we measured three indicators (i) the sticking point frequency, that is the proportion of crop portfolios that generate at least one sticking point (ii) the average number of sticking points per year and (iii) the extent of the sticking points, measured in hours. An example of a random 5-crops portfolio is shown in Figure B-23. Working time data were retrieved from the Chamber of Agriculture of Provence-Alpes-Côte d'Azur region publicly accessible database (<https://paca.chambres-agriculture.fr/>). The 26 main horticultural crops

were selected, 12 fruits and 14 vegetables. The detailed data can be found in Appendix D.1. The model and statistical analyses were implemented with R 3.6.0 (<https://cran.r-project.org>).

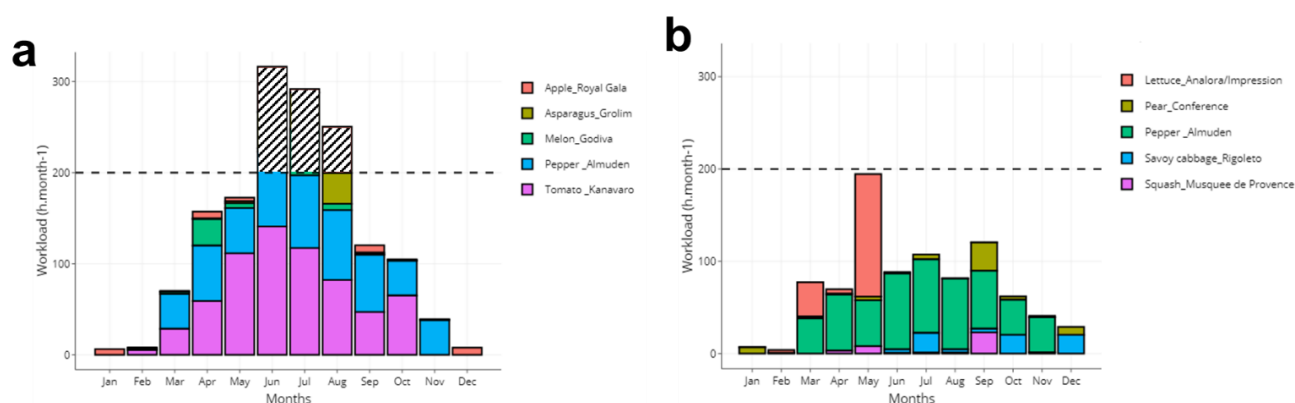


Figure B-23. Examples for rotations with 5 crops, with a working time threshold set at 50h/week. In the crop rotation (a) three hatched areas above the dotted threshold indicates the occurrence of three sticking points. The crop rotation (b) does not induce sticking points.

2.2. Beyond sticking points: a conceptual framework to describe the resulting reconfiguration of farmers’ practices

2.2.1. Management units

The large number of cultivated species, short vegetable rotation cycles, the complex programming, the sustained and uninterrupted pace of production can induce a high degree of mental and physical difficulty in the work (Bon et al., 2010). Combined with perennial species, diversified market gardening systems may sometimes lead some farmers, especially during peak production periods, to adapt their work or to be forced to reconfigure their management practices due to the system’s structural complexification. Aubry et al. (2011) also assumed the modification of management practices, in diversified market gardening systems, by the grouping or the simplification of operations linked to the constraints of working time and organization within the farm. These hypotheses have yet to be tested.

These elements are not fully taken into account in the modeling approach described above, which may be restrictive by the assumption of the proportionality, independence and additivity of working time. We, moreover, hypothesize that MHS constitute a greater degree of structural complexity than simple diversified systems, due to the integration of perennial species

and we will analyze more finely the impact of this type of diversification through the prism of management practices. We defined a “Management Unit” (MU) as the smallest management entity that could describe a task in the labor organization for the farmers surveyed. Analyzing the very definition of management units and their distribution within farms in a variety of situations therefore makes it possible to characterize the influence of mixed horticultural systems on labor organization.

2.2.2. Interviews

We carried out interviews with a set of farmers in two regions of South-East of France: Auvergne-Rhône-Alpes and Provence-Alpes-Côte d’Azur, regions where farmers have been experimenting Mixed Horticultural Systems (MHS) for several years. We surveyed farmers with at least one MHS plot as part of the farm or the farm as a whole. Fifteen farms were selected, that have implemented an MHS for several years. We conducted semi-directive interviews that lasted 2-3 h on average, and were structured in three phases. The first phase consisted of identifying the main characteristics of each farm (utilized agricultural area, MHS plot size, farming system, etc.) and the main management practices (crop rotation, fertilization, soil tillage, etc.). The second phase consisted in understanding how farmers arbitrate their choices between perennials and annuals. Do complementarities or competitions exist between market gardening and orchards in biological and/or organizational terms? We first asked farmers to express on any experience that spontaneously came to mind, but also suggested elements that the farmer could approve or disprove. The last phase consisted in the conceptualization of each farming system by the farmer according to his/her management units.

The farms’ characteristics are highly diverse (Table B-4), but three main farm types can be identified:

- “Mixed horticultural farms” are farms organized to produce fruit and vegetables, and for which MHS represent a very substantial part of the surface area ($n = 4$).
- “Fruits and vegetables farms” refer to farms that integrate an MHS into a wider horticultural production system, consisting of separate fruit and vegetable plots ($n = 4$).
- “Diversified farms” stand for farms that integrate horticulture into a broader production system, including, for example, livestock, cereals or medicinal and aromatic plants (MAP) ($n = 7$).

Table B-4. Farms' structure and crops diversity. MHS: Mixed Horticultural System. MAP: Medicinal and Aromatic Plants. UAA: Utilized Agricultural Area.

Farm id	Years of farming	Years of MHS implementation	Full-time workers	UAA (ha)	MHS area in hectares (% of UAA)	Number of fruit tree species	Number of vegetable species	Other Production
1	23	2	1	16	1.0 (6%)	1	25	Cereals; MAP
2	1	1	1	4.5	0.5 (11%)	11	35	Cereals
3	8	1	2	3.3	0.3 (9%)	10	50	-
4	2	2	1	0.3	0.3 (100%)	10	30	-
5	1	1	6	4.67	1.13 (24%)	12	50	Livestock; MAP
6	4	4	1	0.8	0.6 (75%)	15	30	MAP
7	5	2	2	35	1.0 (3%)	2	10	Cereals
8	13	13	2	25	0.3 (1%)	4	20	Livestock; Cereals; MAP
9	3	3	2.4	2.2	1.0 (45%)	3	40	Livestock
10	12	7	3	16	3.0 (19%)	9	30	Livestock; Cereals; MAP
11	11	4	1	0.4	0.3 (75%)	9	50	Livestock; MAP
12	13	4	2	30	0.5 (2%)	2	31	Livestock; Cereals
13	3	3	3.5	3.65	3 (82%)	6	50	Livestock
14	3	3	2	1.3	0.37 (28%)	11	43	-
15	6	6	1	1.04	1.04 (100%)	5	20	-

3. Results and discussion

3.1. Non-linear effect of increased crop diversity on the occurrence and magnitude of sticking points

The impact of diversification on work organization was first studied by taking into consideration an increase in the number of crops grown in a crop rotation. We can observe a non-linear effect of increased crop diversity on the probability of sticking points (**Figure B-24a**) and on the average number of sticking points (**Figure B-24b**). There is a two-phase phenomenon: at the initial phase, crop diversification generates more friction points, up to 2 to 5 crops –depending on the working time threshold considered. Then, follows a decrease of both probability and average number of sticking points. It is interesting to note at this stage that, whatever the workload threshold considered, crop rotation diversification leads first to an

increase in the probability and average number of sticking points before a gradual decline to zero (except for the 35h/week threshold that remains relatively high). In contrast, the amount of excess hours decreases exponentially with the number of crops in the rotation (**Figure B-24c**). This reflects a more evenly distributed dilution and smoothing of working time over a year.

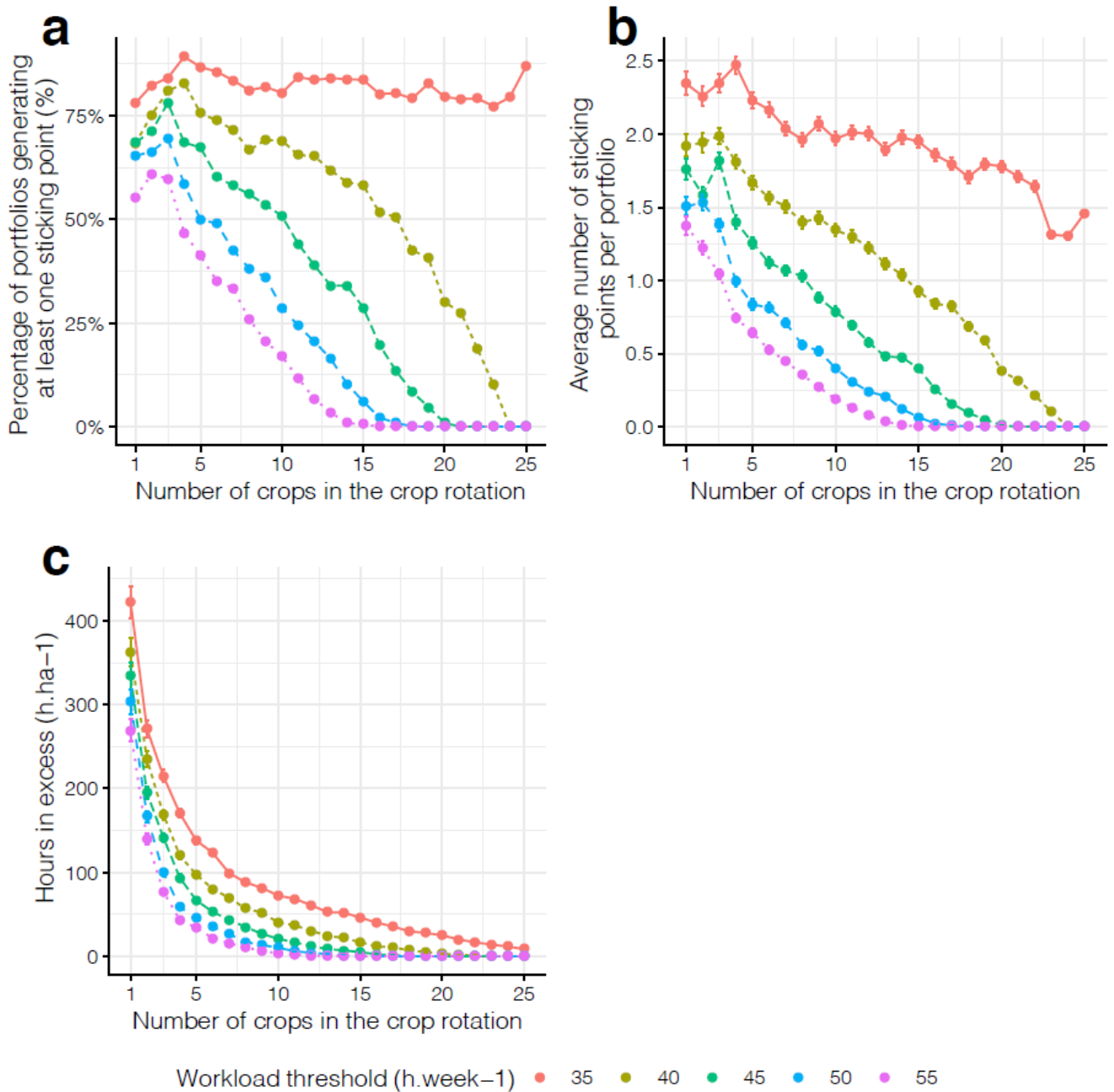


Figure B-24. Effect of increasing number of crops in the crop rotation (x-axis) on: (a) the percentage of portfolios generating at least one sticking point; (b) average number of sticking points per portfolio and (c) the magnitude of sticking points. Error bars indicate the standard deviation of the means.

3.2. A systemic conceptual framework to describe the levels of integration between orchard and market gardening

The preceding analysis of the impact of crop diversification on labor organization using a computational approach revealed the existence of sticking points. These sticking points as we define them seem to reveal a complex relationship between crop diversity and labor organization. This modelling approach shows that increasing crop diversity reduces the number and frequency of sticking points in the system. This is, however, in contradiction with the perception of farmers that often highlight the increased complexification of work associated with an increased number of crops in the association. Our hypothesis is that, by focusing on the working time only, our modelling approach does not capture all the dimensions of complexity associated with an increased crop diversity. Another central dimension of complexity lies in the integration of two very different enterprises with their own characteristics. In fact, adding a vegetable crop to an already diversified vegetable crop rotation will not result in the same management complexity than adding another *functional* workshop as fruit growing. From a practical point of view, the complexification of labor organization induced by a *functional* crop diversification leads farmers, especially during peak production periods, to reconfigure or simplify their work organization.

We propose here a conceptual framework to formalize the reconfiguration of management practices in mixed horticultural systems in an empirical way. Based on the analysis of farmers' practices, we describe how the integration of orchard and market gardening leads to a reconfiguration of the management entities specific to each enterprise. To develop this framework, we must define some of the terms used to describe the different system components. We describe the system's management by distinguishing two sets of entities called enterprise: orchard and market gardening (**Figure B-25**) Each enterprise is defined by a group of management units (MU), which corresponds to the set of management practices available for farmers within each enterprise. The close interweaving of both productions implies a redesign of their management units according to four modalities described below.

3.2.1. Independent management units

Each management unit is independently managed and the integration of the two enterprises has no influence on how the entity is handled. For example, fertilization can be reasoned in a completely independent way taking into account the specific needs of each enterprise over time.

3.2.2. Organizationally inter-dependent management units

The presence of another production generates an adaptation of the management unit, in terms of labor organization. This illustrates the impact of growing fruits and vegetables on the same farm, without taking into account the biological interactions between crops. For instance, sowing or harvesting operations in market gardening may be postponed or even omitted due to an operation on the trees. The reciprocal situation has also occurred.

3.2.3. Biologically inter-dependent management units

Here, the agroforestry configuration, i.e. the fact that there are biological interactions between trees and crops, leads to an adaptation of the nature of the management unit. This illustrates the impact of spatially combining vegetables and fruits in an agroforestry design. Some practices such as phytosanitary treatments can be altered by the fact that crops are spatially close and can lead to biological incompatibilities.

3.2.4. Merged management units

The integration of fruit trees and vegetables leads to a joint management of the units originally specific to each enterprise. In this case, irrigation or fertilization, for example, are managed for the whole system, on the assumption that tree roots would create a “safety net” under vegetables roots and benefit from it indirectly.

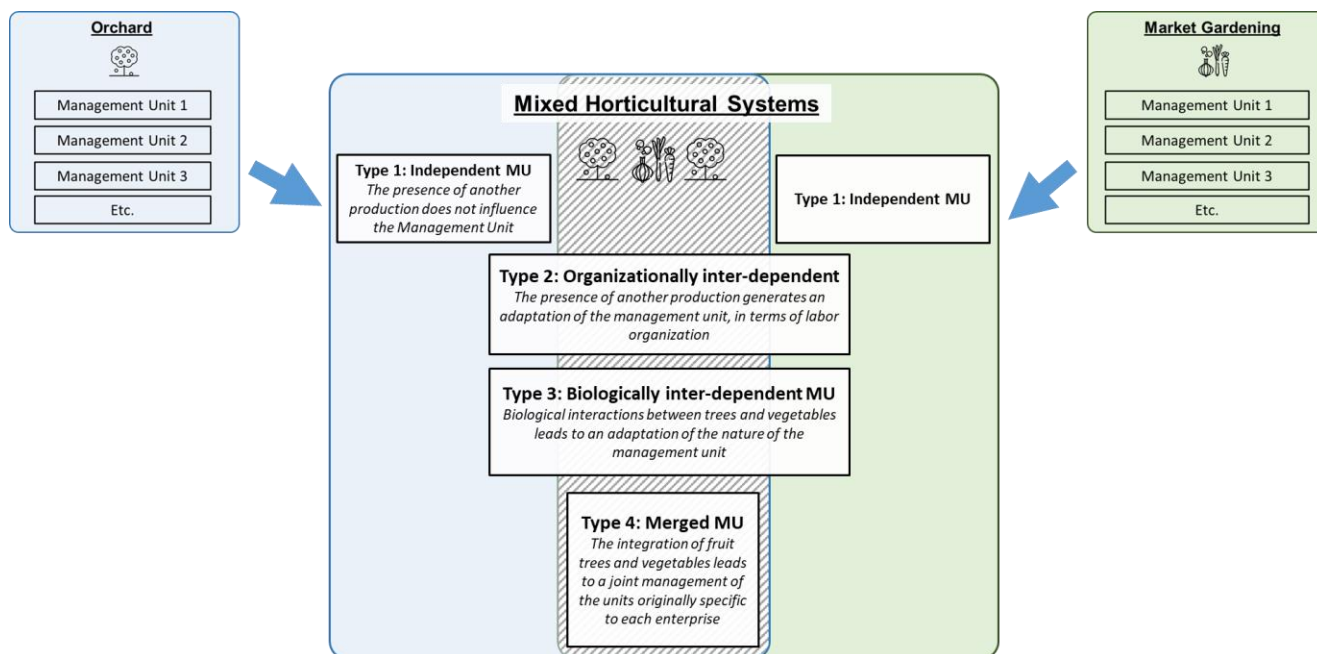


Figure B-25. Graphical representation of the management units (MU) types of a mixed horticultural system. Management units can be of four different types: Independent (type 1), Organizationally inter-dependent (type 2), Biologically inter-dependent (type 3) and Merged (type 4). The overlap area between the two enterprises represents their level of integration.

3.3. Reconfigurations resulting from the joint management of fruit trees and vegetables

3.3.1. Allocation of management units within farms

Depending on farms and cropping systems, each management unit can be of one of the four types described above. We will now analyze how these management units are distributed within the farms studied. **Figure B-26** shows the repartition of MU across studied farms, according to the management unit types described in §3.2. In the mixed horticultural systems studied, one third (32%) of MU remained independent, another third was organizationally inter-dependent (30%) and the last third was either biologically interdependent (16%) or merged (22%). As for crop rotation in diversified market gardening, where it has been shown that farmers reason on groups of crops and not on individual crops because of crop diversity (Mawois, 2009; Petit et al., 2010), our results reveal that in mixed horticultural systems, farmers can no longer only rationalize technical management enterprise by enterprise and operation by operation for each enterprise (MU type 1). In the same way that there may be internal gatherings within diversified market gardening enterprise, the integration of perennials and market gardening also leads to necessary simplifications, particularly by regrouping. Moreover, the difference in

biological nature between perennial trees and annual market gardening means that some MUs cannot be merged (e.g. orchard pruning or thinning), but can be reconfigured from an organizational or biological point of view.

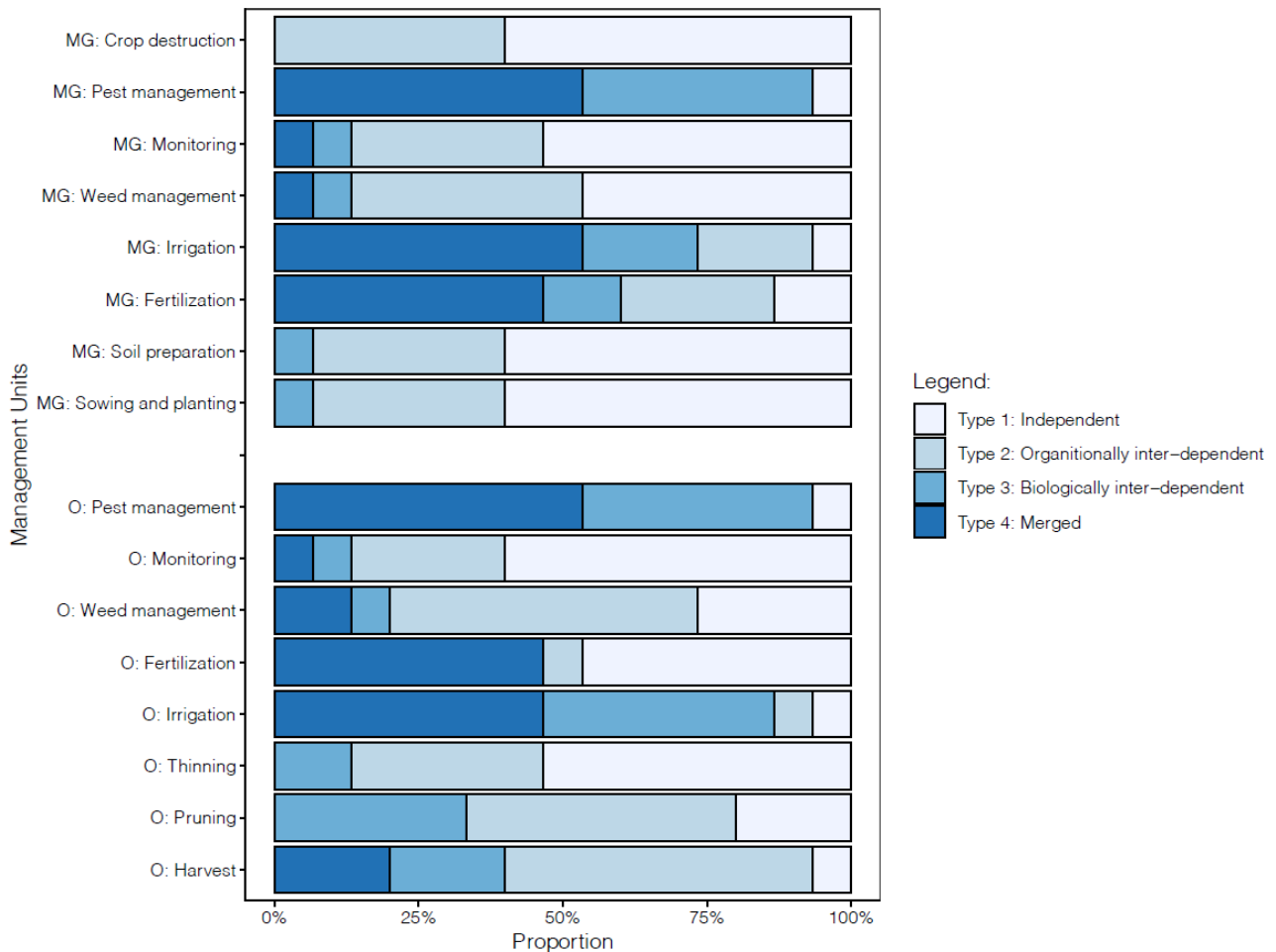


Figure B-26. Distribution of management units across studied farms, according to the management unit types described in § 3.2. MG: market gardening. O: Orchard.

3.3.2. Diversification vs. intercropping

It can be seen that, when they occur, the reconfigurations of management units are mainly of an organizational nature (type 2) compared to reconfigurations of biological origins (type 3). This reflects the fact that practices are mainly modified as a result of technical logic. This was also observed by Léger et al. (2018) who compared technical brakes related to diversification (growing perennials and annuals on the same farm) with the technical brake related to association (i.e. the spatial association of perennials and annuals in agroforestry). This may be due to the fact that the major constraints in the systems studied are mainly organizational rather than biological,

but it can also be put into perspective in view of the relatively recent age of the trees planted (4 years old on average at the time of the survey). The dynamic nature of agroforestry systems leads us to assume that biological interactions will become increasingly important as the systems become more mature (Sun et al., 2018b) thus increasing the prevalence of biologically inter dependent MU.

To distinguish the impact of spatial diversification at farm level from spatial intercropping per se, we can identify here two perspectives offered by our approach: the first one is a more precise analysis in the so-called "fruit and vegetable farms" (i.e. farms that integrate an MHS into a wider horticultural production system, consisting of separate fruit and vegetable plots) in order to deeply differentiate between what comes under crop diversification and what comes under intercropping, also referred to as '*diversified versus integrated systems*' (Keulen and Schiere, 2004). Another option is to apply our analytical framework to a panel of single-enterprise farms (market gardening or orchard farms) in order to conduct a comparative analysis (Cochet et al., 2007).

3.4. A framework to characterize the level of integration of mixed horticultural systems?

3.4.1. Orchard-market gardening integration at the farm level and implications for farm management

By systematically analyzing the distribution of management units within the farms surveyed, it is possible to describe and analyze the existing management range of mixed horticultural systems. One implication of the distribution of MU within a farm is to formalize the causal relation with workload constraints. Very often, integration was a way to reduce the number of management units and thus to reduce the cognitive load: "*I manage crop fertility on my whole farm, I don't manage it species by species and even less with the presence of the trees. It would be a headache. I am probably over-fertilizing, but it is my way of simplifying the system*" said a farmer surveyed.

The distribution of management units according to their "types" within a farm can give contrasting situations ranging from a simple juxtaposition of enterprises to a complete integration. This "*degree of integration*" is often described in crop-livestock systems and some authors have also pointed out that integration between two enterprises can result in different

types of systems. Moraine et al. (2014, 2017) described a gradient of mixed systems by the level of integration of crops and livestock over time and space. In some mixed farms, a simple juxtaposition between crops and livestock has been observed, with a simple coexistence of enterprises. In contrast, they described strong integration through the combination of agronomic integration that made it possible to self-integrate animal feed through produced crops and grasslands and fertilization of plots. Martin et al. (2016) also described a gradient of integration ranging from “coexistence” to “synergy” within and between farms. Our farm-scale analysis indicates that there are many sorts of mixed farming that may lie along a continuum from no integration of orchard and market gardening through to full integration (**Figure B-27**). The relatively small sample of farms we surveyed did not allow us to define farm typologies according to their degree of integration, but further research could shed light on such types at farm scale. The presence of perennial crops, however, makes integration of orchard and market gardening integration difficult to apprehend on a territory scale. Furthermore, the degree to which a particular farm is integrated is influenced not only by biophysical considerations but also by a range of socio-economic objectives and constraints (Bell and Moore, 2012). Therefore, it would not be appropriate to simply classify mixed horticultural systems or the management practices of which they are composed according to a one-dimensional ‘degree of integration’, but rather to put them in perspective with the specific objectives of each system.

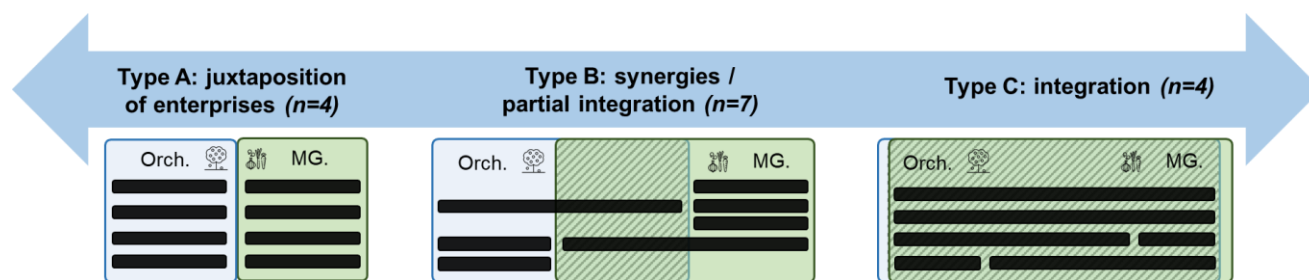


Figure B-27. Gradient of integration among surveyed farms. Black bars are graphical representations of management units. The overlap area between the two enterprises characterizes their level of integration. Orch: orchard. MG: market gardening.

Another implication of integration for farm management is related to farmers' perception of MU. In addition to being primarily driven by organizational concerns, some management units derive their nature from farmers' representation of biological processes that are still uncertain or little known. As also mentioned by research studying agroforestry systems (Blanco et al., 2020; Grandgirard et al., 2016), the perception of ecosystem services plays a very important role in the way the system would be managed. Tree roots pruning, for example, will be managed differently depending on the farmer's representation of the underlying biological

processes. For some farmers, tree-crop root competitions are too strong and encourage them to perform root pruning. For others, the biological compartmentalization of root systems leads to complementarities that make pruning deliberately omitted. This relatively trivial example shows that current state of scientific knowledge on the functioning of these systems does not make it possible to determine which strategy would be suitable.

A final implication of orchard-market gardening integration for management is related to the temporal dynamics of these systems. Over the years, farmers have to make a number of choices concerning the structure and organization of their production system. These choices, described by agronomists as *strategic orientation decisions*, are related to the long-term, for example, the choice of cultivated areas, crops, marketing channels, level of equipment, etc. (Aubry, 2007). These choices strongly influence labor organization and the combination of all these elements constitute the structural framework within which work is organized on a shorter time scale (Petit et al., 2010). It is also widely acknowledged that diversified systems require adaptability and management practices are expected to be adjusted and adapted while the system evolves. Management units described in §3.2 can be evolving and changing in type over time. A perspective of a multi-year analysis of farmers' management practices would be useful to better understand the changes dynamics (Catalogna et al., 2018).

3.4.2. Deepening the relation between integration and system performances

While our approach makes it possible to better characterize the coupling between orchard and market gardening in mixed systems, it remains unclear whether high or low levels of integration are desirable. This characterization raises a methodological difficulty that lies in the diversity of definitions of “integrated systems” in which the coupling of several enterprises are studied can be based on agronomic, economic, structural, capitalist or labor approaches (Mischler et al., 2017). The integration of fruit trees and vegetables is not an objective in itself, but is rather a means to achieve other objectives. Each form of MHS will not aim at the same objectives, nor have the same environmental or economic performances (Martel et al., 2017). In terms of environmental impact, the assessment of mixed farms by their level of integration between crops and livestock showed that an increasing level of integration led to a win–win strategy comprising good economic and environmental performances (Bonaudo et al., 2014; Kronberg and

Ryschawy, 2018). Moraine et al. (2012) refer to the process of substituting inputs with ecosystem services. In our case study, all these hypotheses though remain to be tested and deserve further investigation.

4. Conclusion

Mixed horticultural systems (MHS) are forms of agroforestry combining fruit trees and diversified vegetables (also called market gardening). This type of system represents a potential encouraging model towards a paradigm shift in horticultural production. However, despite the fact that they currently experience a strong growth in temperate regions, little research has investigated this type of system and even fewer from a socio-technical point of view. The objective of this paper was therefore to develop a better understanding of the social and technical constraints induced in orchard and market gardening operations by the intercropping of both. We developed a mixed approach based on modelling and semi-structured interviews of MHS farmers. Our model highlights the existence of trade-offs between the level of cultivated diversity and labor organization complexity. Results showed that the impact of high levels of diversity on working time was not the main driver of management complexification. Moreover, our analytical framework makes it possible to better understand the nature of farmers' management practices and to characterize how farmers reconfigure their practices when they are engaged in a shift towards more integrated systems. It provides an insightful way of analyzing how farmers adjust and adapt their management practices in a context of complexification of farming systems. Besides, to pursue future reflection on mixed horticultural systems, the framework may be useful to think and design systems based on integration patterns that promote biological interactions while reducing negative interactions in terms of management. Since the framework makes it possible to delimit management units in mixed systems and to characterizing, there is also room for it to be adapted to in other areas and for other production systems.

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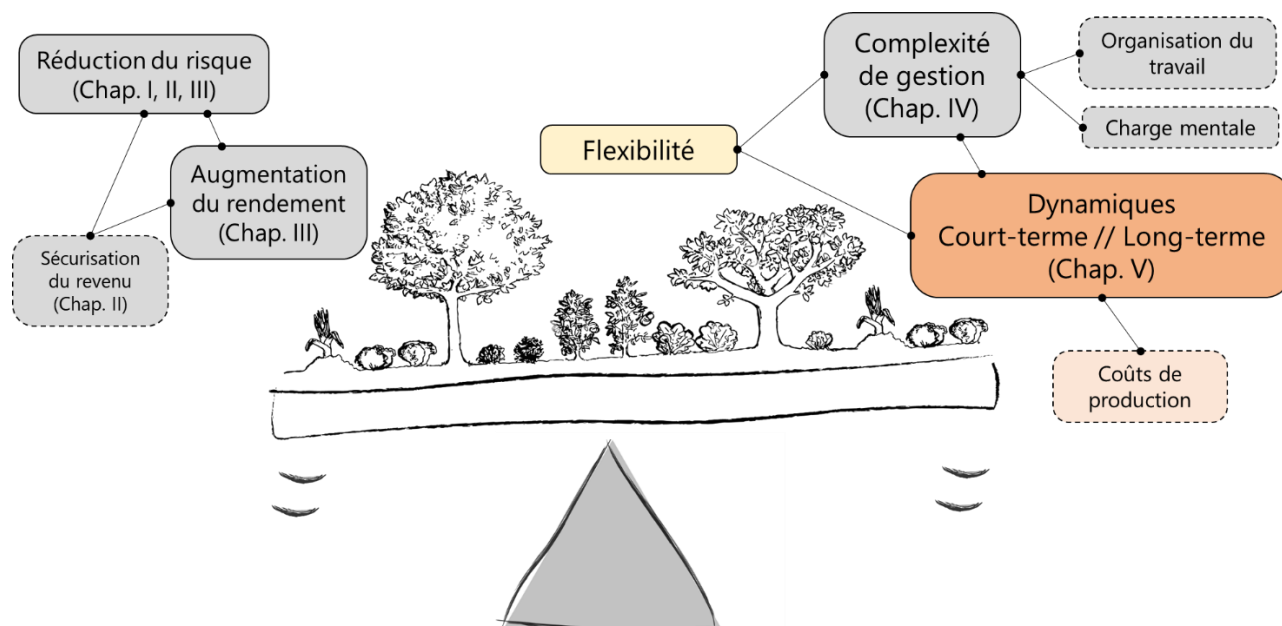
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Chapitre V. Le « temps long » de l'arboriculture versus le « temps court » du maraichage : une approche de modélisation dynamique



Comme nous l'avons vu dans le chapitre précédent, le verger-maraîcher combine deux ateliers très exigeants du point de vue de leur gestion. Cela implique différents degrés d'intégration entre les deux ateliers, et parfois, une reconfiguration des pratiques associées. Une autre caractéristique importante qui contribue à leur complexité de gestion réside dans leurs **dynamiques temporelles très contrastées**. En effet, le maraîchage requiert une gestion et des ajustements quasi quotidiens. Au contraire, l'arboriculture nécessite de se projeter sur du long-terme, sans négliger les opérations essentielles tant que l'arbre n'est pas productif (conduite, taille, suivi phytosanitaire...). Ainsi, conduite simultanée de ces deux ateliers possédant leurs dynamiques propres peut être très complexe ; des conflits mal gérés ou mal anticipés peuvent mettre en péril la viabilité à long terme de l'exploitation (**Figure B-28**). Un des facteurs clés du succès des vergers-maraîchers réside donc dans la bonne allocation des ressources disponibles, et notamment de la main d'œuvre sur l'exploitation.

Dans ce chapitre, nous décrivons un modèle simple de vergers-maraîchers permettant d'évaluer leurs principales propriétés au court du temps. Ce modèle est ensuite implémenté de manière dynamique pour explorer différentes stratégies de gestion. Il répond aux questions suivantes :

- i. Comment les choix des agriculteurs en matière d'assolement et d'allocation de leur temps de travail impactent-ils la dynamique du système à long terme ?
- ii. Comment les agriculteurs peuvent-ils tirer le meilleur parti des complémentarités en termes de temps de travail dans un verger-maraîcher ?
- iii. Comment concilier des objectifs de rentabilité à court et à long-termes dans la gestion des vergers-maraîchers ?

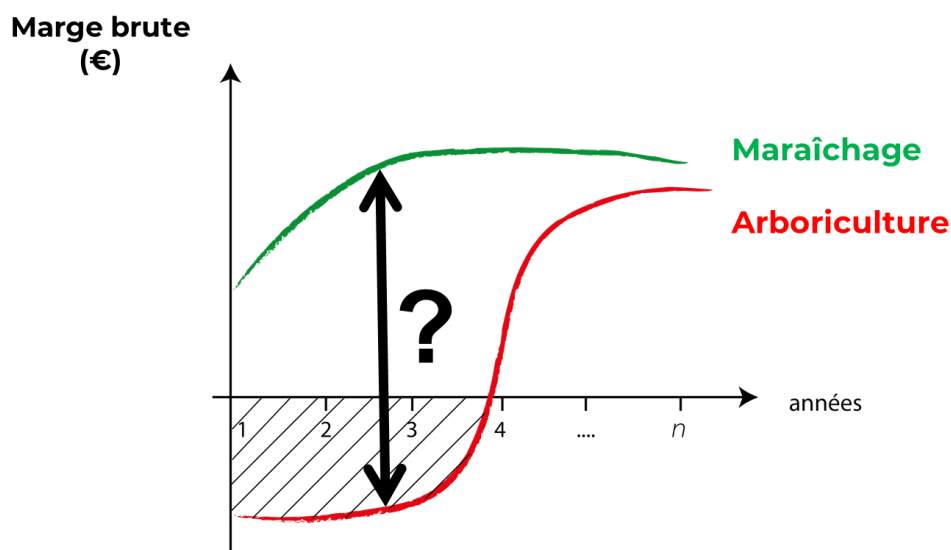


Figure B-28 : Résumé graphique du Chapitre V.

How to reconcile short-term and long-term objectives in agroforestry systems? A dynamic farm model application to mixed fruit tree - vegetable systems

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Abstract

Mixed fruit tree and vegetable (MFV) systems are intercropping of fruit trees and vegetable crops on the same plot. In temperate regions, this emerging form of agroforestry is a potentially attractive land-use to foster the diversification of agricultural systems. However, these systems combine two productive and labor-intensive enterprises (orchards and market gardening) and in practice, the feasibility of the system depends on the availability and need for labor. Long-term yield predictions are needed to assess the economic profitability of such innovative agroforestry systems. A dynamic bio-economic model of MFV systems was developed to assess its main properties over time. This simple state-control model is based on yields, biological dynamics workload requirements and economic profitability of each farming enterprise. Due to the lack of data from long-term experiments, the model was parametrized on data from specialized systems and calibrated with expert knowledge. The implementation of the model made it possible to simulate management strategies for vegetable crops and fruit trees, and to assess their impact on the long-term dynamics of the system. Results show that specialized market gardening enterprise has an overall higher gross margin per hectare than specialized fruit trees. Nevertheless, mixed systems composed of roughly equivalent shares of fruit trees and vegetable crops make it possible to decrease workload constraints while maintaining a high level of

profitability. In addition, intermediate shares of fruit trees and vegetable crops can lead to higher gross margin in the long term, but require addressing both short- and long-term objectives, and the ability for farmers to cope with several consecutive years of lower gross margin. Further research is now needed to better understand the biological processes underlying MFV systems and their evolution in different management configurations.

Keywords: diversification; agroforestry; horticulture; mixed horticultural systems; dynamic modeling

1. Introduction

The productive and environmental challenges that agriculture is facing has led to the emergence of new farming models based on agro-ecological paradigms (Altieri, 2004; Wezel et al., 2014). These systems are built on greater biological diversity that combine cultivated and natural elements within the agroecosystem. One of these, known as Mixed Fruit tree-Vegetable system (MFV), which corresponds to the intercropping of fruit trees and vegetables is attracting a growing interest in Europe, especially among new farmers (Léger et al., 2019; Warlop, 2016). In addition to being highly diversified (up to 20-30 crops species), these agroforestry systems combine two productive and highly labor-intensive strata: orchard and market gardening. This represents a diversification strategy that goes further in increased number of crops, since they add a *functional* diversity provided by fruit trees. These systems, which were still extremely rare at the beginning of this century, are currently undergoing a strong development, in line with the current trend of the establishment of small organic farms, generally created by people without any previous family farming ties (Léger et al., 2018).

The existing literature on MFV deals mainly with their conception (Sieffert et al., 2014; Warlop and Castel, 2016), or consists of detailed descriptive analyses (Léger et al., 2018; Pantera et al., 2018). While this work is important, it leaves farmers somewhat disarmed to manage these systems, as the interactions between agro-ecological processes and actions are not taken into account. However, the management of MFV systems is particularly challenging for two main reasons. The first reason is linked to their complexity, since they add up the intrinsic difficulties

of two very demanding systems -orchard and market gardening-, to which are added the difficulties linked to the interaction between the management of these two systems. It involves, even more than for single production systems, a need for prioritization and trade-offs between objectives and constraints (Navarrete et al., 2014). The second limitation is related to the contrasted temporal dynamics of such systems combining perennials and annuals. The simultaneous management of short-term market gardening and long-term orchards, with their own dynamics, can be very complex and jeopardize the long-term viability of the farm. Following van der Werf et al. (2007) we argue that one of the key factors in the success of agroforestry systems compared to other pure crops is their feasibility, in terms of the use of agricultural resources. In practice, the feasibility of the system depends, among other aspects, on the availability and need of labor. Trade-offs between short term and long-term objectives imply that farmers have to make compromises in the allocation of working time to each enterprise, each of the enterprise therefore being managed in a sub-optimal conditions under time constraints.

Studying the long-term dynamics of mixed fruit tree-vegetable systems based on a modelling approach could then be relevant to capture the main characteristic of such systems and to explore contrasted scenarios. This is especially relevant in the case of MFV since the adoption dynamic is relatively recent and empirical data on mature systems are still very rare. The existing literature on dynamic models in agroforestry focuses mainly on process based models, like tree-soil-crop interactions (Dupraz et al., 2019, 2005; van Noordwijk and Lusiana, 1999). Some models that integrate socio-economic components mainly deal with timber-based agroforestry (Graves et al., 2011, 2007) and do not consider perennials with annual production such as fruit trees.

In the present study, we built a simple dynamic model of mixed fruit tree-vegetable systems making it possible to assess its main properties through time. This model is then implemented to explore different management strategies in MFV systems. The ultimate goal of our model is to predict dynamically long-term fruit trees and vegetable crops dynamics under competitive conditions on workload between both enterprises. Running the model under different configurations and settings enables to address the following questions:

- How do farmers' choices on crop rotation and allocation of their working time impact the system dynamics in the long term?

- How can farmers make the most of the complementarities in terms of working time in a mixed orchard market gardening system?
- How can short and long-term profitability objectives be reconciled in MFV systems management?

2. Material and methods

2.1. Qualitative description of the model

To answer the questions mentioned above, we define a discrete time state-control model of a mixed orchard-market gardening system at a plot scale (one hectare). The model (**Figure B-29**) is a simplification of a real system in order to grasp the main biological dynamics while being simple enough to remain understandable. The model is based on two sub-models: market gardening and orchard models that are described in the following sections (§2.3 and §2.4). It is set on a yearly time step over a period of 20 years. We analyze the dynamics of fruit trees state ($X[0]$) and the capital, which is the annual gross margin cumulated over time ($X[1]$). The dynamics are steered by two control variables: (*i*) the crop rotation ($U[0]$) which represents the choice of tree species and vegetable crops grown each year; (*ii*) the workload allocation ($U[1]$) which refers to the farmer's prioritization of labor between orchard and market gardening.

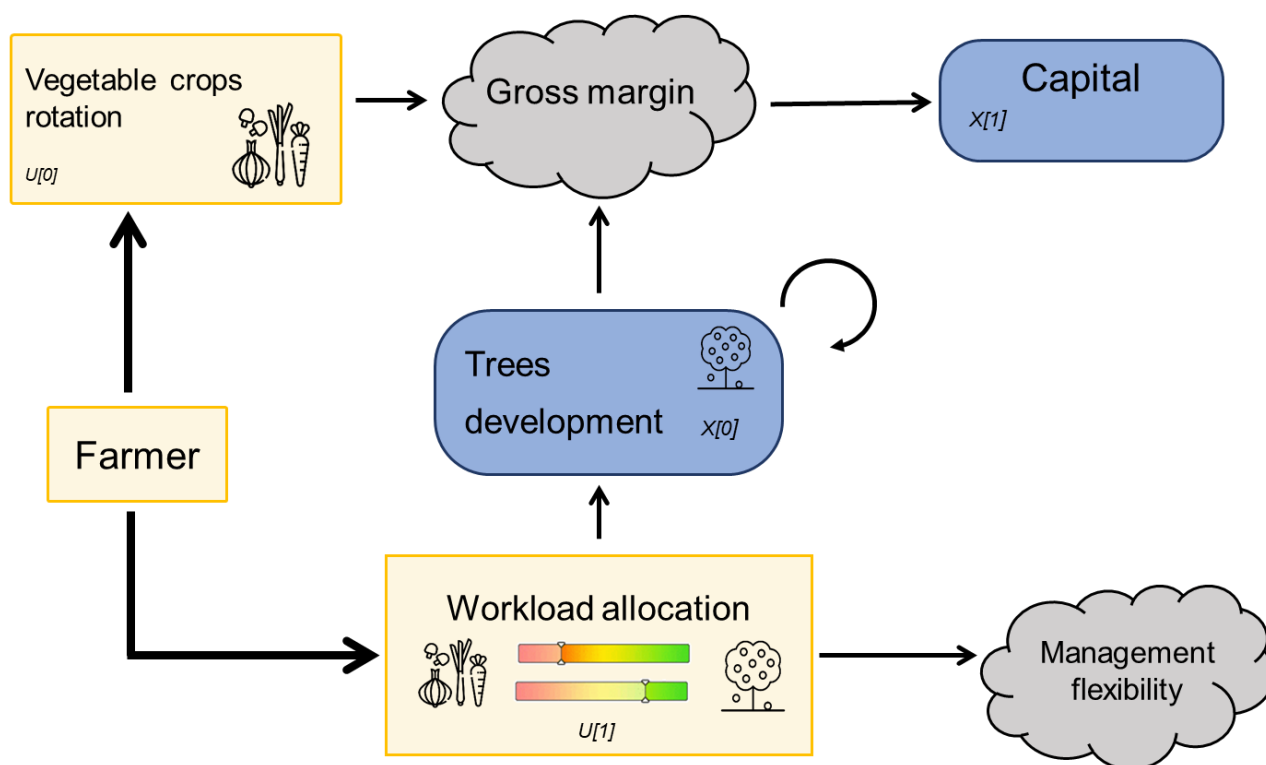


Figure B-29: Conceptual representation of the model of mixed fruit tree – vegetable systems. Blue round boxes stand for the state variables, yellow boxes stand for the control variables and cloud boxes stand for the performance indicators.

2.2. A field-scale bio-economic analysis

A variety of conceptual models of agroforestry economics have been developed depending on specific contexts and analysis objectives (Luedeling et al., 2016). When comparing perennial and arable systems, while the economic results of vegetables occur on an annual basis, timber revenues from trees generally occur once, many years after the system establishment. (Graves et al., 2007). The profitability of such agroforestry systems relative to pure arable agriculture and forestry can be determined by comparing their net present value (NPV), calculated from cost–benefit analysis by discounting future benefits and costs (Graves et al., 2011, 2005; van der Werf et al., 2007). In our case study, the NPV is less relevant because fruit trees are expected to produce on an annual basis and timber products are not valued at the end of the cycle. We thus developed a bio-economic model at the plot scale in the specific case of mixed fruit tree-vegetable systems. The economic value of each enterprise was defined as the annual gross margin (GM) calculated as the revenue (R) minus production costs (including supply costs, labor, machinery) associated with the enterprise (C), Eq. (14).

$$\text{Annual Gross Margin} = R - C \quad (14)$$

The fixed costs of structures are therefore not taken into account. The economic data was retrieved from the Regional Chamber of Agriculture of Provence-Alpes-Côte d'Azur region. All detailed data for the model is available in Appendix E.1.

2.3. Market gardening sub-model

The market gardening sub-model consists in an intra-annual rotation of vegetable crops, where each crop represents an equivalent $1/N_v$, N_v being the total number of crops. Each vegetable crop is defined by a gross margin (VGM) and a workload requirement (WR). Depending on the workload allocation control ($U[1]$), workload requirement for vegetable crops may or may not be fulfilled. The amount of working time dedicated to vegetables (W_v) is therefore the ratio between crop workload requirements (WR_v) and the time actually allocated (WL_v):

$$W_v = \frac{WL_v}{WR_v} \quad (15)$$

Ultimately, the annual gross margin for vegetables $MG(t)$ depends on the theoretical vegetable gross margin $VGM(t)$ multiplied by the workload actually available for vegetable crops (Eq. (16)).

$$MG(t) = \frac{1}{N_v} \sum_{v=1}^{N_v} VGM(t) W_v(t) \quad (16)$$

In order to select contrasting market gardening strategies, we simulated all possible combinations of 5 vegetable crops. Based on these simulations, we chose three contrasting management strategies: (1) a low labor-intensive and low-paying strategy; (2) an intermediate labor-intensive and paying strategy; (3) highly labor-intensive, high-paying strategy. These crop rotations are labelled A, B and C respectively in Figure B-30a. On this preliminary result, it is interesting to note that the two Pareto fronts intersect: $A(a) > A(b)$ but $C(a) < C(b)$. Increasing profitability in fruit growing is less time-consuming than increasing profitability in market gardening.

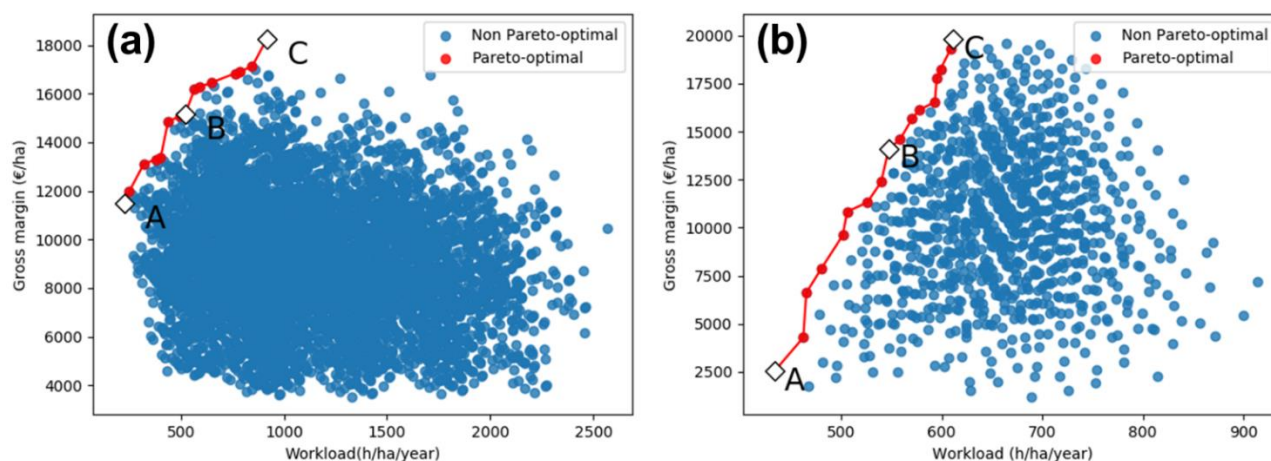


Figure B-30: Gross margin as a function of workload for all possible portfolios of (a) 5 vegetable crops and (b) at least 3 fruit tree species.

2.4. Orchard sub-model

The orchard sub-model is more complex because, due to the perennial nature of fruit species, it is essential to take into account their inter-annual dynamics. To our knowledge, there is no reference on fruit tree dynamics growing in sub-optimal conditions. We therefore used data from pure crop systems, which we calibrated according to experts' knowledge to express their dynamic with a suboptimal management. The orchard sub-model was calibrated in a 3-hours collective workshop in February 2020, bringing together 10 fruit tree experts (7 fruit tree technicians and 3 researchers). The production dynamics of each fruit tree species was characterized according to three contrasted scenarios: (i) optimal investment, corresponding to the systematic prioritization of trees in the system management, so that they develop optimally; (ii) minimal investment, where only essential operations such as irrigation and training are carried out; (iii) the intermediate scenario stands for an in-between situation where tree operations are not done perfectly or are staggered in time. These three scenarios for fruit tree management differ on the factor of the working time that the farmer can allocate to the fruit-growing enterprise. This made it possible to characterize fruit tree growth as a function of workload allocation. Some experts were also consulted individually afterwards to refine the data.

The resulting fruit tree dynamics were fitted using Nonlinear Least Squares method (Bates and Watts, 1988). Note that the fitted curve has been assumed to have a sigmoidal shape (detailed in Appendix E.2). Similar to vegetables, the annual gross margin of trees $FT(t)$ was modeled as:

$$FT(t) = \frac{1}{N_f} \sum_{f=1}^{N_f} FGM(t)W_f(t) \alpha(t) \quad (17)$$

where N_f is the total number of fruit tree species in the rotation, $FGM(t)$ is the gross margin of fruit trees, W_f is the workload allocation dedicated to fruit trees and $\alpha(t)$ is the annual tree development coefficient.

As for vegetables crops, we simulated all possible combinations of at least 3 fruit tree species and we chose three contrasting management strategies: (1) a low labor-intensive and low-paying strategy; (2) an intermediate labor-intensive and paying strategy; (3) highly labor-intensive, high-paying strategy. These crop rotations are labelled A, B and C respectively in Figure B-30b.

2.5. Performance indicators and simulations

Two indicators were computed for production performance at the farm level, the average gross margin and a workload constraint indicator. Average gross margin was calculated as the yearly average of total gross margin from orchard and market gardening (€/ha per year):

$$\text{Average Gross Margin} = \frac{1}{T} \sum_1^T FT(t) + MG(t) \quad (18)$$

with T = the number of years to the horizon. Gross margin standard deviation can also be calculated based on annual gross margins.

The second indicator was workload constraint, which was expressed as the yearly relative workload in excess compared to the workload required by both orchard and market gardening enterprises. It reflects the number of adaptations that farmers could make when managing the system:

$$\text{Workload Constraint Indicator} = \frac{1}{T} \sum_1^T 1 - \frac{1}{2} \left(\frac{WL_v(t)}{WR_v(t)} + \frac{WL_f(t)}{WR_f(t)} \right) \quad (19)$$

where $WL_v(t)$ is the workload effectively allocated to vegetables at year (t) and $WR_v(t)$ is the workload requirement for vegetables at year (t).

In order to study the temporal dynamics of mixed systems, we modeled the combination of three market gardening crop rotation types and three fruit tree portfolios (labelled respectively A, B and C in **Figure B-30**). The combination of these three strategies per enterprise generates nine scenarios. In each scenario, the two controls presented in **Figure B-29**, $U[0]$ and $U[1]$ can vary: $U[0]$, the relative area of fruit trees over vegetables is a continuous variable that ranges between 0.1 and 0.9. $U[1]$, the allocation of working time, is a continuous variable that ranges between any 0 and 1 (i.e. between from a systematic prioritization of working time towards market gardening to fruit trees).

As a preliminary approach, we simulated 10,000 random scenarios in which the crop rotation and the controls described above are chosen randomly. In a second step, due to computation limitations, we modelled the nine contrasted scenarios described above, screening in detail controls $U[0]$ and $U[1]$ with a 30 steps each. All computations were performed with Python 3.8.1 (www.python.org/), graphical outputs were realized alternatively with Python and R software 3.6.0 (<https://cran.r-project.org>).

3. Results

3.1. Fruit tree dynamics

The collective experts' knowledge sharing workshop, completed with additional expert interviews, made it possible to describe six main species of fruit trees most cultivated in the South-East of France: Apple (*Malus domestica*), Peach (*Prunus persica*), Pear (*Pyrus communis* L.), Apricot (*Prunus armeniaca*), Cherry (*Prunus cerasus*) and Prune (*Prunus domestica*). The dynamics are presented in **Figure B-31**, they illustrate the potential yield of each fruit trees according to three level of workload allocation: (i) optimal investment; (ii) minimal investment; (iii) the intermediate scenario. At this stage, two types of fruit trees can be distinguished: those that require a high degree of investment to produce (Figure B-31c, d, f), and the ones that are less sensitive to a lower maintenance and that can produce in the long term despite suboptimal management (Figure B-31a, b, e). Fruit tree species also differ in the timing of management and therefore in the dates on which workload conflicts may arise. These characteristics are important features to take into account in the design of a MFV system and will greatly influence the dynamics of the system in the long run.

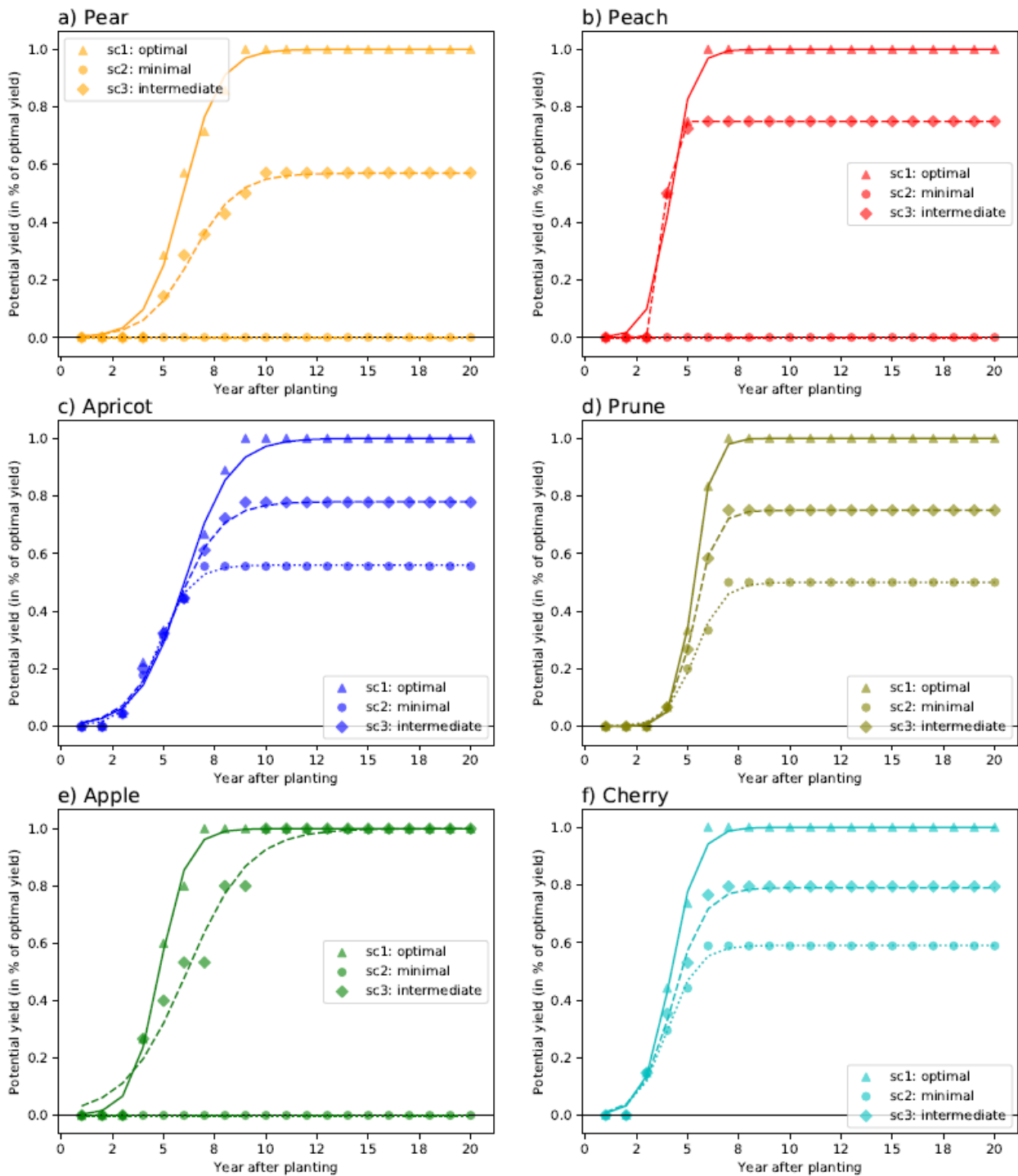


Figure B-31: Expert knowledge-based characterization of six main fruit tree dynamics over time according to three contrasted scenarios: (1) optimal investment; (2) intermediate investment and (3) minimum investment (Cf. §2.4).

3.2. Crop rotation and workload allocation

As a preliminary approach, we modelled 10,000 random portfolios of 10 crops. Each portfolio is a random combination of fruit tree and vegetable enterprises, and a random workload

allocation between both enterprises. From these simulations, average and standard deviation of the annual gross margin have been calculated (**Figure B-32**). At this stage, the average gross margin (GM) does not show clear trends, but we can observe that standard deviation of GM is mainly driven by the relative share of each enterprise in the crop rotation.

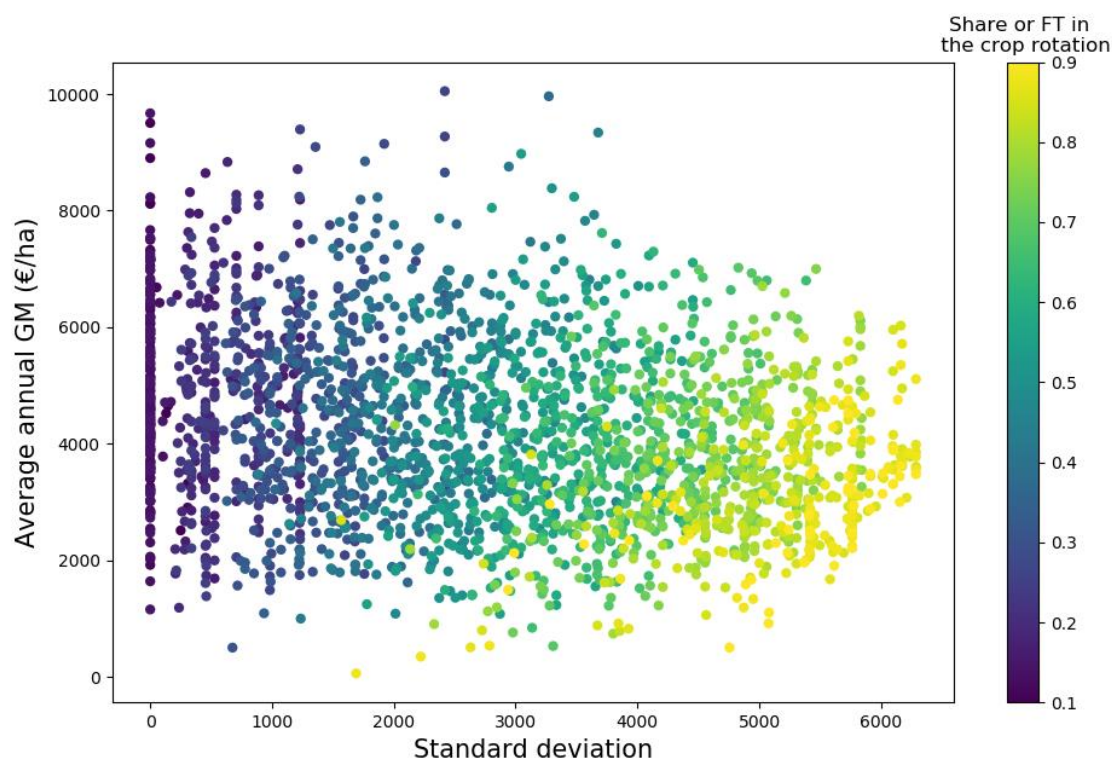


Figure B-32: Model-derived average gross margin and its standard deviation from both orchard and market gardening enterprises, relative share of each enterprise in the crop rotation. FT: fruit trees; GM: gross margin

The workload constraint indicator provides an indication of the ratio between the working time required by a given crop rotation and the work time available. This reflects the notion of feasibility (or unfeasibility) of a crop rotation, and whether adjustments are needed in work organization over the duration of trees' lifespan. The measurement of workload constraints for the 10,000 random shows that the indicator is > 0 for 85,4% of the scenarios, which implies that adaptations are necessary for all these scenarios (**Figure B-33**). The number of adaptations needed increased with the prioritization of one or another of the crops. This indicates that lower constraints on working time are found for intermediate strategies, balancing trees and vegetables within the system. Furthermore, workload constraints decrease with the relative share of fruit in the crop rotation; highlighting the existence of a trade-off between gross margin standard deviation and workload constraint.

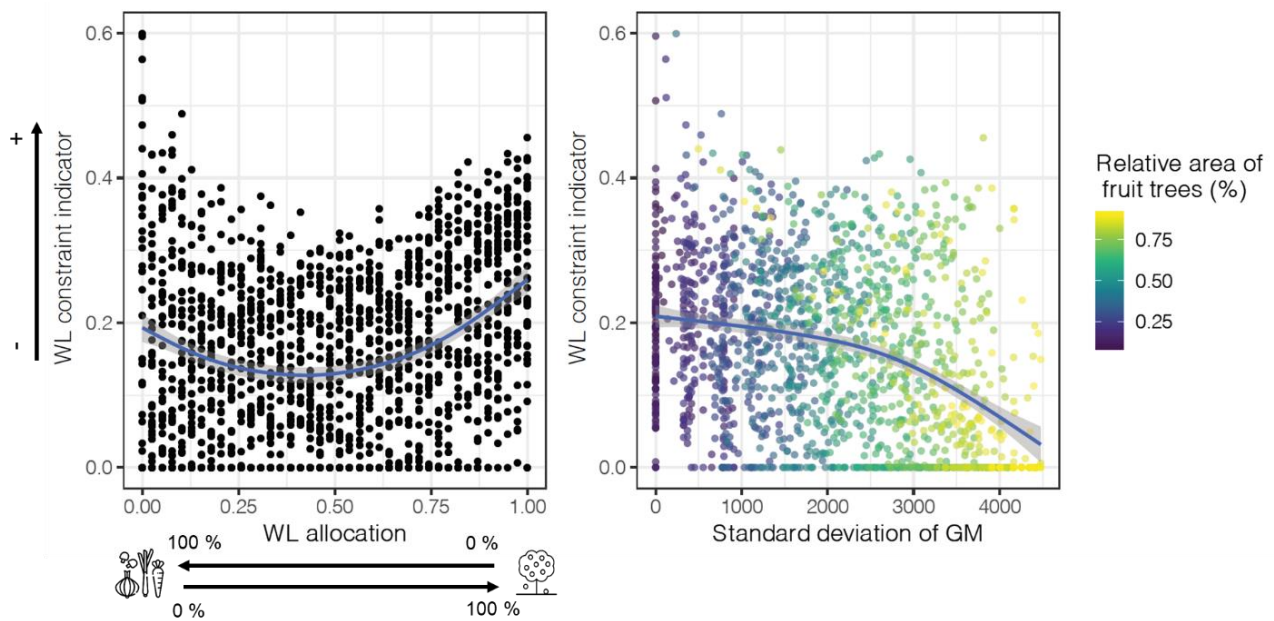


Figure B-33: Workload constraint indicator as a function of (left) workload allocation between both enterprises (right) standard deviation of gross margin and relative area of fruit trees in the crop rotation, for all random scenarios simulated. The blue curve displays the smoothed conditional mean. WL: workload; GM: gross margin.

3.3. Trade-offs between short term and long term objectives

To deepen the analysis of trade-offs between short-term and long-term objectives, we investigated the combination of the two means of control (workload allocation and share of each enterprise) on system dynamics, in contrasted situations. Three distinct vegetables crop rotations and three distinct fruit tree portfolios were selected (labelled respectively A, B and C in Figure B-30). The combination of these three strategies per enterprise generates nine scenarios which are displayed in **Figure B-34**. The relation between the workload allocation and the relative share of each enterprise in the crop rotation shows that overall a better average gross margin is obtained with a higher proportion of vegetables (x-axis) and higher workload allocated to vegetables (y-axis) (**Figure B-34a**). Nevertheless, for intensive market gardening (vegs = C), it seems that a combination of a significant part of fruit trees with an allocation of working time towards fruit trees brings satisfactory results. The workload constraint indicator provides additional information (**Figure B-34b**). For low-intensity vegetable crop rotation (Vegs = A), the overall trend is that high gross margins are associated with low workload constraints. However, for intermediate and intensive vegetable crop situations (Vegs = B and C), the increased part of fruit trees in the crop rotation makes it possible to maintain high levels of gross margin while decreasing workload constraints.

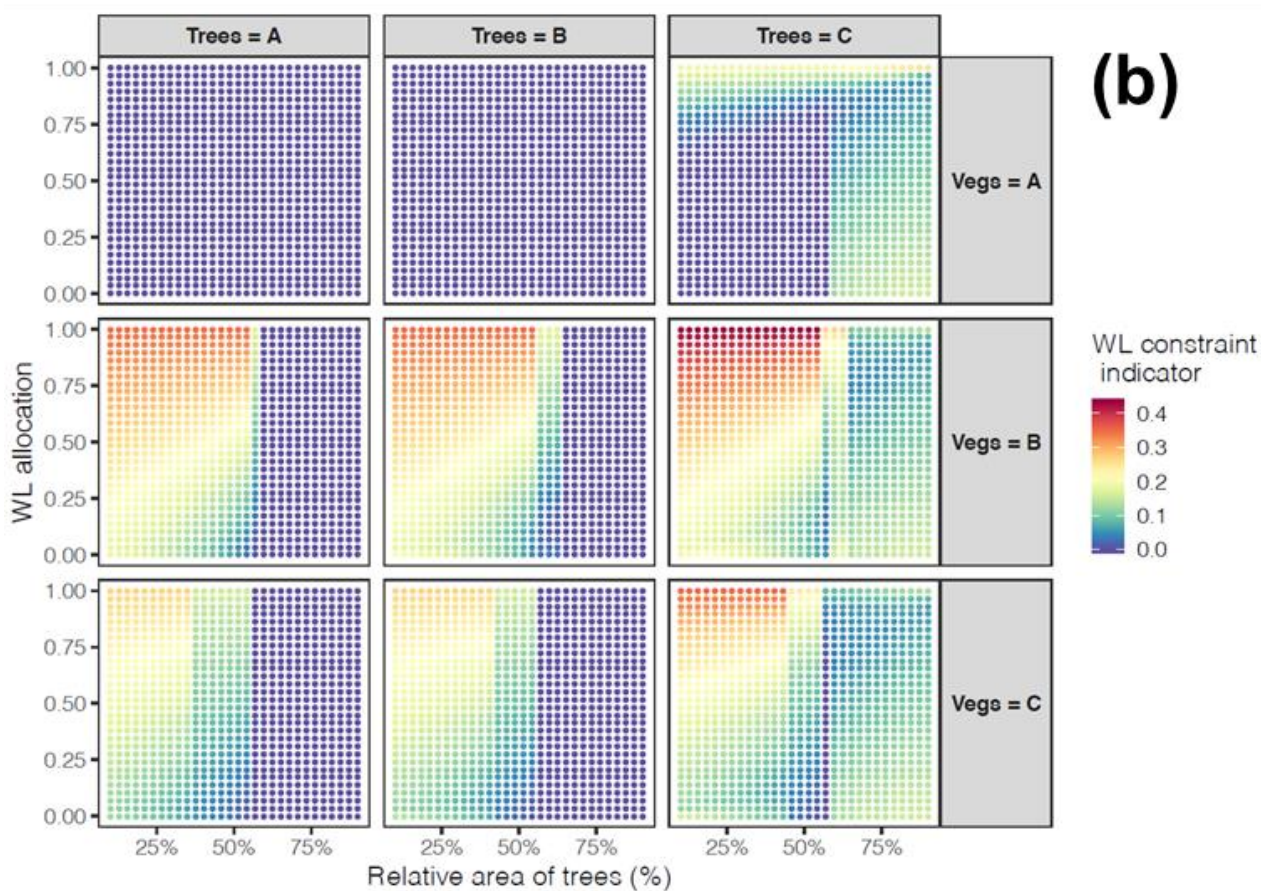
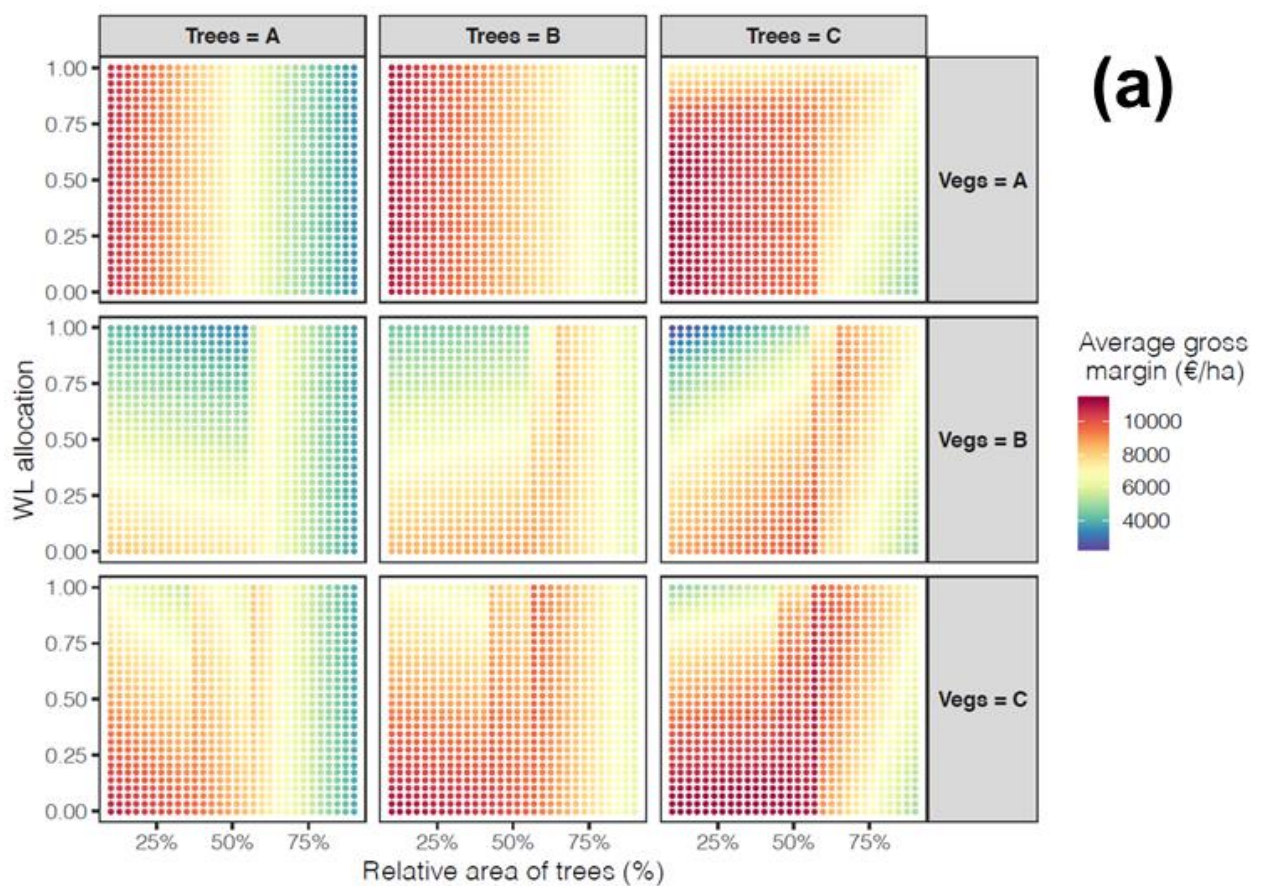


Figure B-34: Model-derived (a) average gross margin and (b) workload constraint indicator, according to nine strategies combining fruit trees and vegetables. WL: workload.

These results give us a first insight into what the different combinations of controls can achieve under very contrasted scenarios. However, as mentioned in §2.4, it is important to further analyze these characteristics, particularly their evolution over time. Figure B-35 presents the dynamic evolution of gross margin within the scenario combining intermediate vegetables scenario (Vegs = B) and intensive fruit trees scenario (Trees = C). Over twenty years, the annual gross margin (GM) is represented as a function of the share of each enterprise in the crop rotation (Figure B-35a). To compare contrasted values of the control $U[0]$, we plotted the cumulative GM difference between three values of $U[0]$: 0.1 (\blacktriangle), 0.5 (\bullet) and 0.9 (\blacklozenge). The difference between these three $U[0]$ values is given pair by pair (Figure B-35 b, c, d).

These results shows that crop rotation promoting a larger share of vegetable crops lead systematically to a better short-term productivity. However, the long-term profitability shows contrasted features. In Figure B-35b, for instance, if we consider the difference between strategies promoting vegetables (FT_{\min}) and intermediate strategies (FT_{interm}), we can observe two tipping points. First, the gap between both strategies is compensated from the fifth year onwards, and FT_{interm} becomes more effective on an annual basis. Second, the cumulative gross margin over the entire period indicates that the FT_{interm} strategy is generally more profitable (second switchover at 10 years after planting). In Figure B-35c, the comparison between FT_{\min} and FT_{\max} shows that both strategies have a similar cumulative gross margin over 20 years, but FT_{\min} is more profitable in the first 6 years. Finally, comparing FT_{interm} and FT_{\max} (Figure B-35d) shows that the intermediate strategy is always more profitable than a strategy promoting fruit trees.

This indicates that in the long term, a strategy favoring intermediate share of fruit trees can be more desirable than a strategy promoting one or another enterprise. However, strategies implying large share of fruit trees require being able to cope with several successive years of low gross margin, either by consenting a lower income in the first years, or through a larger starting capital. This also underlines the importance of analyzing not only the overall annual gross margin but also its dynamics through time, as it is likely to fluctuate significantly.

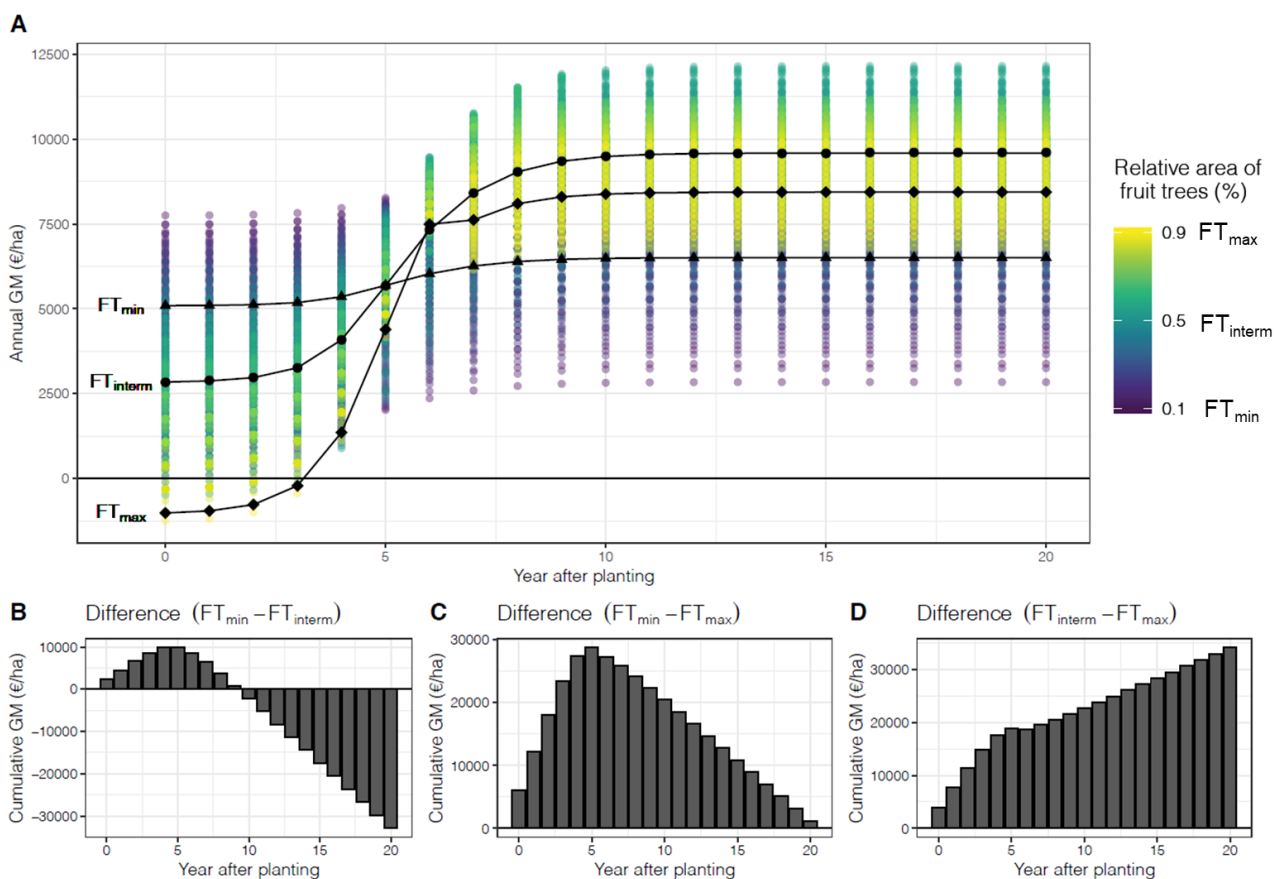


Figure B-35: (a) Evolution of the overall annual gross margin in the scenario combining intermediate vegetables scenario (Vegs = B) and intensive fruit trees scenario (Trees = C), according to the relative share of each enterprise in the crop rotation ($U[0]$). Three contrasted values of $U[0]$ are compared pair by pair: (b) $FT_{min} - FT_{interm}$; (c) $FT_{min} - FT_{max}$ and (d) $FT_{interm} - FT_{max}$

4. Discussion

4.1. Model strengths and limitations

Mixed fruit tree-vegetable agroforestry systems, which correspond to the intercropping of fruit trees and vegetables, are currently undergoing strong development in France and Europe. However, since this is a relatively recent dynamic, empirical data on these systems are very rare and biological processes are still very uncertain (Imbert et al., 2020; Lauri et al., 2019). In the present study, we built a simple model of mixed fruit tree vegetable (MFV) system to assess its main properties through time. The approach presented in this study has been to combine in a dynamic way quantitative elements from both fruit trees and vegetables with qualitative and quantitative elements from expert knowledge to develop a model of MFV systems at plot scale. This model was dynamically implemented to (i) explore different management strategies in MFV

systems and (ii) to predict dynamically long-term fruit trees and vegetable crops dynamics under competitive conditions on workload between both enterprises. This is, to our knowledge, the first attempt to model dynamics of MFV systems. Existing dynamic model applications of agroforestry systems do not consider the existence of two annually productive plants (van der Werf et al., 2007; van Noordwijk and Lusiana, 1999) and they also rarely take into account labor constraints linked to the presence of other enterprises (but see Graves et al., 2011).

The use of a dynamic analytical framework applied to MFV systems made it possible to highlight the relation between different dimensions of system performance. The simulation of contrasting characteristic scenarios also better explains the relationships between the share of each enterprise in the crop rotation (fruit trees and vegetables), the workload allocation and system bio-economic performances. Our results indicate that specialized market gardening enterprise has an overall better short-and long-term gross margin per hectare (but not necessarily per working hour) than specialized fruit trees. Nevertheless, mixed systems composed of roughly equivalent shares of fruit trees and vegetable crops make it possible to decrease workload constraints while maintaining a high level of profitability. In addition, these intermediate situations can lead to better gross margin in the long term, but require addressing both short-and long-term objectives, and the ability to cope with several consecutive years of lower gross margin.

Due to the simplicity of its individual components, the overall model was still manageable in terms of complexity and number of inputs required. This deliberately simplistic model makes it possible to model a large panel of situations, it has nevertheless some limitations that deserve to be discussed in more details. A first limit of our approach is that the model does not take into account some tree-crops important but unknown biological processes. In mixed fruit trees – vegetable systems, crops are often organized in intercropping or agroforestry design, where crops have biological interactions with each other (Paut et al., 2020). These interactions may lead to a different overall yield and gross margins, but also may influence the yields of vegetables and fruit trees in a dynamic way (Burgess et al., 2019; Paul et al., 2017). In view of the current state of the literature on these systems, these components have not been included in the analysis, but it would be important to integrate them for further development of our model (Van Vooren et al., 2016).

Another limitation to our approach is that the model was deterministic and did not capture the uncertainty on parameter values. In fruits production, in particular, some key elements such as alternate bearing or climatic factors can affect inter-annual yield variability (Beattie and Folley, 1977). These sources of uncertainty are all the more justified in MFV systems as there is very little knowledge about the evolution of fruit trees under suboptimal management conditions. The introduction of stochasticity on key parameters (e.g., fruit tree yields) would be an approach to overcome these limitations. In this perspective, dynamic stochastic modelling approaches are very useful for characterizing the management adaptability of a system a highly fluctuating and uncertain environment (Accatino et al., 2014; Sabatier et al., 2015).

4.2. Implications and perspectives

Our approach makes it possible to quantify dynamically the annual gross margin of a fruit tree-vegetable agroforestry plot. Combined with the characterization of implications in terms of labor constraints at different times of the year, it made it possible to highlight determining factors of success at plot level. This one-hectare scale analysis may in turn be mobilized for farm scale analysis, with the integration of farm fixed costs (García de Jalón et al., 2018; Graves et al., 2011, 2007).

Finally, as with other integrated systems, an important aspect that would require further investigations is the dynamic and adaptive system management (Bell and Moore, 2012; Hendrickson et al., 2008). In our approach, we simulated scenarios where controls were defined as strategies for the entire cycle duration. However, it has been shown that adaptive management is a crucial factor to integrate in the analysis of agroecological systems (Catalogna et al., 2018). In MFV systems, trees are planted and fixed in the system but vegetable crop rotation may vary over time. The management needs to be adapted to structural and functional changes that these systems undergo over time (Léger et al., 2019). Trade-offs that relate to the immediate provision of the production service (in our case, market gardening) may be to the detriment of other services in the future (e.g., fruit production). These trade-offs over time have a decisive impact on the biological dynamics of the agrosystem. Many natural processes, such as those affecting tree training, occur at such a rate that several years may pass before significant effects are perceived by the farmer (Lauri et al., 2016, 2019). The consequences of these trade-offs then become externalities borne with a time lag. A useful method to capture the evolution of a dynamically managed system is viability theory (Aubin, 1991). This mathematical framework

makes it possible to study the evolution of dynamical systems under constraints on the system states and controls. Its recent applications to natural resource management have proved to be particularly relevant on livestock systems (Sabatier et al., 2017; Tichit et al., 2004) or sylviculture (Domenech et al., 2011) and would be particularly relevant for improving our approach.

5. Conclusion

Our model was the first to attempt to analyze mixed fruit tree vegetable (MFV) systems at field scale. We developed a dynamic bio-economic model to investigate the consequences of farmers' management decisions in terms of crop rotation and workload allocation on the dynamics of MFV systems. Using this dynamic approach based on states and controls, we simulated management strategies for both market gardening and orchard, and assessed their impact on the long-term dynamics of the system. The results made it possible to illustrate the consequences of different types of trade-offs between management objectives when making decisions in the steering of these systems, taking into account uncertainty linked to the lack of knowledge about these processes. Further research will nevertheless be needed to better understand the processes underlying MFV systems and their evolution in different management configurations.

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Partie C. Discussion générale

Dans cette thèse, différents cadres d'analyse ont été mobilisés : mise à l'épreuve de cadres théoriques et d'outils existants (théorie du portefeuille -Chapitres I et II-, modélisation dynamique -Chapitre V-), mais aussi construction de cadres d'analyse appropriés (Chapitre III et IV). Ma recherche a été hybride, combinant des méthodes de modélisation quantitative avec des méthodes qualitatives empruntées aux sciences sociales. Ces approches et outils ont permis de mieux caractériser les arbitrages entre les bénéfices attendus et la complexité de gestion générée par les vergers-maraîchers. Si elle permet d'éclairer la complexité de situations atypiques, localisées, cette thèse permet plus largement la production de résultats généralisables. Dans cette discussion nous allons dans un premier temps, passer en revue les principaux apports de la thèse. Nous décrirons ensuite leurs implications à d'autres échelles ou pour d'autres systèmes agricoles. Les résultats ayant déjà fait l'objet de discussions dans les différents chapitres de la thèse, cette discussion générale met en perspective l'ensemble des résultats et leurs apports pour mieux appréhender les compromis diversité-complexité dans les systèmes agricoles. Enfin, nous présenterons les perspectives qu'offrent ces travaux pour la recherche et le développement.

1. Diversifier et associer en contexte d'incertitudes : principaux apports de la thèse

Les premiers résultats de cette thèse (Chap. I et II) ont permis de mettre en évidence les relations entre rendement et risques, par le biais de la théorie du portefeuille comme outil d'évaluation des systèmes horticoles diversifiés. Alors que la plupart des études liant l'agriculture et la biodiversité ont reconnu que les agrosystèmes diversifiés sont mieux à même de faire face aux perturbations, peu d'informations sont disponibles sur une évaluation quantitative de cet avantage comparatif. Nos résultats montrent que le risque global peut être réduit par la diversification des cultures et que cette réduction du risque, quantifiable par la métrique du « bénéfice de diversification », peut atteindre 77 % en choisissant la bonne combinaison de cultures. En outre, les simulations de portefeuilles plus larges nous montrent qu'une grande proportion du risque est atténuée à partir de 10 cultures. Au-delà, il semblerait que la réduction du risque apportée par une culture supplémentaire soit marginale. Ces résultats corroborent les observations rapportées dans le domaine de la sylviculture (Crowe and Parker, 2008), de la pêche (DuFour et al., 2015) ou de la gestion des ressources en eau (Aerts et al., 2015) et soulignent donc la pertinence de la théorie du portefeuille pour définir des stratégies de diversification basées sur la réduction des risques. Par ailleurs, les stratégies de diversification reposant sur des typologies

naturalistes ne sont pas les plus pertinentes dans notre étude et n'ont pas été utiles pour saisir les complémentarités dans le comportement des cultures. Plusieurs auteurs (Pennington and Fisher, 2009; Song et al., 2014) ont suggéré que d'autres systèmes de classification, tels que les traits fonctionnels, peuvent être pertinents, car ils reposent sur les caractéristiques physiologiques du développement, de la croissance et de la structure des plantes. La diversité de ces traits de réponse pourrait alors améliorer le maintien des fonctions de l'agroécosystème (Lavorel and Garnier, 2002). Des études supplémentaires sur les traits fonctionnels des cultures pour un large éventail de cultures sont toutefois encore nécessaires pour développer cette approche.

Le Chapitre III complète notre approche de modélisation de stratégies de diversification, en y intégrant les processus d'interactions entre cultures. L'approche que nous proposons prend en compte la double dimension du rendement et du risque dans un cadre combiné d'évaluation et de comparaison de deux stratégies de diversification : (i) une stratégie de diversification simple considérée comme un nombre croissant de cultures sur des parcelles séparées au sein d'une exploitation et (ii) une stratégie de cultures associées considérée comme une diversité accrue au sein d'une même parcelle. Les portefeuilles de cultures ne sont alors plus considérés comme des ensembles de cultures séparées dans l'espace, mais bien comme des ensembles de cultures en interaction. Ce cadre conceptuel formalise, en les séparant, ce que nous appelons les « effets de diversification » et « effets d'association ». Les résultats montrent que les cultures associées, en plus d'être intéressantes en termes de productivité, peuvent avoir un effet supplémentaire sur la réduction du risque par rapport à une simple stratégie de diversification. Nos travaux contribuent à une meilleure compréhension des impacts possibles des stratégies de diversification sur les compromis entre rendement et risque, mais soulignent également l'importance de prendre en compte la variabilité des rendements dans les prochaines recherches.

Si ces premiers résultats permettent d'apporter un éclairage nouveau sur le potentiel de la diversification et de l'association de cultures en horticulture, ils doivent cependant être mis en regard de deux caractéristiques essentielles des vergers-maraîchers : ces systèmes intègrent deux ateliers (i) très exigeants en termes de gestion et (ii) caractérisés par des dynamiques biologiques nettement contrastées. Le Chapitre IV fournit des clés pour analyser les changements de pratiques de gestion induits par le niveau d'intégration entre le verger et le maraîchage. Il apparaît que l'organisation du travail et les opérations culturales sont altérées à la fois par la diversité fonctionnelle des cultures présentes sur l'exploitation, mais également par la configuration agroforestière de ces cultures. Si ces résultats sont complémentaires à ceux mis en évidence en

maraîchage diversifié (Aubry et al., 2011; Petit et al., 2010) l'introduction de l'arbre comme nouveau « type fonctionnel » de cultures induit une reconfiguration relativement importante de la nature des pratiques. Une des spécificités supplémentaires des vergers-maraichers par rapport à d'autres systèmes intégrés comme les systèmes de polyculture-élevage (Moraine et al., 2012) réside dans le fait que l'agrosystème n'est pas constitué d'ateliers combinés pour améliorer l'efficacité des ressources, ou entre lesquels circulent des flux de matières, mais il est constitué d'objets biologiques qui peuvent être gérés de manière commune. Ainsi, le décloisonnement et l'imbrication étroite de l'arboriculture et du maraîchage questionne la définition même « d'atelier », car elle implique une redéfinition des pratiques de gestion qui sont transversales aux ateliers.

Finalement, le Chapitre V met en évidence l'importance de prendre en compte les dynamiques du système. En effet, comment faire plus différent, du point de vue de la dynamique, qu'un radis de 18 jours associé à un pommier dont la durée de vie peut se compter en décennies ? Le modèle bio-économique développé dans ce chapitre nous permet d'analyser les relations entre la répartition de la surface cultivée en arboriculture et en maraîchage, l'allocation du temps de travail entre ces deux ateliers et la dynamique biologique de l'agrosystème. Son implémentation à l'échelle de la parcelle permet de prévoir de manière dynamique la production et la rentabilité économique à long terme des arbres fruitiers et des légumes dans des conditions de concurrence sur la charge de travail entre les deux ateliers. Les résultats mettent en évidence qu'un système purement maraîcher est globalement plus rentable qu'un système purement arboricole, notamment à cause de la phase d'entrée en production des arbres. Néanmoins, dans certaines configurations, l'intégration de l'arbre dans le système permet de maintenir un niveau de production élevé sur le long terme tout en diminuant les contraintes sur le travail. Bien que cette approche soit nouvelle et que les données empiriques sur ces systèmes soient encore rares, mes travaux peuvent avoir des implications plus larges. (i) La caractérisation de la phase d'installation des fruitiers est d'intérêt pour d'autres systèmes agroforestiers basés sur des arbres dits « à haute valeur ajoutée » (den Herder et al., 2017; Lauri et al., 2019). (ii) La prise en compte des contraintes sur le temps de travail constitue un atout pour étudier la faisabilité de ces systèmes a priori, et donc leur potentiel d'adoption *in fine*.

2. Implications de ces travaux à d'autres échelles et pour d'autres systèmes agricoles

2.1. Changer d'échelle

Notre approche centrée sur la parcelle a décrit dans quelles mesures la diversité des cultures peut être source de résilience face aux risques, mais aussi source de complexité de gestion. La transposition des cadres analytiques produits dans cette thèse à des niveaux d'organisation supérieurs peut être envisagée moyennant certaines précautions. Ainsi nos approches sont à priori opportunes pour caractériser et analyser la diversification à différents niveaux d'organisation :

2.1.1. Au niveau de l'exploitation

Considérée comme un ensemble de parcelles en rotation, l'exploitation agricole semble propice à une adaptation de nos modèles de choix de portefeuilles de cultures *stricto sensu* (c'est-à-dire tels qu'ils sont envisagés dans les Chapitres I & II, sans interactions entre les cultures). Deux principaux points de vigilance peuvent toutefois être soulignés. Tout d'abord, les modèles proposés ne prennent pas en compte la cohérence agronomique d'un assolement donné : celui-ci nécessite d'être raisonné de manière pluriannuelle en prenant en compte par exemple l'effet précédent (Anderson, 2005), la gestion de la fertilité du sol sur le long terme (Durand et al., 2017) ou la gestion des bioagresseurs. Le deuxième point de vigilance porte sur la présence d'une diversité culturelle à l'échelle de l'exploitation qui nécessite de contrebalancer les économies d'échelles (à l'origine des phénomènes d'expansion et de spécialisation des exploitations) par des économies de gammes (Perrot et al., 2011). Pour assurer la viabilité des systèmes diversifiés, certains auteurs soulignent qu'il faut préciser les modalités de transition d'un système de production spécialisé, basé sur la production d'un bien en grande quantité, vers des systèmes à économies de gammes, où les complémentarités entre différentes productions permettent notamment de réduire l'usage des intrants (Détang-Dessendre et al., 2018). Les approches présentées dans les trois derniers chapitres permettent de donner un éclairage sur ces éléments de complémentarités, que celles-ci soient spatiales (Chap. III), temporelles (Chap. V) ou organisationnelles (Chap. IV).

2.1.2. À l'échelle du territoire ou de la filière :

À des échelles supérieures, l'effet bénéfique de la diversification sur le risque peut s'envisager à différents niveaux d'organisation (Kimura et al., 2010; Renard and Tilman, 2019). À l'échelle d'un groupement de producteurs, la réponse à un marché public nécessitant un apport régulier (et avec une variabilité minimale) d'une certaine gamme de produits pourrait par exemple s'envisager avec les outils développés dans cette thèse. En écho, une échelle plus agrégée, comme celle de la filière, peut elle aussi bénéficier des outils de gestion du risque que nous avons développés : chaque culture qui compose un portefeuille peut théoriquement être une exploitation spécialisée. Cela nécessiterait néanmoins une prise en charge collective du risque à l'échelle d'un ensemble de producteurs ou d'une filière¹¹. À ce titre, des auteurs montrent que la biodiversité cultivée et les mécanismes assurantiels sont deux moyens tout aussi viables pour stabiliser les revenus des agriculteurs (Di Falco and Perrings, 2005). Certains argumentent que la disponibilité d'une assurance financière contre l'insuffisance d'un service écosystémique, ou d'autres produits financiers permettant de couvrir le risque sur le revenu, peut être considérée comme un substitut à l'assurance naturelle fournie par la biodiversité (Baumgärtner, 2008). En d'autres termes, l'aversion pour le risque et la diversité cultivée peuvent être dissociées dans le cas où interviennent des aides financières. Les politiques visant à stabiliser les revenus en soutenant spécifiquement certaines espèces peuvent modifier ce lien en dissociant la diversité cultivée de la gestion du risque économique. L'articulation entre les approches agronomiques que nous proposons et les mécanismes assurantiels seraient d'intérêt, mais à ce stade, bien au-delà du périmètre de notre étude (Müller et al., 2017).

Enfin, que l'on considère le niveau de l'exploitation, de la région ou de la filière, la question du rapport entre la diversification et la gestion du risque est donc cruciale. Elle est d'autant plus importante que les déterminants de la diversification des cultures (*ex-ante*) interagissent avec d'autres mécanismes, tels que les assurances (*ex-post*) ou la contractualisation, et que chacun de ces mécanismes peut constituer une entrave ou au contraire un levier à la diversification des cultures (Détang-Dessendre et al., 2018; Meynard et al., 2013).

¹¹ La société d'assurance AXA a exprimé son intérêt pour la démarche en déclinant cette approche à des systèmes de grandes cultures dans le cadre d'un mémoire d'actuariat : Olive X. (2019) Modélisation et assurabilité du revenu agricole probable. Mémoire présenté pour la validation du cursus à la Formation d'Actuaire de l'Institut du Risk Management.

2.2. Formaliser les effets de diversification et d'association pour d'autres systèmes

Les cadres d'analyse élaborés dans cette thèse et leurs applications illustrent le cas particulier des vergers-maraîchers, vus comme des systèmes horticoles diversifiés et associés. Néanmoins, les approches développées ici ont une forme de généralité dans leur structure, qui les rend potentiellement applicables à la plupart des systèmes agricoles. Il faut cependant au préalable bien caractériser et distinguer les **effets de diversification** (juxtaposition de plusieurs productions ou ateliers au sein d'une même exploitation) des **effets d'association**, où les interactions entre les différentes composantes du système sont prises en compte. Cette dichotomie est semblable à celle faite entre effets de composition et de configuration à l'échelle du paysage (Alignier et al., 2020; Duru et al., 2015).

2.2.1. Les effets de diversification

Dans les Chapitres I et II, notre modèle ne requiert que des données communément disponibles et pertinentes pour la plupart des systèmes agricoles : la nature des composants de l'exploitation (cultures ou produits animaux), leur rendement et leur variance. Dans cette perspective, notre méthode et nos résultats peuvent avoir des applications plus larges pour de nombreux systèmes. La généralité des entrées que requiert notre modèle permet d'envisager des articulations avec des modèles de choix d'assolement développés en grandes cultures (Dury and Bergez, 2012) ou en maraîchage (Mawois et al., 2012; Morel et al., 2017; Navarrete and Le Bail, 2007).

Les résultats du Chapitre V se situent à l'interface entre ce que nous qualifions d'effets de diversification et d'association. En effet, le modèle est conçu pour étudier la dynamique des vergers-maraîchers en fonction de contraintes sur le temps de travail, des dynamiques propres à chaque atelier, mais aussi des dynamiques d'interactions entre arboriculture et maraîchage. Néanmoins, dans son application, le manque de données empiriques sur ces systèmes rend impossible la formulation d'hypothèses sur les processus d'interactions entre les ateliers. Les effets d'association ont été négligés et seuls les effets de diversification ont été pris en compte (i.e. la coexistence de plusieurs ateliers). Il pourrait être particulièrement adapté à l'étude de systèmes combinant plusieurs ateliers ayant des dynamiques contrastées au sein d'une exploitation (Hendrickson et al., 2008).

2.2.2. Les effets d'association

Le modèle conceptuel que nous proposons en Chapitre III prend en compte les interactions biologiques entre éléments d'un système et permet d'analyser comment ces interactions façonnent la relation rendement-risque dans les systèmes de cultures associées, comparés à des systèmes simplement diversifiés. En cela, il reste adaptable à d'autres systèmes mixtes combinant plusieurs espèces cultivées, tels que les associations céréales-légumineuses (Bedoussac et al., 2015), les mélanges variétaux (Kjær and Skovgaard, 2012; Newton et al., 2009) ou les associations « cultures de rente – plantes de services » (Valantin-Morison et al., 2019), Il est également transposable sur des systèmes qui valorisent les synergies entre ateliers, comme les systèmes sylvopastoraux (Burgess et al., 2017; Dufils, 2017; Geddes and Kohl, 2009), les systèmes de polycultures-élevage (Kronberg and Ryschawy, 2018; Ryschawy et al., 2014) ou encore les élevages mixtes (Martin et al., 2020).

Au même titre que la théorie du portefeuille *stricto sensu* développée plus haut, l'approche présentée au Chapitre III peut être utile pour envisager des synergies au-delà de l'exploitation. A cette échelle, les effets d'association peuvent intervenir lorsque des exploitations interagissent de manière à ce que la performance de N exploitations soit supérieure à la somme des performances individuelles. En polycultures-élevage (Martin et al., 2016) l'intégration entre exploitations permet aux agriculteurs de concevoir des nouvelles formes de coordination spatiale, temporelle et organisationnelle. Elle est aussi considérée comme une manière de stimuler l'apprentissage chez les agriculteurs et de réduire l'incertitude quant à leur adoption. On retrouve également ces principes de coordination spatiale dans l'Écologie Industrielle et Territoriale, au premier rang desquels apparaît le bouclage des flux, de telle sorte que le déchet de l'un devienne une ressource pour l'autre, sur une zone géographique définie (Brullot et al., 2017).

Enfin, le Chapitre IV a permis de distinguer ce qui relève des effets de diversification et des effets d'association dans les pratiques de gestion des vergers-maraîchers. Ce travail donne un éclairage sur les changements de pratiques induits par une plus grande diversité de configuration. Si ce cadre d'analyse a été construit de manière inductive à partir d'études de vergers-maraîchers existants, la description de typologies de pratiques permet une plus grande généralité. Il serait intéressant de tester la transférabilité de ce cadre d'analyse sur d'autres systèmes mixtes (observerait-on les mêmes typologies de pratiques par exemple ?).

2.2.3. Besoins de recherche sur les processus

Dans cette thèse, la majorité des processus biologiques étudiés n'ont pas été explicités, ou l'ont été sur la base de dire d'experts. Les connaissances sur les processus en jeu restent encore parcellaires, du fait de la complexité structurelle de ces systèmes : on est ici dans un contexte d'incertitude « agroécologique ». Cet aspect est aussi central pour les agriculteurs s'engageant dans ce type de démarches, pour qui l'enjeu est d'apprendre en situation (Girard and Magda, 2018). En acceptant le fait que ces systèmes complexes et évolutifs ne peuvent être entièrement contrôlés, les agriculteurs consentent à « *laisser faire* », « *travailler avec le vivant* » vocabulaire régulièrement employé par les agriculteurs rencontrés. Bien qu'une compréhension approfondie des interactions biologiques entre arbres et cultures ou des régulations naturelles fasse encore défaut, elle est souvent présentée comme un gage permettant aux agriculteurs de concevoir de nouveaux mélanges et de nouvelles façons d'organiser des cultures compatibles dans l'espace du champ (Francis, 1989). La compréhension du fonctionnement écologique est en effet importante et souvent mise en avant dans les études traitant des cultures associées, mais notre approche basée sur les données offre un point de vue complémentaire qui permet de surmonter le manque de connaissances sur les processus écologiques.

Les cadres d'analyse que nous fournissons relèvent de l'évaluation des impacts de l'agrosystème sur la production et le risque, en le considérant comme une « boîte noire ». Nos approches s'affranchissent ainsi de la connaissance des processus en tant que tels, en partant de la donnée brute. Elles sont particulièrement adaptées à l'étude des systèmes écologisés, qui peuvent faire émerger des nouvelles propriétés, du fait de leur complexité d'organisation. Cela nous renvoie au concept « d'émergence », qui considère qu'un système composé de sous-unités en interaction acquiert des propriétés qualitativement nouvelles qui ne peuvent être comprises comme la simple addition de leurs contributions individuelles (Beckenkamp, 2006; Camazine et al., 2001). L'analyse du fonctionnement interne de ces agrosystèmes demeure cependant essentielle pour comprendre les processus à l'œuvre et identifier les leviers d'action (Therond, 2019). Mes travaux sont ainsi complémentaires d'autres approches qui tentent de comprendre finement les processus en jeu. Par exemple, une fois identifiées les associations de cultures bénéfiques sur plan agronomique, connaître les processus de régulations (Imbert et al., 2020, 2019) ou de développement racinaire (Sun et al., 2018b; Xu et al., 2019) au sein de systèmes agroforestiers permet de fournir des clés pour aider à la conception et au pilotage de ces systèmes.

3. La diversité : atouts et/ou contraintes ? une conciliation nécessaire entre les bénéfices attendus et la complexité générée

3.1. La diversification, moyen de réduire le risque... et source de risques nouveaux ?

Nous avons exploré les intérêts de la diversification et de l'association de cultures sur le rendement et le risque (vu comme la variabilité interannuelle de la production). Les théories mobilisées permettent, à travers la modélisation d'une multitude de scénarios, de définir des stratégies de diversification pertinentes du point de vue de la gestion de ce risque. Cependant, dans la pratique, cela est à nuancer. La prise de décision concernant l'allocation spatiale des cultures et leurs séquences temporelles, plus difficile pour les cultures maraîchères à cycle court que pour les cultures arables, est encore plus complexe lorsque beaucoup de travail manuel est nécessaire et lorsque la diversité des cultures est accentuée par l'introduction de l'arbre. Le verger-maraîcher remettrait ainsi pour partie en cause l'hypothèse initiale de réduction du risque par l'introduction d'autres formes d'incertitudes. Comme nous l'avons décrit dans le Chapitre IV, l'intégration de l'arboriculture et du maraîchage conduit dans certains cas à une « simplification » de leur gestion par le groupement de certaines opérations. Cela a été également observé en maraîchage diversifié, où les agriculteurs raisonnent davantage sur des « groupes de cultures » et non sur des cultures uniques. (Mawois, 2009; Petit et al., 2010). Il est en effet difficile de raisonner et de gérer toutes les pratiques culturales sur une quarantaine d'espèces de manière individuelle, l'agriculteur procédera donc à des simplifications (Aubry et al., 2011). Cela est bien résumé dans le témoignage d'Aurélien, maraîcher : *« Je pense qu'une diversification est nécessaire sur les fermes c'est certain. Mon point de vue par contre est d'être très prudent avec l'éparpillement du travail lié à un excès de diversification. Je suis installé depuis 9 ans, j'ai commencé, comme beaucoup, avec 70 à 100 variétés différentes. J'ai passé des années à disperser de l'énergie à tout faire. Aujourd'hui je suis à 20 variétés sur toute l'année. Je m'arrange avec des collègues pour avoir une gamme complète pour ma partie vente directe. Je suis maintenant plus efficace et j'ai l'impression de diminuer les risques, car je maîtrise et j'ai plus de temps pour soigner la culture ».*

Ainsi, la diversification, au départ conçue comme stratégie de réduction du risque, peut avoir l'effet insidieux inverse d'introduire une incertitude d'une autre nature, liée à ce qu'on

pourrait qualifier de « charge mentale », maîtrise technique ou dynamique d'apprentissage. Nous pouvons donc faire l'hypothèse qu'une diversification (qui conduit à une simplification des opérations dans le cas du maraîchage diversifié couplé à l'arboriculture) pourrait rendre les éléments du système plus **interdépendants**. L'impossibilité cognitive et logistique de mettre en place des conduites différenciées pour chacune des cultures pourrait en effet en augmenter la corrélation, en considérant l'homogénéisation des itinéraires techniques comme une source supplémentaire de risque d'échec. L'augmentation de la diversité cultivée, couplée à une uniformisation de leur conduite pourrait faire croître les probabilités d'évènements exceptionnels ou de loupés agronomiques. Ces hypothèses restent néanmoins à tester.

Il existe théoriquement un point optimal qui maximise un service donné tout en minimisant la complexité de gestion. La **Figure C-1** représente schématiquement les hypothèses que nous pouvons formuler sur la construction de ces compromis. Ce point peut être variable en fonction de contraintes organisationnelles, commerciales, agronomiques ou encore cognitives. Il est également variable dans le temps. Il s'agit donc pour l'agriculteur de choisir stratégiquement des assolements pour tendre vers un optimum maximisant les services attendus et minimisant la complexité (Ryan et al., 2018).

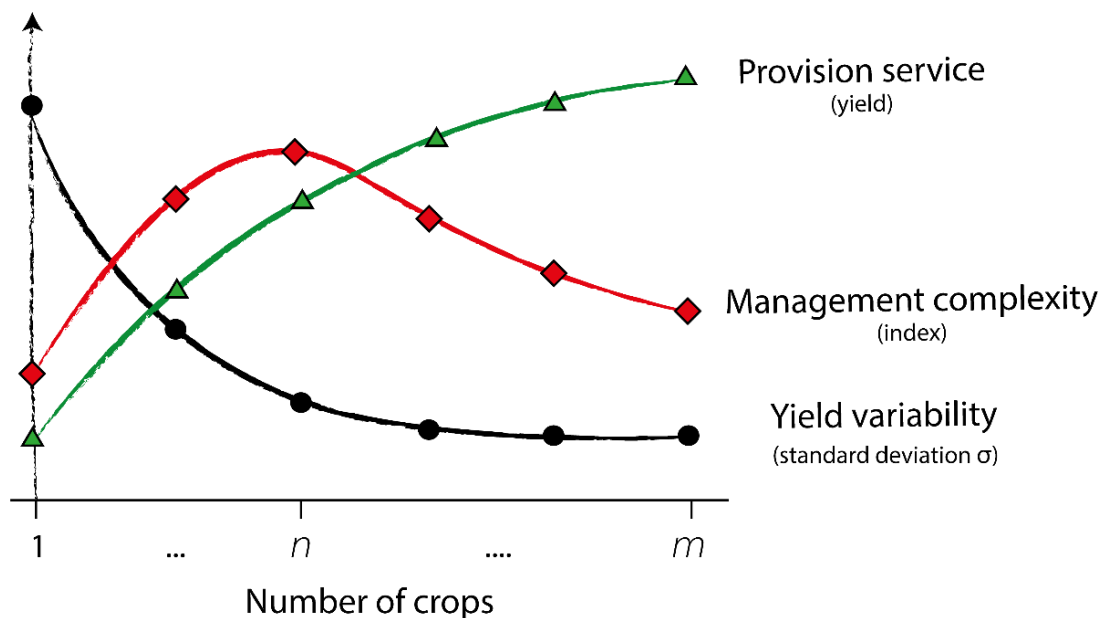


Figure C-1: Hypothèses de relations entre les services attendus (courbes verte et noire) et la complexité de la gestion (courbe rouge) en fonction du nombre d'espèces cultivées

3.2. Intégration de dimensions socio-techniques dans l'analyse d'un verger-maraîcher

3.2.1. Priorisation des arbitrages et logiques d'apprentissage

Une écrasante majorité des agriculteurs rencontrés dans le cadre de cette thèse se déclarent « *maraîchers avant tout* ». Chez les agriculteurs ayant conçu un verger-maraîcher *ex nihilo*, face à la difficulté de monter en compétences sur deux métiers simultanément, l'activité de maraîchage est (quasi) systématiquement priorisée sur l'arboriculture. La nécessité de faire des ajustements tactiques de manière quasi quotidienne en maraîchage diversifié laisse en effet peu de marge de manœuvre et d'adaptabilité pour l'acquisition d'une nouvelle compétence. Dans le cas de figure de maraîchers *expérimentés* ayant planté des arbres, nous pouvons formuler en écho l'hypothèse contraire. Leur maîtrise technique plus importante leur permettrait de dégager le temps et les ressources nécessaires à l'apprentissage de l'arboriculture tout en assurant la production maraîchère. Or, on observe de manière surprenante le même phénomène : les agriculteurs font le choix prioritaire de bien conduire leurs cultures maraîchères au détriment de la production de fruits.

Ces aspects d'élaboration et d'évolution des compétences en lien avec les priorisations entre les composantes maraîchères ou arboricoles des vergers-maraîchers dépassent les questions agronomiques abordées dans cette thèse. Néanmoins, les conséquences de la diversification d'un système agricole par l'ajout d'une production nouvelle (et donc moins bien maîtrisée) sur les performances du système à court et à long terme restent pertinentes à explorer. Cela pourrait notamment permettre d'identifier une éventuelle allocation optimale des ressources humaines et cognitives entre les deux sous-systèmes pour bénéficier de la diversification des productions tout en minimisant le risque lié à la moins bonne maîtrise de la nouvelle production. Au même titre que les simplifications de pratiques observées dans le Chapitre IV, les logiques d'apprentissage et la faisabilité « *cognitive* » de ce type de système méritent donc d'être approfondies.

3.2.2. Une externalisation possible ?

Le temps de travail nécessaire à la mise en place d'une activité de maraîchage diversifié et d'arboriculture ainsi que les difficultés d'organisation que cela occasionne sont les principales raisons citées par les agriculteurs lorsqu'il s'agit d'évoquer les contraintes des vergers-maraîchers.

Par ailleurs les choix de diversification dans les exploitations maraîchères dépendent fortement de leurs complémentarités possibles au niveau commercial (Bressoud et al., 2009). Dans le cas de la vente directe, un « trou » de production lié à la conduite de l'arbre ne serait pas accepté du point de vue des consommateurs qui attendent une quantité et une diversité de légumes tout au long de l'année (Samak, 2013).

Pour ces mêmes raisons de charge de travail ou de technicité, l'externalisation peut être un levier majeur d'amélioration des conditions de travail. On retrouve cela communément dans des filières comme l'élevage avec les naisseurs-engraisseurs (Andersson et al., 2005), l'apiculture avec l'élevage de reines (Kouchner et al., 2019) ou en polycultures-élevage avec la fabrication d'ensilage (Martin et al., 2016). En maraîchage diversifié, la production de plants est très chronophage et peut être déléguée. Certaines cultures de type tubercules nécessitant des sols aux propriétés particulières peuvent aussi passer sous le régime de l'achat/revente pour compléter une gamme de vente directe. Cette simplification du système peut avoir plusieurs objectifs : réduire le temps de travail, étaler des pics de travaux ou sous-traiter certaines tâches nécessitant une grande technicité. Dans le cas des vergers-maraîchers, l'externalisation de certaines activités maraîchères (notamment par l'achat/revente) à des moments clés de la conduite de l'arbre pour mieux gérer les conflits sur le temps de travail entre les deux ateliers pourrait ainsi être une solution à explorer. Cela pourrait en particulier permettre une gestion adaptative de l'assolement au cours du temps, pour libérer le temps nécessaire aux opérations cruciales pour l'arbre (taille de formation, éclaircissage, prophylaxie...) dans les premières années du système. Inversement, l'externalisation de la gestion de l'arbre, notamment les premières années de taille de formation peut être une option envisageable, bien que celle-ci soit moins usuelle en arboriculture fruitière.

3.2.3. La place de l'arbre dans l'exploitation

La fonction donnée à l'arbre dans l'exploitation joue un rôle prépondérant dans l'allocation du temps de travail et les dynamiques d'apprentissage décrites ci-dessus. Au-delà d'un aspect purement utilitaire et productif, la diversité apportée par l'arbre remplit aussi des aspirations esthétiques (paysagères), écologiques (refuges pour la faune) ou même nourricières (autonomie alimentaire sur la ferme) chez certains agriculteurs rencontrés. Deux profils d'agriculteurs se distinguent en fonction des services attendus de l'arbre. Si l'agriculteur n'en attend qu'un service esthétique ou écologique, cela peut conduire à une priorisation systématique

du maraîchage. S'il en attend un service de production, le conflit est plus important et l'arbitrage sera plus complexe. Compte tenu de l'attention croissante accordée aux dimensions environnementales, sociales et immatérielles dans les systèmes horticoles diversifiés (Morel and Léger, 2016) une analyse strictement basée sur la production n'est pas suffisante et des critères révisés doivent être élaborés. De manière plus large, ces observations interrogent la manière dont l'agronomie prend en compte les aspirations, les valeurs et l'éthique des agriculteurs dans l'étude de leurs systèmes (Morel, 2016). La mise en œuvre de méthodes comme les analyses multicritères DEXi (Alaphilippe et al., 2019; Vaskou, 2017), qui considèrent des dimensions économiques, mais également environnementales et sociales, est un premier pas vers l'intégration de dimensions autres qu'agronomiques, mais leurs applications sont encore rares.

4. Diversité, diversification, dé-spécialisation

4.1. Du processus de diversification à l'état de diversité

Dans de nombreuses études, il n'existe pas de distinction claire entre les concepts de diversité et de diversification, ces deux termes étant souvent utilisés de manière substituable (Hufnagel et al., 2020). Du point de vue agronomique, le premier traite de principes tels que la diversité génétique ou spécifique, le second traite de l'allongement des rotations, l'association de cultures ou l'agroforesterie. La diversification prend plus précisément le sens de « processus qui conduit à un état de plus grande diversité ». Dans cette thèse, mes travaux se sont concentrés sur des systèmes très diversifiés et intégrés. À l'instar de systèmes maraîchers alternatifs (Morel et al., 2017; Morel and Léger, 2016) ils sont construits *ex-nihilo* dans une démarche d'écologisation forte et souvent sur petite surface. Nous pouvons faire ici l'hypothèse que les avantages de la diversification en horticulture ne concernent pas uniquement ces systèmes fortement diversifiés, mais sont également d'intérêt pour des systèmes moins alternatifs orientés vers des filières longues (Boulestreau et al., 2018; Navarrete et al., 2014). Venant de systèmes spécialisés, la diversification est alors considérée comme une « **dé-spécialisation** ».

Ce processus de dé-spécialisation cristallise de nombreux enjeux : (i) contraintes fortes sur les circuits de commercialisation (Meynard et al., 2016); (ii) maîtrise technique et logiques d'apprentissage (Cf. supra) ; (iii) mobilisation et affectation des ressources de l'exploitation, plus particulièrement du travail (Dupré et al., 2017). Les approches développées dans cette thèse

permettent d'éclairer une partie de ce processus, par la caractérisation des changements de pratiques (Chap. IV), la modélisation de stratégies de diversification (Chap. I, II, III), ou l'analyse des trajectoires techniques et temporelles qu'impose la diversification (Chap. V). Cependant, ils ne permettent pas de caractériser la situation initiale, les étapes, ni le temps nécessaire pour atteindre le niveau de diversité des systèmes que nous avons étudiés. La mise en perspective des approches développées dans ma thèse avec des systèmes plus spécialisés constitue ainsi une piste de recherche à envisager.

4.2. Vers une spécialisation dans la diversité ?

Les systèmes diversifiés et associés semblent pertinents tant du point de vue de la maîtrise du risque que de l'augmentation du rendement (Chap. I, II & III), mais ils sont aussi source de complexité pour les gestionnaires de ces agroécosystèmes. Cette complexité s'exprime notamment par la réorganisation des entités de gestion propre à chaque atelier, présentée dans le Chapitre IV, et conduit à la nécessité de faire des arbitrages entre l'immédiateté qu'impose l'activité de maraîcher et la patience qu'impose l'activité d'arboriculteur (Chapitre V). L'agriculteur doit ainsi concilier la volonté de diversifier son système et une simplification des éléments unitaires de ce même système, cette dichotomie « **Diversité vs. Complexité** » est également identifiée dans d'autres travaux (Détang-Dessendre et al., 2018). La **spécialisation dans la diversité** peut notamment apparaître comme un mode d'organisation permettant de répondre à cette problématique, en considérant l'agrosystème comme une unité comprenant l'ensemble des ateliers en imbrication étroite. L'arboriculture, le maraîchage et/ou l'élevage coexistent dans une configuration agro-forestière (ou sylvo-pastorale) au sein de l'exploitation, ou chaque atelier est géré de manière spécialisée, par exemple en étant réparti entre les différents travailleurs de l'exploitation. Ainsi, les agrosystèmes bénéficient des avantages qu'apportent la diversification et l'association arbre-cultures (ou arbres-élevage), tout en minimisant les sources de complexité menant à une moindre maîtrise technique de chaque atelier : chaque travailleur n'a qu'un atelier à maîtriser.

Ce type d'organisation est à mon sens, et sur la base des différentes configurations que j'ai pu rencontrer au cours de ma thèse, celui qui offre le meilleur compromis entre les performances agronomiques et la complexification du système à gérer. Il nécessiterait néanmoins

des modifications relativement profondes dans la manière de gérer les agroécosystèmes. D'une part, car ils requièrent une organisation en collectifs d'agriculteurs comme co-gestionnaires spécialisés d'un même agrosystème en évolution. C'est le mode d'organisation que l'on peut retrouver en GAEC ou en « collectifs » (Morel, 2018). Cependant, la plupart des collectifs sont organisés soit autour d'un atelier avec une répartition des tâches, soit dans la coexistence de plusieurs ateliers interagissant entre eux par des flux de matières (Moraine et al., 2014; Ryschawy et al., 2014). Dans le cas présent, il s'agit d'**envisager la coexistence de plusieurs ateliers, leurs interactions et leurs dynamiques**. D'autre part, le partage des objectifs globaux de l'exploitation entre associés est alors un enjeu central du fonctionnement du collectif, plus encore que pour les collectifs cités précédemment et alors même que les objectifs des différents ateliers peuvent être antagonistes. Le collectif permet ainsi de faire émerger des exploitations agronomiquement « cohérentes » où se côtoient un grand nombre de productions fonctionnellement différentes, dans une logique de bouclage des cycles de nutriments (Morel, 2018). Il rend également possible une division du travail indispensable pour composer avec la complexité inhérente d'exploitations très diversifiées qui serait par ailleurs difficilement gérable. Finalement, cette approche plaide pour une dé-spécialisation des systèmes de cultures sans dé-spécialisation des compétences liées à la conduite des cultures.

5. Apports de la thèse sur le plan opérationnel

5.1. Perspectives pour le développement agricole

En termes de développement agricole, les résultats de cette thèse contribuent à une meilleure compréhension des tensions entre les différentes dimensions de la résilience des vergers-maraîchers et les difficultés de leur mise en œuvre. Ces travaux peuvent avoir plusieurs implications en termes d'outils d'aide à la conception ou d'aide à la décision. Plusieurs outils préliminairement développés peuvent servir de base pour l'élaboration d'outils d'accompagnement. Tout d'abord, sur la base des Chapitres I et II, un outil de choix de portefeuilles de cultures basé sur la réduction du risque a été développé¹². À partir d'une liste de

¹² https://paut-et-al.shinyapps.io/Marko_VM/

cultures, il permet de choisir la meilleure pondération des cultures sélectionnées pour constituer un assolement qui minimise le risque. Ensuite, ma revue de littérature sur les cultures associées a permis la construction d'un prototype d'outil d'aide à la conception d'associations de cultures, basé à la fois sur la quantification des Land Equivalent Ratio (LER), mais aussi sur la littérature dite « grise » (Cf. §5.2). Enfin le modèle dynamique que nous avons décrit dans le Chapitre V peut servir d'outil d'analyse et de prédiction *ex-ante* de l'évolution d'un assolement donné, notamment en indiquant les phases critiques de compétition sur le temps de travail.

Ces outils sont avant tout des prototypes permettant une première évaluation de leurs potentialités d'application. Pour qu'ils soient utilisables par des agriculteurs, porteurs de projets ou conseillers, ils nécessitent néanmoins des efforts de développement et d'ergonomie.

5.2. Articuler les connaissances scientifiques et empiriques : une application Web interactive pour aider la conception des systèmes maraîchers agroforestiers

La grande diversité des cultures en termes de phénologie (tubercules, légumes fruits feuilles ou racines, fruits à pépins, à noyau ou à noix, baies, etc.), le nombre d'associations possibles, les différentes interactions biologiques à prendre en compte et la nature de ces interactions rendent très difficile l'acquisition de connaissances scientifiques sur les associations de cultures en horticulture. Alors que des recherches sont en cours pour comprendre les interactions entre arbres fruitiers et légumes (Imbert et al., 2020, 2019) le nombre quasi illimité de combinaisons de cultures rend ce travail très fastidieux. Il existe par ailleurs une importante littérature « grise » sur ce sujet. Cette littérature inclut des livres de jardinage ou de vulgarisation, des sites Web ou des magazines spécialisés. Elle compile principalement des connaissances empiriques résultant de la capitalisation d'expériences localisées. L'objectif du présent travail est donc de combiner littérature scientifique et littérature grise afin de fournir un outil d'aide à la décision aux agriculteurs ou aux nouveaux praticiens de l'agroforesterie. Toutes les données de notre analyse bibliographique ont été combinées dans une plate-forme Web interactive. L'utilisateur peut alors choisir une ou plusieurs cultures et explorer l'ensemble des associations de cultures concernant celles-ci. Plusieurs formes de représentations graphiques sont disponibles : (i) lorsque les données sont disponibles dans la littérature scientifique, les valeurs des LER (Land Equivalent Ratio) sont fournies pour la culture choisie ainsi que pour toutes les autres cultures avec lesquelles elle peut être associée ; (ii) lorsque les données sont disponibles

dans la littérature « grise », ces données sont compilées, pondérées et représentées sous forme de diagramme en réseau (voir **Figure C-2** ci-dessous). L'application Web¹³ est disponible à l'adresse suivante : <https://tinyurl.com/paut-et-al-en>.

Outre l'intérêt de cette plateforme pour l'appui à la conception de systèmes maraîchers agroforestiers, celle-ci pose des questions épistémiques sur la construction des savoirs et l'articulation de connaissances au regard de leur nature. En effet, quelle valeur donner à une connaissance établie dans le cadre d'un protocole de recherche ou d'expérimentation par rapport à celle qui relève d'un adage populaire « *le poireau préfère les fraises* » ? Et quelle posture adopter lorsque ces sources d'informations sont contradictoires ? Compiler des connaissances entre expériences singulières et savoirs génériques, mettre en forme les expériences d'individus, situées dans des contextes pédoclimatiques contrastés, pour les transformer en ressources utiles pour d'autres n'est pas trivial et nécessiterait de plus amples recherches (Girard and Magda, 2018). Cet outil fournit néanmoins des ressources qui pourraient être utiles à des agents de développement dans leurs démarches d'accompagnement des agriculteurs et porteurs de projets.

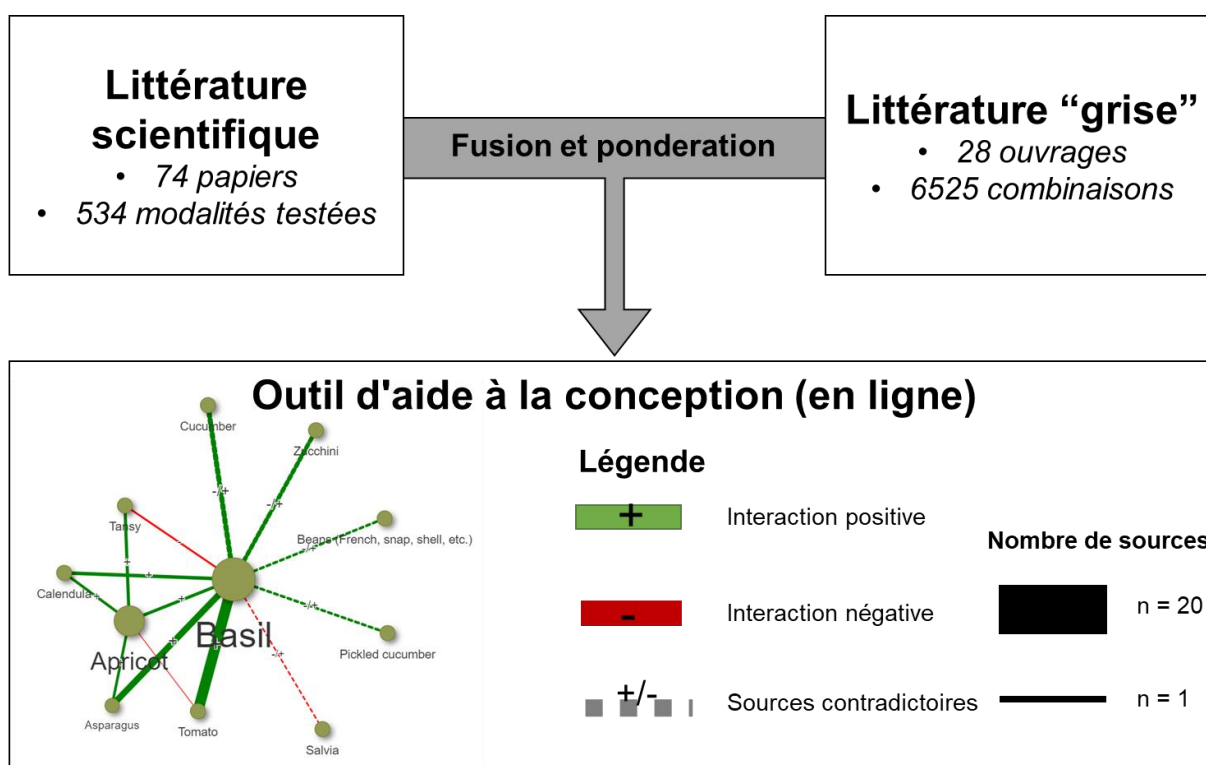


Figure C-2: Capture d'écran de l'application Web

¹³ Veuillez contacter l'auteur (raphael.paut@zaclys.net) si la plate-forme n'est plus disponible à l'adresse indiquée.

Conclusion

À travers l'articulation de démarches de recherche s'appuyant sur de la modélisation et sur des méthodes qualitatives, mon travail de thèse a permis une meilleure compréhension de la manière dont se construisent les compromis entre diversité cultivée et complexité de gestion, à travers le cas d'étude du verger-maraicher. En cela, ces systèmes horticoles très diversifiés constituent un très bon terrain d'étude du potentiel de la complémentarité des productions dans les transitions actuelles de l'agriculture vers l'agroécologie.

Les principaux résultats de ma thèse mettent en lumière que la diversification et l'association de cultures sont des leviers pertinents pour concilier des hauts niveaux de rendement et des faibles risques en horticulture. Néanmoins, mes travaux ont également montré que la mise en pratique d'une grande diversité de cultures, conduites en agroforesterie, n'est pas élémentaire. Les difficultés de mise en œuvre sont nombreuses (*i*) la prise de décision concernant la planification culturale est très complexe ; (*ii*) la gestion concomitante de systèmes très exigeants nécessite une technicité accrue ; (*iii*) la présence des arbres rend la phase de démarrage d'activité encore plus délicate qu'elle ne l'est en maraîchage diversifié (Morel, 2016). Ainsi, dans la pratique, la complexité structurelle et organisationnelle des vergers-maraichers nécessite de faire de nombreux compromis entre toutes ces dimensions.

Les différents cadres d'analyses mobilisés ou construits dans le cadre de cette thèse permettent ainsi de mieux comprendre en quoi la diversification et l'association peuvent représenter des atouts ou au contraire des freins à la mise en œuvre de systèmes agricoles écológisés. Si elles font ressortir la complexité de situations particulières et localisées, les méthodes développées dans cette thèse (théorie du portefeuille, surface équivalente assolée, modélisation dynamique, analyse des changements de pratiques par l'intégration de plusieurs ateliers) peuvent avoir des implications plus larges pour des systèmes horticoles plus spécialisés, mais également pour d'autres systèmes de production.

En outre, la récente crise sanitaire que nous traversons¹⁴ met en lumière l'importance de la diversité comme source de résilience. L'uniformisation des paysages et la perte de biodiversité (au sens large) sont souvent présentées comme des facteurs créant des conditions propices à la multiplication des maladies infectieuses et à leur globalisation. Cette crise souligne également

¹⁴ Cette thèse s'achève dans un contexte de pandémie mondiale de covid-19, maladie infectieuse virale causée par la souche de coronavirus SARS-CoV-2

l'importance de la relocalisation de nos systèmes agri-alimentaires pour une plus grande sécurité alimentaire. Ce travail de thèse suggère que les vergers-maraichers peuvent ainsi représenter des zones *cibles* où cette sécurité peut se construire. Pour relever le double défi productif et environnemental auquel est confrontée l'agriculture aujourd'hui, il appartient alors à l'ensemble des acteurs concernés (politiques publiques, acteurs économiques, recherche et développement, mais également consommateurs) de faire émerger les conditions pour que l'adoption de ce type de système puisse continuer à se développer.

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Annexe A. L'approche portefeuille, ou comment ne pas mettre tous ses légumes dans le même panier...

1. Introduction et justification de la mobilisation de la théorie du portefeuille

La Théorie Moderne du Portefeuille (« **MPT** » en anglais) trouve ses racines dans l'économie, où les gestionnaires de placements financiers se trouvaient dans des situations d'incertitude quant aux choix parmi un ensemble d'actifs dont les taux de rentabilité varient. **Markowitz (1952)** fût le premier à démontrer que les investisseurs pouvaient atténuer leur risque en détenant une variété d'actifs dont les rendements ne sont pas parfaitement corrélés. Sur cette base, il a proposé des variantes du modèle de sélection de portefeuilles afin de choisir systématiquement les combinaisons d'actifs qui produiraient le rendement maximal avec le risque le plus faible possible.

Par la suite, Van Noordwijk et al. (1994) et surtout Figge (2004) ont posé les premières pierres du pont conceptuel entre la théorie du portefeuille et son application à des problématiques d'ordre biologique. Dans les années suivantes, le modèle de sélection de portefeuilles a été proposé et illustré comme un outil de gestion des ressources naturelles permettant d'obtenir le rendement le plus élevé possible (en termes de services écosystémiques) avec un risque minimal. La MPT a été mobilisée comme outil de gestion d'un large éventail de services écosystémiques : (i) la conservation de la biodiversité (Hoekstra, 2012; Koellner, T., Schmitz, 2006) ; (ii) la pêche (DuFour et al., 2015; Halpern et al., 2011; Schindler et al., 2010) ; (iii) la foresterie (Crowe and Parker, 2008; Knoke, 2008; Knoke et al., 2005); (iv) la gestion des ressources eau (Aerts et al., 2015; Beuhler, 2006; Paydar and Qureshi, 2012) ; (v) la surveillance des ravageurs et maladies invasives (Prattley et al., 2007; Yemshanov et al., 2014) ; (vi) et enfin, la conservation en climats incertains (Ando and Mallory, 2012; Crowe and Parker, 2008).

Les écologues ont également reconnu un effet « portefeuille » à l'œuvre dans les systèmes naturels, qui se traduit par le fait que les communautés à forte diversité ont tendance à produire des services écosystémiques de manière plus stable (Anderson et al., 2013; Balvanera et al., 2014; Schindler et al., 2010; Tilman et al., 2006). A l'instar des investisseurs, les écosystèmes semblent

bénéficier de la formation d'un ensemble diversifié « d'actifs », car les effets de la variabilité naturelle sont partiellement atténués par la diversification. L'effet « portefeuille » serait donc analogue à celui observé par Markowitz : si l'on compare la biodiversité à un patrimoine boursier, la diversification minimise la volatilité des investissements, ou dans le cas de la biodiversité, le risque d'instabilité des services écosystémiques (Tilman et al., 1998).

Ceci est lié à l'idée qu'une diversité d'espèces donnera une diversité de réponses à une même perturbation environnementale, et par conséquent lorsqu'elles sont considérées ensemble, elles créent une fonction stabilisatrice qui préserve l'intégrité d'un service écosystémique (Elmqvist et al. 2003). L'objectif d'un gestionnaire de portefeuille étant précisément de diversifier le portefeuille de manière optimale, la tâche d'un gestionnaire de biodiversité (cultivée ou non), par analogie, serait de construire un portefeuille avec un rapport risque-rendement optimisé en fonction du mélange d'espèces. On retrouve aussi ces arguments dans les travaux sur la conservation de la biodiversité, qui sont souvent fondés sur la diversité des services écosystémiques, mais il n'est pas clair si peu (Ridder, 2008) ou beaucoup (Duffy, 2009) d'espèces sont nécessaires pour maintenir les services écosystémiques (Isbell et al., 2011).

2. Application de la théorie du portefeuille en agriculture

2.1. Le couple rendement – risque

La théorie du portefeuille de Markowitz prend en compte deux variables : **le rendement et le risque (la variabilité du rendement)**. Elle permet donc à un investisseur de déterminer le meilleur rendement espéré pour un certain niveau de risque, sur un ensemble d'actifs déterminé, ou inversement, le plus faible niveau de risque possible pour un rendement donné. Le rendement d'un portefeuille $E(R_p)$ est une combinaison linéaire de celui des actifs qui le composent, pondérés par leur poids w_i dans le portefeuille :

$$E(R_p) = \sum_i w_i E(R_i) \tag{1}$$

où :

w_i = poids relatif de la culture i (c'est à dire la proportion de la culture i dans l'assolement)

$E(R_i)$ = rendement espéré de la culture i

$\sum_i w_i = 1$

La **variance du portefeuille** σ_P est une fonction de la corrélation entre les cultures qui le composent. Contrairement au rendement cette fonction n'est pas linéaire :

$$\sigma_P = \sqrt{\sum_i \sum_j w_i w_j \sigma_{ij}}$$

où σ_{ij} est la covariance des cultures i et j

Chaque culture présente un degré d'incertitude qui lui est propre et qui dépend de nombreux facteurs tels que (i) les facteurs biotiques (fertilité du sol, ravageurs, auxiliaires...), (ii) les facteurs abiotiques (aléas climatiques, précipitations...), (iii) la maîtrise technique de la culture, (iv) la volatilité des prix agricoles.

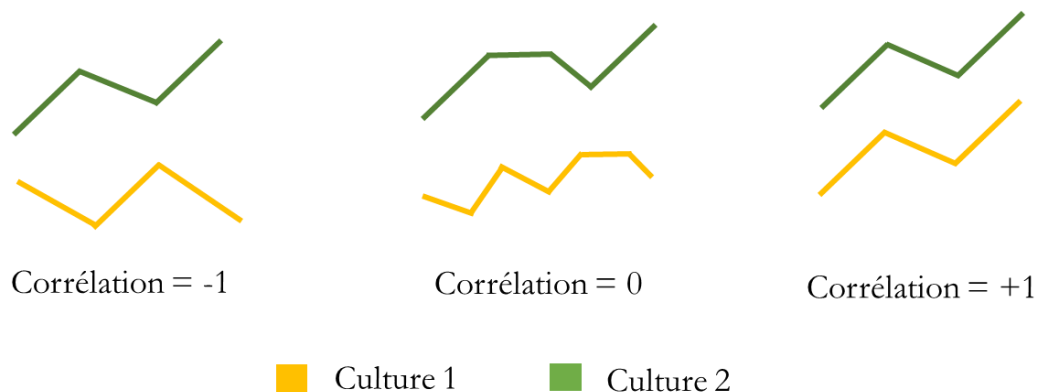


Fig. 1. Représentation schématique des différences de comportement entre deux cultures. À gauche, elles sont parfaitement négativement corrélées, à droite elles sont parfaitement positivement corrélées.

2.2 Modèle de choix d'assolement

En théorie, si l'on choisit deux cultures afin de constituer un portefeuille, une multitude de portefeuilles différents s'offrent à nous, par le simple fait de faire varier la part de chaque culture dans notre portefeuille. D'après les formules développées ci-dessus, on comprend que lorsque le coefficient de corrélation ρ entre deux cultures est inférieur à 1, la variance du portefeuille est plus petite que la simple somme pondérée des variances individuelles. Par exemple, dans la **Figure 2**, la combinaison rendement/ risque générée lorsque nous passons de A (100 % de la culture A) à B (100 % de la culture B) peut prendre plusieurs formes. La courbe **c.** représente les combinaisons rendement/ risque du portefeuille si les deux cultures sont parfaitement corrélées ($\rho = +1$). La courbe **a.** représente la situation extrême opposée, lorsque les deux cultures sont parfaitement négativement corrélées ($\rho = -1$). Enfin la courbe **b.** représente

une situation intermédiaire ($\rho = 0$). On observe que plus la valeur du coefficient de corrélation entre les rendements des 2 cultures est faible, plus le risque global du portefeuille est faible.

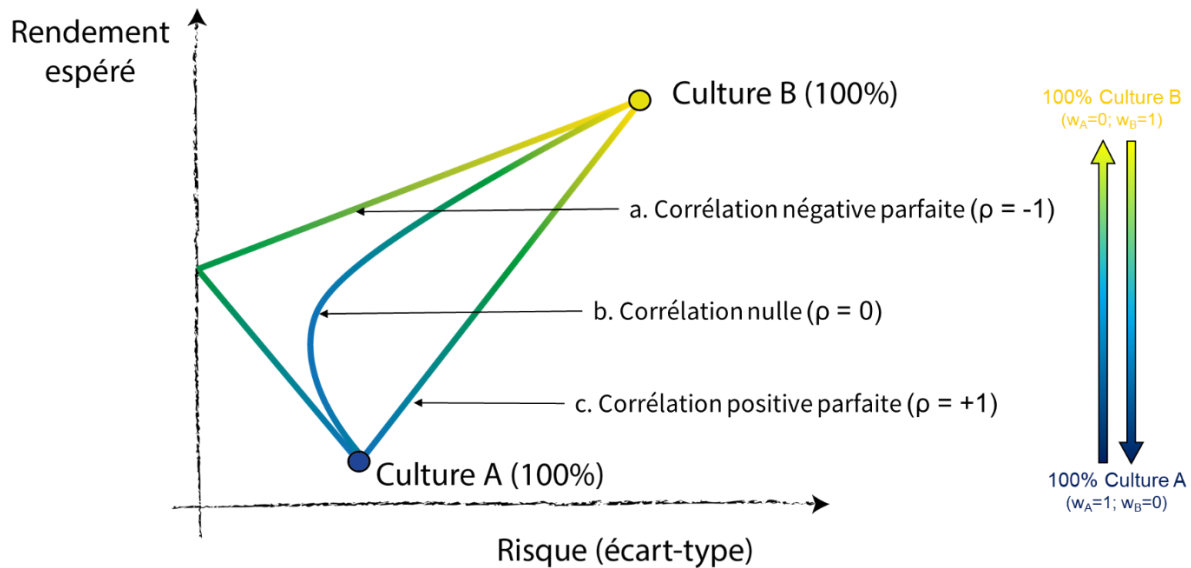


Fig. 2. Combinaisons rendement-risque pour des portefeuilles composés de la culture A et de la culture B.

2.3. Les risques systématiques et non systématiques

L'effet de la diversification sur le risque peut être renforcé par l'intégration d'un nombre croissant de cultures dans le portefeuille. La **Figure 3** montre l'évolution typique du risque en fonction du nombre de cultures dans le portefeuille. Nous pouvons observer que la diversification des cultures ne permet pas de réduire tout le risque. Il existe en effet deux types de risque. Le **risque systématique** (segment BC) touche toutes cultures de la même manière et ne peut être éliminé par une stratégie de diversification. Par exemple, l'effet d'un épisode de sécheresse sur une culture sera corrélé avec l'effet de cette même sécheresse sur une autre culture. À l'inverse, le **risque non-systématique** (ou **diversifiable**) représente le risque qui peut être éliminé par une stratégie de diversification. Cette source de risque ne touche que certaines cultures, cela peut être par exemple un bioagresseur ou une maladie spécifique. Plus le nombre de cultures dans le portefeuille augmente, plus le risque non systématique, représenté par AB, est faible. Le segment BC représentant le risque systématique qui ne peut être réduit via le processus de diversification. Le risque total AC est donc une asymptote qui a pour limite la ligne de risque systématique.

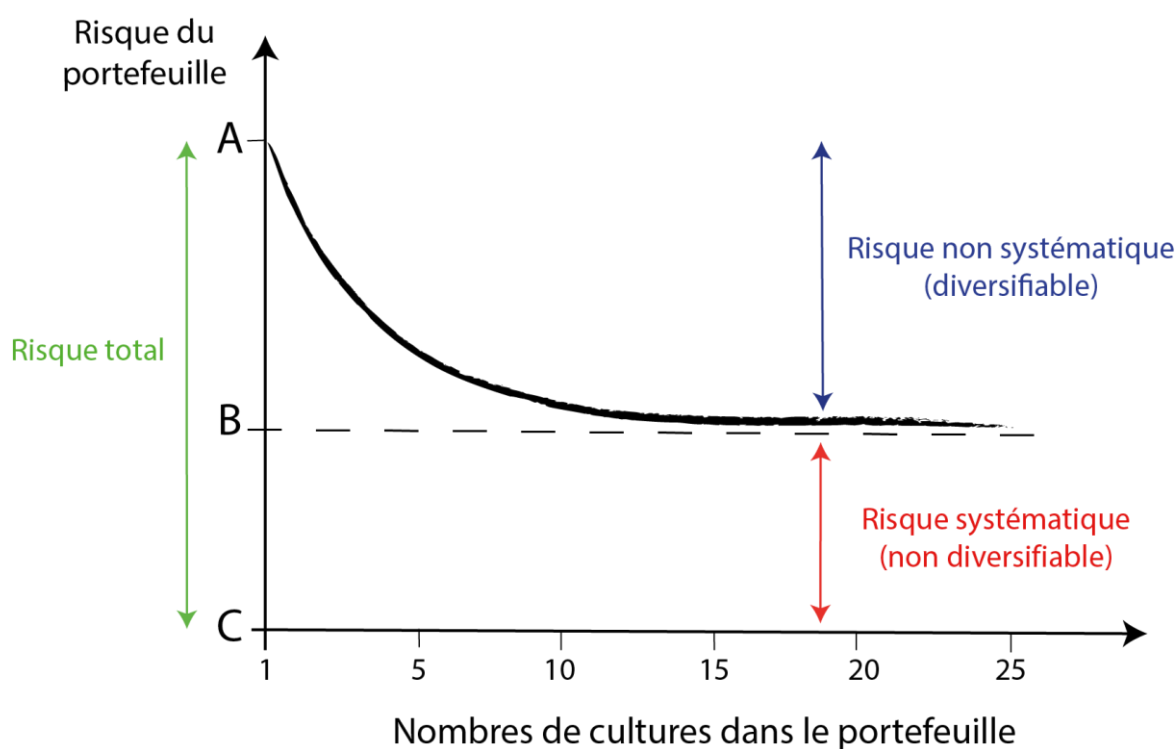


Fig. 3. Evolution du risque en fonction du nombre de culture dans le portefeuille. Plus un portefeuille est diversifié, plus le risque non systématique est réduit. Le risque systématique reste lui inchangé.

2.4. La frontière d'efficience

Dans le cas d'un portefeuille de cultures très diversifié, on peut obtenir la **Figure 4**. Dans cet exemple, l'extrémité (E) représente la solution qui permet d'obtenir le meilleur rendement, l'autre extrémité (A) désigne le portefeuille le moins risqué. Le portefeuille (D) est dit « sous-optimal », car pour le même niveau de risque, le portefeuille (C) offre un rendement supérieur. De la même manière, à niveau de rendement équivalent, le portefeuille (B) offre un risque plus faible. Ainsi, la frontière [AE] est appelée **Frontière Efficiente** : chaque solution se trouvant sur cette frontière « domine » les autres. On peut également la définir comme l'ensemble des options pour lesquelles on ne peut pas améliorer une dimension sans compromettre l'autre.

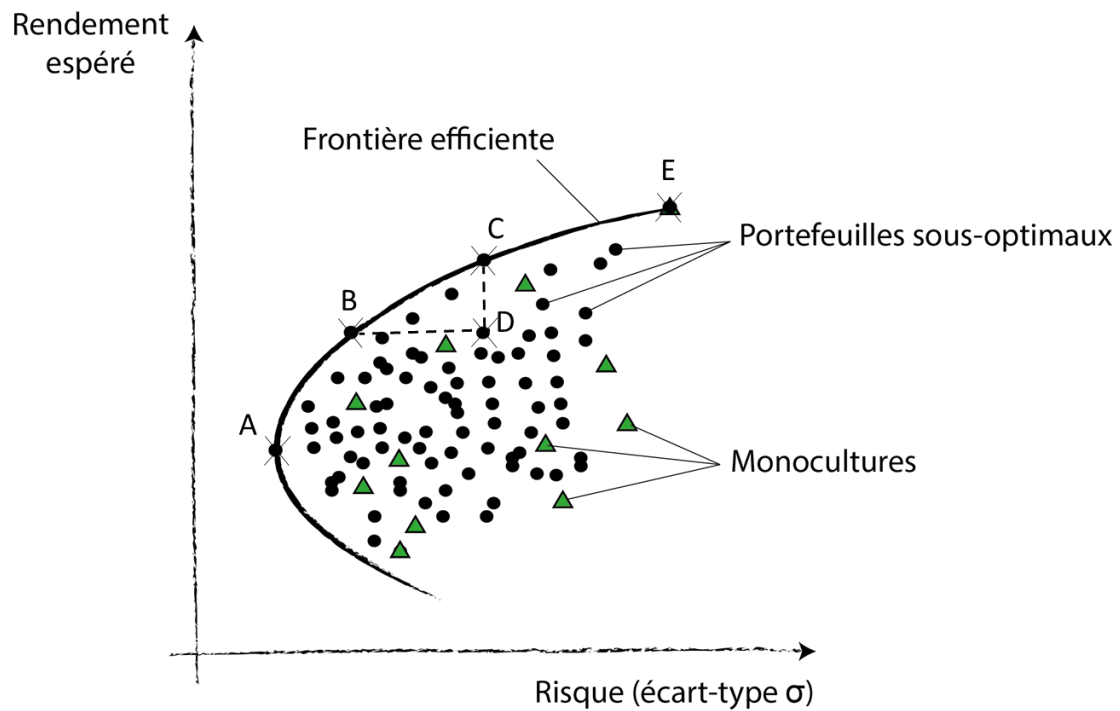


Fig. 4. Combinaisons rendement- risque pour un portefeuille comprenant de nombreuses cultures

2.5. Diversification par classe

Une bonne stratégie de diversification ne passe pas forcément par l'ajout de plusieurs espèces possédant les mêmes caractéristiques, mais plutôt d'un nombre restreint d'espèces possédant des caractéristiques bien différentes (Fraser et al., 2005). Ainsi, selon Figge (2004) on peut donc classer les espèces en fonction de leur « traits fonctionnels ». Les éléments du portefeuille sont supposés corrélés si les mêmes conditions affectent chaque élément de manière similaire. Par exemple, le chou, le brocoli et le navet sont des cultures de la même famille botanique (Brassicacées), ils sont vulnérables à des bioagresseurs communs et ont des exigences pédoclimatiques semblables. Ces cultures peuvent être considérées comme ayant une **covariance élevée** et n'offrent à priori pas un degré assez fort de diversification pour réduire le risque. On peut s'attendre à ce que des cultures présentant des traits fonctionnels différentes aient une plus faible covariance avec ces cultures et seraient donc plus adaptées pour une diversification.

Annexe B. Annexes du Chapitre I

Appendix B.1. List of crops and classifications used in the present study

Crops	Scientific name	Type (Pennington et al. 2009)	Botanical family	CTIFL classification (functional traits)
Almonds	<i>Prunus dulcis</i>	Fruit	Rosaceae	Nut fruits
Apple	<i>Malus pumila</i>	Fruit	Rosaceae	Pome fruits
Apricot	<i>Prunus armeniaca</i>	Fruit	Rosaceae	Stone fruits
Artichoke	<i>Cynara cardunculus</i>	Vegetable	Asteraceae	Leaf vegetables
Asparagus	<i>Asparagus officinalis</i>	Vegetable	Asparagaceae	Leaf vegetables
Aubergine	<i>Solanum melongena</i> L.	Vegetable	Solanaceae	Fruiting vegetables
Beetroot	<i>Beta vulgaris</i>	Vegetable	Amaranthaceae	Root vegetables
Blackcurrant	<i>Ribes nigrum</i>	Berries	Grossulariaceae	Berries
Broccoli	<i>Brassica oleracea</i> var. <i>italica</i>	Vegetable	Brassicaceae	Leaf vegetables
Brussels sprouts	<i>Brassica oleracea</i> var. <i>gemmifera</i>	Vegetable	Brassicaceae	Leaf vegetables
Carrot	<i>Daucus carota</i> subsp. <i>Sativus</i>	Vegetable	Apiaceae	Root vegetables
Cauliflower	<i>Brassica oleracea</i> var. <i>botrytis</i>	Vegetable	Brassicaceae	Leaf vegetables
Celeriac (Stor.)	<i>Apium graveolens</i> var. <i>rapaceum</i>	Vegetable	Apiaceae	Root vegetables
Celery	<i>Apium graveolens</i>	Vegetable	Apiaceae	Leaf vegetables
Chard	<i>Beta vulgaris</i> L. subsp. <i>Vulgaris</i>	Vegetable	Amaranthaceae	Root vegetables
Cherry	<i>Prunus avium</i>	Fruit	Rosaceae	Stone fruits
Cucumber	<i>Cucumis sativus</i>	Vegetable	Cucurbitaceae	Fruiting vegetables
Fig	<i>Ficus carica</i>	Fruit	Moraceae	Miscellaneous
French bean	<i>Phaseolus vulgaris</i>	Vegetable	Fabaceae	Leguminous vegetables
Garlic	<i>Allium sativum</i>	Vegetable	Alliaceae	Root vegetables
Gooseberry	<i>Ribes uva-crispa</i>	Berries	Grossulariaceae	Berries
Kiwi	<i>Actinidia deliciosa</i>	Fruit	Actinidiaceae	Berries
Lamb lettuce	<i>Valerianella locusta</i>	Vegetable	Caprifoliaceae	Leaf vegetables
Leek	<i>Allium ampeloprasum</i>	Vegetable	Alliaceae	Leaf vegetables
Lettuce	<i>Lactuca sativa</i>	Vegetable	Asteraceae	Leaf vegetables
Melon	<i>Cucumis melo</i>	Vegetable	Cucurbitaceae	Fruiting vegetables
Nectarines	<i>Prunus persica nucipersica</i>	Fruit	Rosaceae	Stone fruits
Onion	<i>Allium cepa</i> L.	Vegetable	Alliaceae	Root vegetables
Pea	<i>Pisum sativum</i>	Vegetable	Fabaceae	Leguminous vegetables
Peach	<i>Prunus persica</i>	Fruit	Rosaceae	Stone fruits

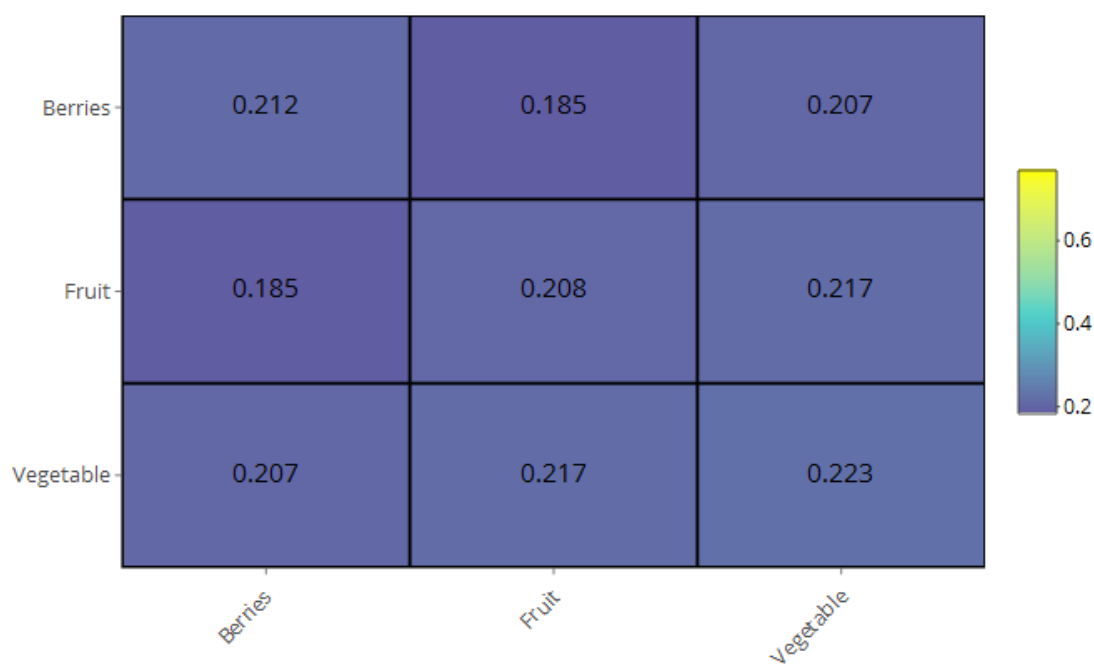
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Pear	<i>Pyrus communis</i>	Fruit	Rosaceae	Pome fruits
Plum	<i>Prunus domestica</i>	Fruit	Rosaceae	Stone fruits
Radish	<i>Raphanus sativus</i>	Vegetable	Brassicaceae	Root vegetables
Raspberry	<i>Rubus idaeus</i>	Berries	Rosaceae	Berries
Shallot	<i>Allium cepa</i> var. <i>aggregatum</i>	Vegetable	Alliaceae	Root vegetables
Spinach	<i>Spinacia oleracea</i>	Vegetable	Amaranthaceae	Leaf vegetables
Squash	<i>Cucurbita moschata</i>	Vegetable	Cucurbitaceae	Fruiting vegetables
Strawberry	<i>Fragaria</i> × <i>ananassa</i>	Vegetable	Rosaceae	Fruiting vegetables
Sweet corn	<i>Zea mays</i>	Vegetable	Poaceae	Fruiting vegetables
Sweet pepper	<i>Capsicum annuum</i> L.	Vegetable	Solanaceae	Fruiting vegetables
Tomato	<i>Solanum lycopersicum</i>	Vegetable	Solanaceae	Fruiting vegetables
Turnip	<i>Brassica rapa</i> subsp. <i>Rapa</i>	Vegetable	Brassicaceae	Root vegetables
Watermelon	<i>Citrullus lanatus</i> var. <i>lanatus</i>	Vegetable	Cucurbitaceae	Fruiting vegetables
Zucchini	<i>Cucurbita pepo</i>	Vegetable	Cucurbitaceae	Fruiting vegetables

Appendix B.2. Matrix of optimal diversification strategies. The figure at the intersection of rows and columns represents the proportion of crops that maximizes the risk reduction (e.g. for a portfolio composed of Apple and Almonds, the maximum risk reduction would be achieved for a proportion of 78% of Almonds and 22% of Apple).

Crop	Almonds	Apple	Apricot	Artichoke	Asparagus	Aubergine	Beetroot	Blackcurrant	Broccoli	Brussels sprouts	Carrot	Cauliflower	Celeriac (Stor.)	Celery	Chard	Cherry	Cucumber	Fig	French bean	Garlic	Gooseberry	Kiwi	Lamb lettuce	Leek	Lettuce	Melon	Nectarines	Onion	Pea	Peach	Pear	Plum	Radish	Raspberry	Shallot	Spinach	Squash	Strawberry	Sweet corn	Sweet pepper	Tomato	Turnip	Watermelon	Zucchini	
Almonds		22	41	18	46	7	24	55	38	21	16	29	12	17	18	43	3	37	60	49	50	31	31	25	25	31	17	16	55	25	19	28	20	44	31	39	15	37	38	14	2	26	17	10	
Apple	78		48	42	74	21	53	81	68	48	39	59	31	42	43	73	11	67	84	77	77	61	60	53	54	61	41	40	81	53	45	58	47	73	61	69	37	67	68	36	8	55	42	29	
Apricot	79	52		45	76	22	55	82	70	51	42	61	33	44	45	75	12	69	85	79	79	63	63	55	56	64	44	43	82	56	48	60	49	75	63	71	39	69	70	38	8	58	44	31	
Artichoke	82	58	55		80	26	60	85	74	56	47	66	38	49	50	78	14	74	88	82	82	68	67	60	61	68	49	48	85	61	53	65	54	79	68	75	44	73	74	43	10	62	49	35	
Asparagus	54	26	24	20		8	28	59	42	24	18	33	13	20	20	48	4	41	64	53	54	35	34	28	29	35	19	19	59	28	22	32	23	49	35	44	17	41	42	16	3	30	20	12	
Aubergine	93	79	78	74	92		81	94	89	78	71	85	64	73	74	91	32	89	95	93	86	86	81	82	86	73	72	94	81	76	84	77	91	86	90	69	89	89	68	24	83	74	61		
Beetroot	76	47	45	40	72	19		79	66	46	37	56	29	39	40	70	10	65	82	75	76	58	58	50	51	59	39	38	79	51	43	55	44	71	59	67	35	64	66	33	7	52	39	27	
Blackcurrant	45	19	18	15	41	6	21		34	18	13	25	10	15	15	39	3	33	56	44	45	27	27	21	22	28	14	14	50	21	17	25	17	40	27	35	12	32	34	12	2	23	15	9	
Broccoli	62	32	30	26	58	11	34	66		31	23	40	18	25	26	55	6	49	71	61	62	42	42	35	35	43	25	24	66	35	28	39	29	56	42	51	22	48	50	21	4	37	25	16	
Brussels sprouts	79	52	49	44	76	22	54	82	69		41	60	32	43	44	74	12	69	85	78	79	62	62	54	55	63	43	42	82	55	47	59	48	75	62	71	38	68	69	37	8	57	43	30	
Carrot	84	61	58	53	82	29	63	87	77	59		69	41	52	54	80	16	76	89	84	84	70	70	64	64	71	52	51	87	64	56	68	57	81	71	78	48	76	77	46	11	66	53	39	
Cauliflower	71	41	39	34	67	15	44	75	60	40	31		24	33	35	65	8	59	79	70	71	52	52	44	45	53	33	32	75	44	37	49	38	66	52	61	29	58	60	28	5	46	34	22	
Celeriac (Stor.)	88	69	67	62	87	36	71	90	82	68	59	76		61	62	85	21	82	92	88	88	77	77	71	72	78	61	60	90	72	65	75	66	86	78	83	57	82	82	55	15	73	61	47	
Celery	83	58	56	51	80	27	61	85	75	57	48	67	39		51	79	15	74	88	82	83	68	68	61	62	69	50	49	85	62	54	66	55	80	69	76	45	74	75	44	10	63	50	36	
Chard	82	57	55	50	80	26	60	85	74	56	46	65	38	49		78	14	73	87	82	82	67	67	60	61	68	48	47	85	60	52	64	54	79	68	75	44	73	74	43	10	62	49	35	
Cherry	57	27	25	22	52	9	30	61	45	26	35	15	21	22			4	44	66	56	57	37	37	30	31	37	21	20	61	30	24	34	25	51	37	46	18	43	45	17	3	32	21	13	
Cucumber	97	89	88	86	96	68	90	97	94	88	84	92	79	85	86	96		94	98	96	97	93	93	90	90	93	85	85	97	90	87	92	88	96	93	95	83	94	94	82	40	91	85	77	
Fig	63	33	31	26	59	11	35	67	51	31	24	41	18	26	27	56	6		72	62	63	43	43	35	36	44	26	25	67	36	29	40	30	57	43	52	22	49	51	21	4	37	26	16	
French bean	40	16	15	12	36	5	18	44	29	15	11	21	8	12	13	34	2	28			39	40	23	23	18	18	23	12	11	44	18	14	21	14	35	23	30	10	28	29	10	2	19	12	7
Garlic	51	23	21	18	47	7	25	56	39	22	16	30	12	18	18	44	4	38	61		51	32	32	25	26	32	18	17	56	25	20	29	21	45	32	40	15	38	39	14	2	27	18	11	
Gooseberry	50	23	21	18	46	7	24	55	38	21	16	29	12	17	18	43	3	37	60	49		31	31	25	25	32	17	16	55	25	19	28	20	44	31	40	15	37	38	14	2	26	17	11	
Kiwi	69	39	37	32	65	14	42	73	58	38	30	48	23	32	33	63	7	57	77	68	69		50	42	43	51	31	31	73	43	35	47	36	64	51	59	28	57	58	27	5	44	32	21	
Lamb lettuce	69	40	37	33	66	14	42	73	58	38	30	48	23	32	33	63	7	57	77	68	69	50		42	43	51	32	31	73	43	35	47	36	64	51	60	28	57	58	27	5	45	32	21	
Leek	75	47	45	40	72	19	50	79	65	46	36	56	29	39	40	70	10	65	82	75	75	58	58		51	58	39	38	79	50	42	55	44	71	58	67	34	64	65	33	7	52	39	26	
Lettuce	75	46	44	39	71	18	49	78	65	45	36	55	28	38	39	69	10	64	82	74	75	57	57	49		58	38	37	78	49	41	54	43	70	57	66	34	63	65	32	7	51	38	26	
Melon	69	39	36	32	65	14	41	72	57	37	29	47	22	31	32	63	7	56	77	68	68	49	49	42	42		31	30	72	42	34	46	36	64	50	59	27	56	57	26	5	44	31	20	
Nectarines	83	59	56	51	81	27	61	86	75	57	48	67	39	50	52	79	15	74	88	82	83	69	68	61	62	69		49	86	62	54	66	55	80	69	76	45	74	75	44	10	63	50	36	
Onion	84	60	57	52	81	28	62	86	76	58	49	68	40	51	53	80	15	75	89	83	84	69	69	62	63	70	51		86	63	55	67	56	80	70	77	46	75	76	45	11	64	51	37	
Pea	45	19	18	15	41	6	21	50	34	18	13	25	10	15	15	39	3	33	56	44	45	27	27	21	22	28	14	14		21	17	25	17	40	27	35	12	32	34	12	2	23	15	9	
Peach	75	47	44	39	72	19	49	79	65	45	36	56	28	38	40	70	10	64	82	75	75	57	57	50	51	58	38	37	79		42	54	43	71	58	66	34	64	65	33	7	52	39	26	
Pear	81	55	52	47	78	24	57	83	72	53	44	63	35	46	48	76	13	71	86	80	81	65	65	58	59	66	46	45	83	58		62	51	77	66	73	42	71	72	40	9	60	47	33	
Plum	72	42	40	35	68	16	45	75	61	41	32	51	25	34	36	66	8	60	79	71	72	53	53	45	46	54	34	33	75	46	38		39	67	54	62	30	60	61	29	6	47	35	23	
Radish	80	53	51	46	77	23	56	83	71	52	43	62	34	45	46	75	12	70	86	79	80	64	64	56	57	64	45	44	83	57	49	61		76	64	72	40	70	71	39	9	58	45	32	
Raspberry	56	27	25	21	51	9	29	60	44	25	19	34	14	20	21	49	4	43	65	55	56	36	36	29	30	36	20	20	60	29	23	33	24		36	45	18	42	43	17	3	31	21	13	
Shallot	69	39	37	32	65	14	41	73	58	38	29	48	22	31	32	63	7	57	77	68	69	49	49	42	43	50	31	30	70	42	34	46	36	64		59	27	56	58	26	5	44	31	21	
Spinach	61	31	29	25	56	10	33	65	49	29	22	39	17	24	25	54	5	48	70	60	60	41	40	33	34	41	24	23	65	34	27	38	28	55	41		21	47	49	20	4	35	24	15	
Squash	85	63	61	56	83	31	65	88	78	62	52	71	43	55	56	82	17	78	90	85	85	72	72	66	66	73	55	54	88	66	58	70	60	82	73	79		77	78	49	12	68	55	41	
Strawberry	63	33	31	27	59	11	36	68	52	32	24	42	18	26	27	57	6	51	72	62</																									

Appendix B.3. a) Matrix of diversification benefits according to Pennington's functional classifications. The figure at the intersection of rows and columns represents the average diversification benefit between the corresponding classifications (*e.g. the average diversification benefit for portfolios composed of Berries and Vegetables is 0.207*).

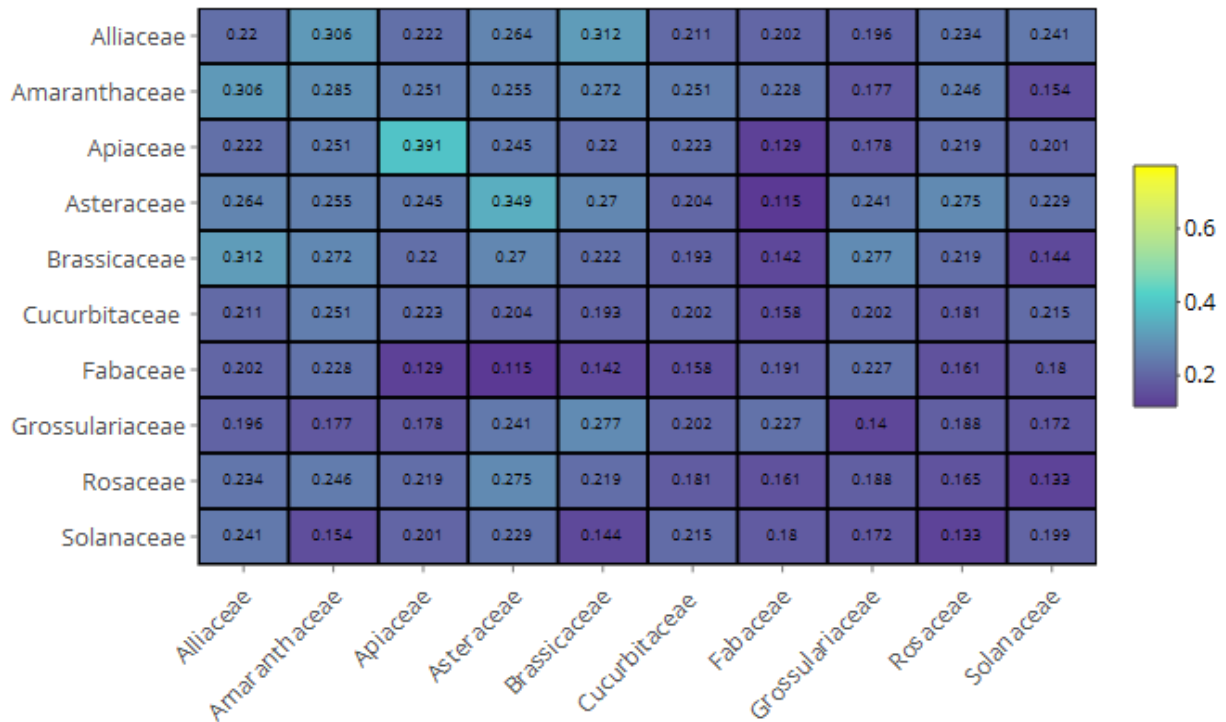


Appendix B.3. b) Matrix of diversification benefits according to CTIFL's functional classifications. The figure at the intersection of rows and columns represents the average diversification benefit between the corresponding classifications (*e.g. the average diversification benefit for portfolios composed of Root vegetables and Berries is 0.199*). Classifications that included only one crop were removed because they did not represent a group.



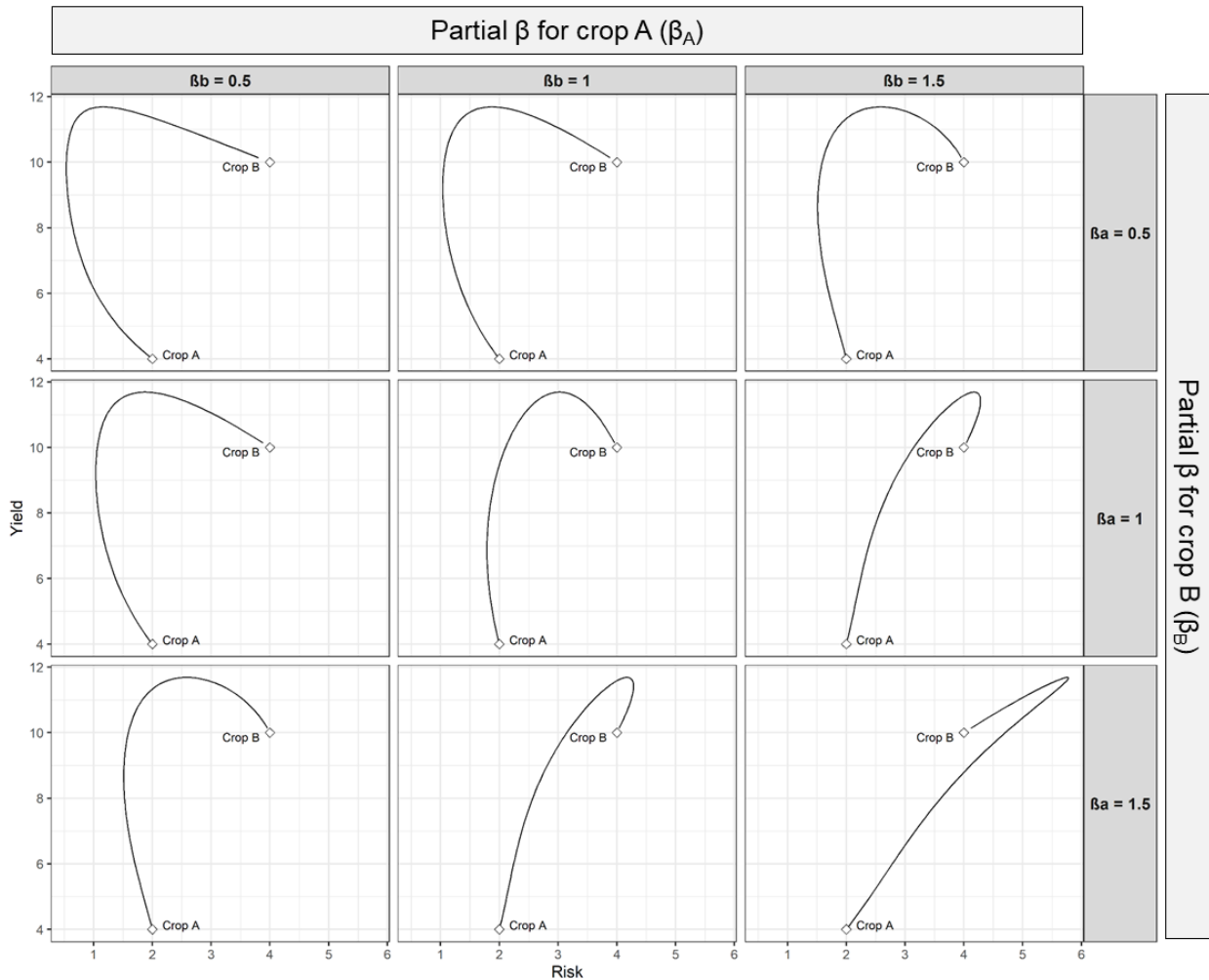
Appendix B.3. c) Matrix of diversification benefits according to botanical classifications.

The figure at the intersection of rows and columns represents the average diversification benefit between the corresponding classifications (*e.g. the average diversification benefit for portfolios composed of Actinidiaceae and Alliaceae is 0.167*). Classifications that included only one crop were removed because they did not represent a group.



Annexe C. Annexes du Chapitre III

Appendix C.1. Exploration of different values of crop partial coefficients (β_A and β_B) on yield variability



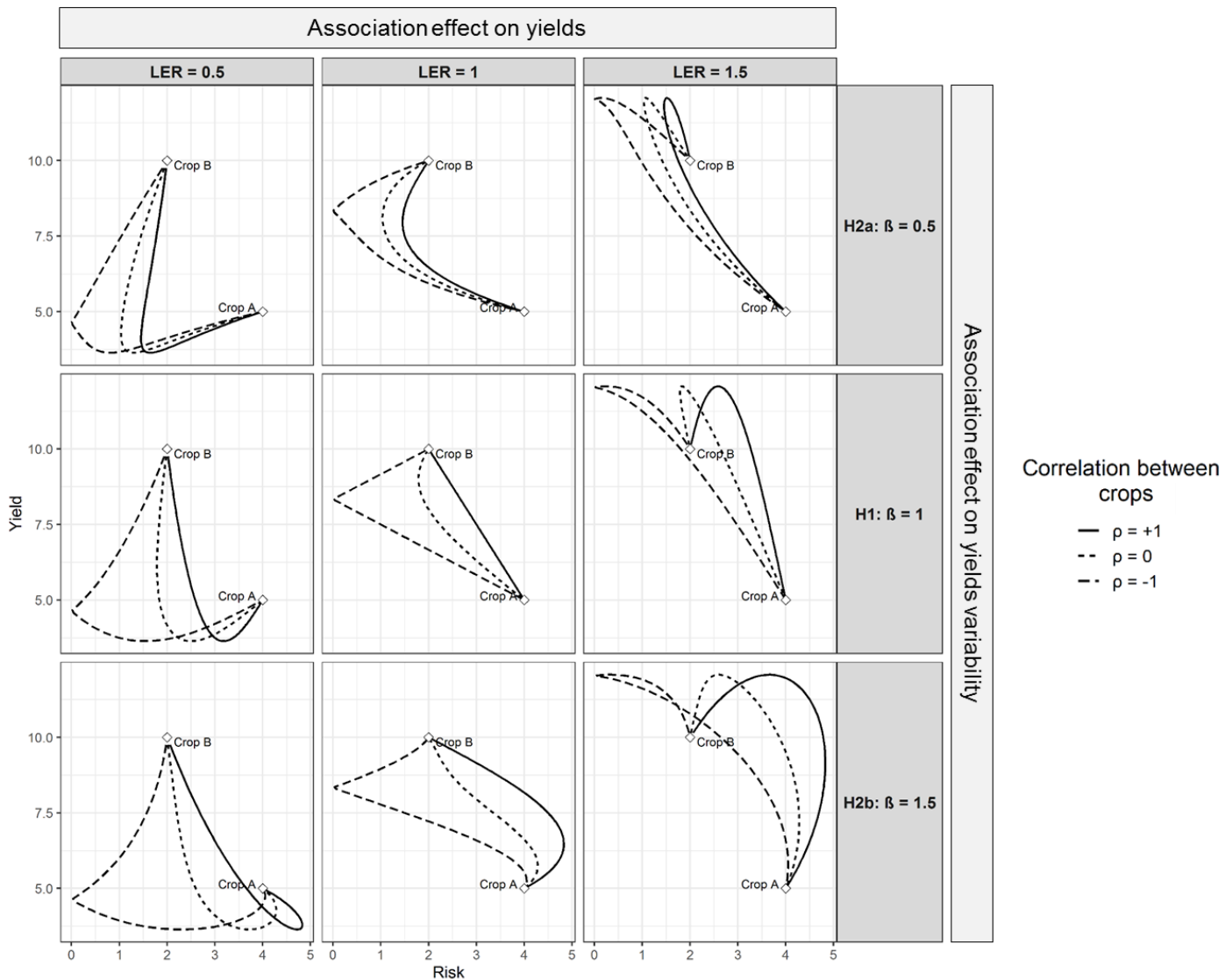
This figure shows, at constant LER = 1.5 and $\rho = 0$, how the variation of crop partial coefficients (β_A and β_B) influence the trade-offs between yield and risk.

Appendix C.2. List of published articles reporting intercropping experiments in horticulture used in our analysis.

Article no.	Reference	Country	Period	Crops
1	Abou-Hussein et al., 2005	Egypt	2003-2004	Bean , Lettuce, Onion
2	Adeniyi, 2011	Nigeria	2007-2008	Tomato , Okra, Cowpea
3	Ahmed et al., 2016	Bangladesh	2014-2015	Maize , Chili
4	Al-Dalain, 2009	Jordan	2006-2008	Potato , Maize
5	Anjum et al., 2015	Pakistan	2010–2012	Pea , Garlic, Pea , Turnip, Cauliflower
6	Badawy and Shalaby, 2015	Egypt	2012-2014	Beetroot , Onion, Garlic
7	Bai et al., 2016	China	2012-2013	Apricot , Peanut, Millet, Sweet_potato
8	Baumann et al., 2001	Switzerland	1995	Leek , Celery
9	Bavec et al., 2012	Slovenia	2007-2009	Cabbage , Lettuce, Bean, Beetroot, Tomato, Leek, Celery
10	Begum et al., 2015	Bangladesh	2014-2015	Chili , Radish, Carrot, Onion, Garlic
11	Bhat et al., 2014	India	2008-2009	Apple , Maize, Pea, Strawberry, Cabbage, Red_clover, Bean, Oats
12	Blazewicz-Wozniak and Wach, 2011	Poland	2004-2006	Carrot , Parsley, Onion, Marigold, Root_parsley , Marigold
13	Bomford, 2004	USA	2000	Tomato , White_clover, Bean, Brussels_sprout, Basil
14	Bomford, 2009	USA	2001-2002	Tomato , Basil, Brussels_sprout
15	Brintha and Seran, 2012	Bangladesh	2010	Chili , Onion
16	Cecílio Filho et al., 2007	Brazil	2004	Lettuce , Radish
17	Cecílio Filho et al., 2010	Brazil	2009	Tomato , Lettuce
18	Cecílio Filho et al., 2011	Brazil	2003-2004	Tomato , Lettuce
19	Chaubey, 2002	India	2000-2001	Mango , Turmeric, Colocasia, Yam
20	Choudhuri and Jana, 2015	India	2008-2009	Potato , Mustard
21	Çiftçi et al., 2006	Turkey	2001-2003	Bean , Maize
22	de Lima et al., 2010	Brazil	2006	Carrot , Rocket
23	de Lima et al., 2014	Brazil	2006	Carrot , Rocket
24	Demir and Polat, 2011	Turkey	2006-2007	Broccoli , Lettuce
25	El-Gaid et al., 2014	Egypt	2010-2012	Tomato , Bean
26	Favacho et al., 2017	Brasil	2014	Carrot , Cowpea
27	Fonseca et al., 2016	Brasil	2014	Lettuce , Marigold
28	Gao et al., 2013	China	2011-2012	Apple , Soybean, Peanut
29	Gawade and Path, 2004	India	1995-1998	Cauliflower , Radish, Coriander, Spinach, Fenugreek, Aneth
30	Ghanbari et al., 2010	Iran	2007-2009	Maize , Cowpea
31	Güvenç and Yildirim, 2005	Turkey	2000	Eggplant , Bean, Lettuce
32	Guvenc and Yildirim, 2006	Turkey	2000-2002	Cabbage , Lettuce, Onion, Radish, Bean
33	Hadidi et al., 2011	Jordan	2007	Bean , Okra, Lettuce, Okra, Squash
34	Hamdani and Suradinata, 2015	Indonesia	2014	Potato , Maize
35	Haque et al., 2003	Bangladesh	2000-2001	Bean , Lettuce, Spinach
36	Islam et al., 2014	Bangladesh	2011-2012	Maize , Sweet_potato
37	Jett et al., 2015	USA	2002-2003	Tomato , Lettuce

38	Kabiraj et al., 2017	India	2013-2015	Cauliflower , Bean, Pea, Beetroot, Carrot, Spinach, Coriander
39	Kabura et al., 2008	Nigeria	2002-2004	Onion, Chili
40	Karlidag and Yildirim, 2007	Turkey	2002-2003	Strawberry, Fava_bean
41	Karlidag and Yildirim, 2009	Turkey	2005-2006	Strawberry , Lettuce, Radish, Onion
42	Kour et al., 2016	India	2011-2012	Maize , Bean
43	Leishangthem et al., 2016	India	2012	Cassava, Sapota , Greater_yam, Tannia, Turmeric
44	Liu et al., 2014	China	2012	Tomato , Garlic
45	Mahant et al., 2012	India	2009-2010	Banana , Onion, Garlic, Cauliflower
46	Mbah and Ogbodo, 2013	Nigeria	2009-2010	Maize , Cowpea
47	Motagally and Metwally, 2014	Egypt	2011-2013	Onion , Beetroot
48	Newman, 1986	England	1981	Pear , Radish
49	Nwofia et al., 2017	Nigeria	2011-2012	Eggplant , Cowpea
50	Ogbuehi and Orzolek, 1987	USA	1984	Sweet_corn , Carrot
51	Olasantan, 1991	Nigeria	1986-1987	Tomato , Cowpea, Okra
52	Ali Qasim et al., 2013	Pakistan	2010-2012	Garlic , Pea, Turnip, Cauliflower
53	Rao and Singh, 1990	India	1979-1982	Sorghum , Pigeon_pea, Sorghum , Millet, Peanut
54	Rao and Willey, 1980	India	-	Sorghum , Pigeon_pea
55	Reynafarje et al., 2016	Peru	-	Tomato , Zucchini, Crotalaria, Basil, Bean, Lettuce
56	Ribeiro et al., 2017	Brazil	2013-2014	Carrot , Cowpea
57	Rodrigo et al., 1997	Sri Lanka	-	Rubber , Banana
58	Schultz et al., 1982	USA	1980	Tomato , Cucumber
59	Schulz et al., 1987	-	-	Tomato , Cucumber
60	Sharaiha and Gliessman, 1992	USA	1990	Fava_bean , Lettuce, Pea
61	Singh et al., 2011	India	2004-2006	Pigeon_pea, Safed_musli , Maize, Okra, , Cowpea, Bottle_gourd, Basil, Lablab_bean
62	Srivastava et al., 2007	India	1999-2002	Rough_lemon , Wheat, Maize, Cotton, Marigold, Chickpea, Soybean, Okra
63	Stavridou et al., 2012	Denmark	2009-2010	Broccoli , Lettuce
64	Suresha et al., 2007	India	2005-2006	Chili , Radish, Carrot, Onion, Garlic, Cluster_bean, Lablab_bean
65	Tarafder et al., 2003	Bangladesh	1999-2000	Chili , Onion
66	Temesgen et al., 2015	Australia	2011-2012	Maize , Bean
67	van Asten et al., 2011	Uganda	2006-2007	Coffee_Arabica , Coffee_Robusta , Banana
68	Varghese, 2000	India	1999	Cabbage , Beetroot, Cabbage , Radish, Fenugreek, Coriander, Spinach, Sorrel
69	Vilhekar et al., 2014	India	-	Maize , Fenugreek, Spinach, Coriander, Garlic, Aneth
70	Xiao et al., 2012	China	2009-2010	Cucumber , Garlic
71	Xie and Kristensen, 2017	Denmark	2012-2013	Leek , Dyer's_wood
72	Yildirim and Guvenc, 2004	Turkey	2000-2001	Cucumber , Bean, Lettuce
73	Yildirim and Guvenc, 2005	Turkey	2000-2002	Cauliflower , Bean, Cauliflower , Lettuce, Cauliflower , Radish, Cauliflower , Onion
74	Zhang et al., 2017	China	2014	Jujube_tree , Wheat

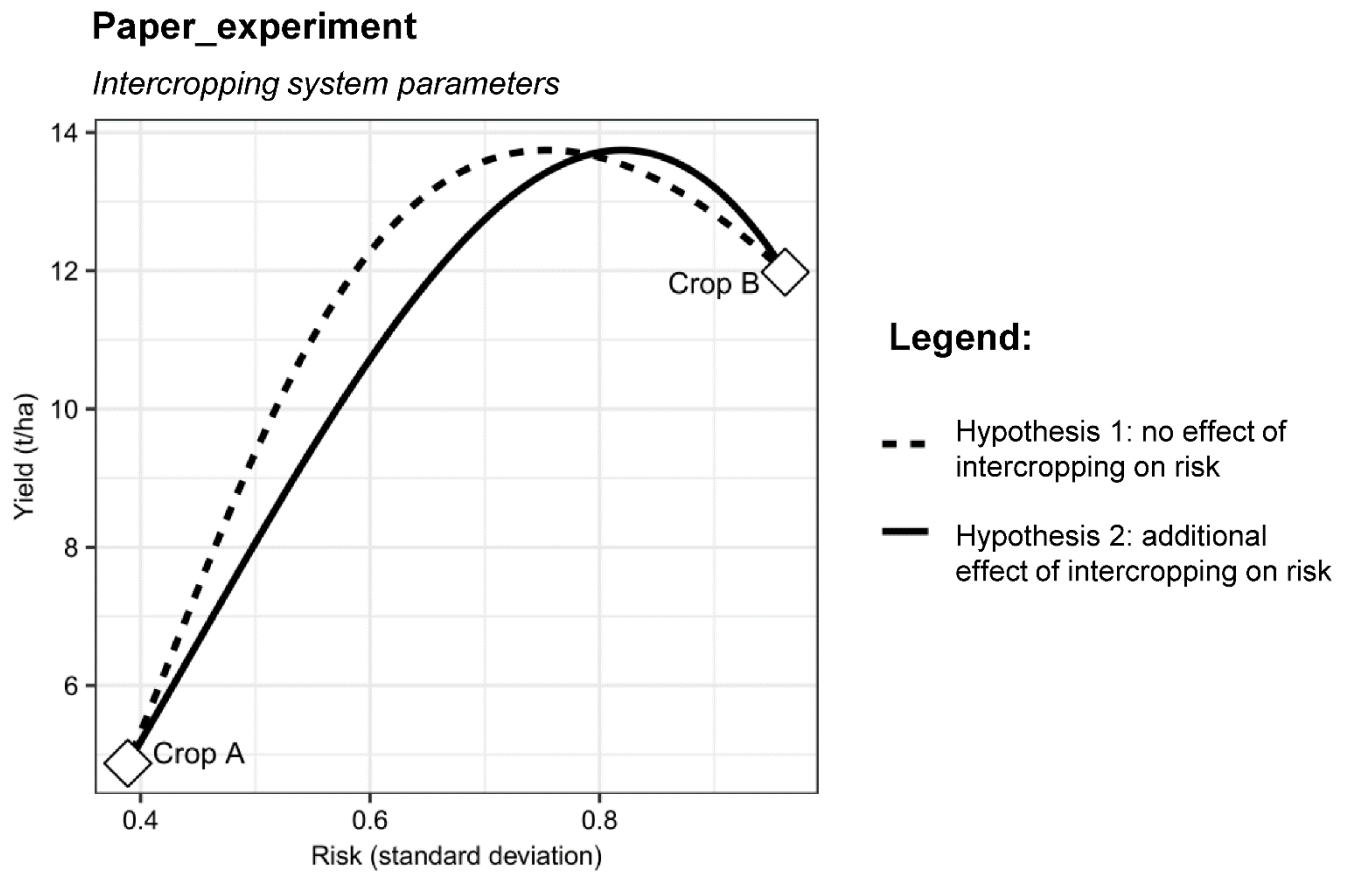
Appendix C.3. Risk and yield combinations for a high yield – low risk crop intercropped with a low yield – high risk crop.



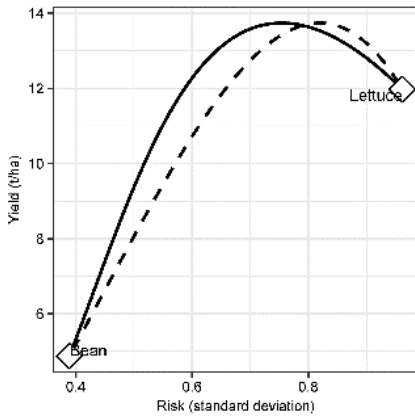
Yield and risk trade-offs among 27 contrasting scenarios of land-use options. Each curve represents a unique combination of LER, β and ρ coefficient. Moving from point Crop A to point Crop B corresponds to the consideration of systems with an increasing area allocated to crop B.

Appendix C.4. Risk and yield combinations for all the reviewed papers

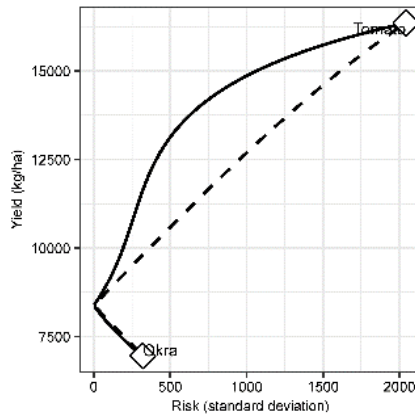
The figure below presents the reading guidelines for the figures presented in the appendix



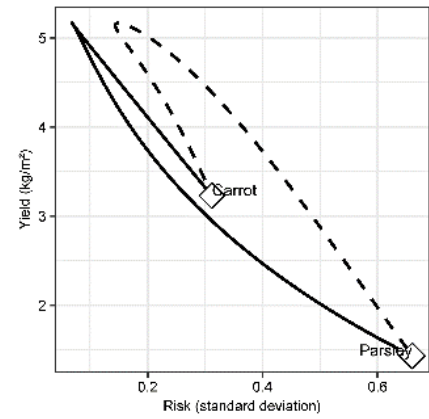
(Abou-Hussein et al. 2005)_Bean_Lettuce
LER= 1.46 | rho_AB= 1 | beta= 0.89



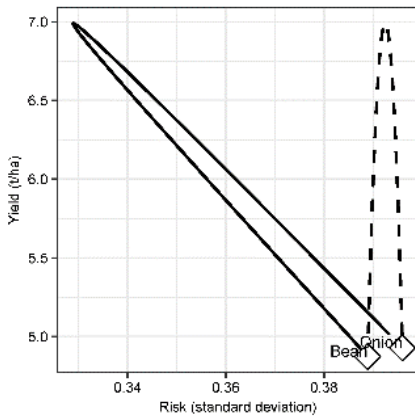
(Adeniyi 2011)_Tomato_Okra
LER= 1.04 | rho_AB= -1 | beta= 0.43



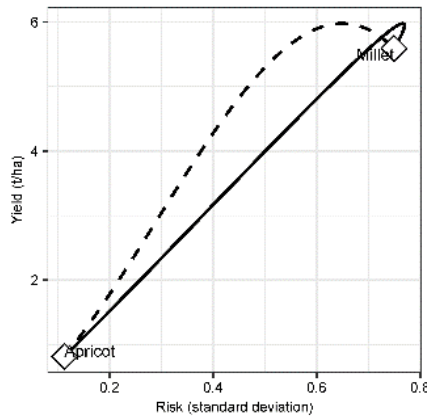
(Blazewicz-Wozniak and Wach 2011)_Carrot_Parsley
LER= 2.08 | rho_AB= -0.77 | beta= 0.4



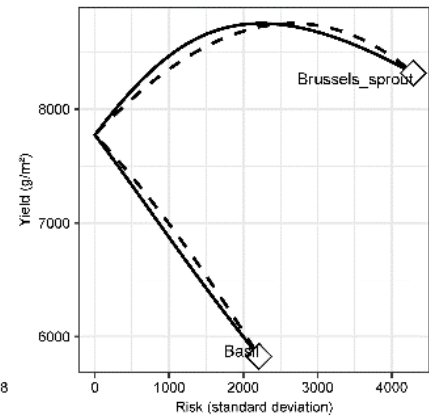
(Abou-Hussein et al. 2005)_Bean_Onion
LER= 1.43 | rho_AB= 1 | beta= 0.84



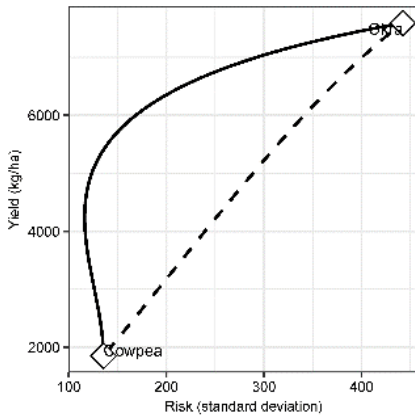
(Bai et al. 2016)_Apricot_Millet
LER= 1.44 | rho_AB= 1 | beta= 1.34



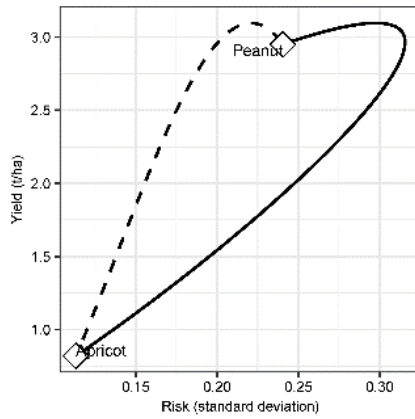
(Bomford 2009)_Brussels_sprout_Basil
LER= 1.18 | rho_AB= -1 | beta= 0.79



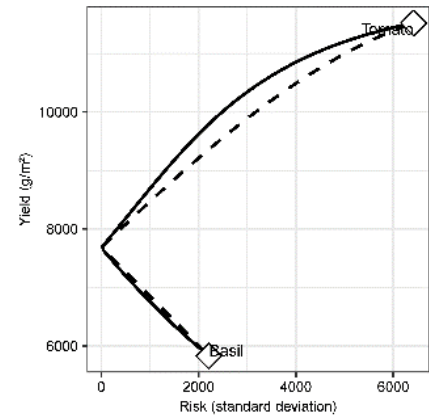
(Adeniyi 2011)_Okra_Cowpea
LER= 1.06 | rho_AB= 1 | beta= 0.43



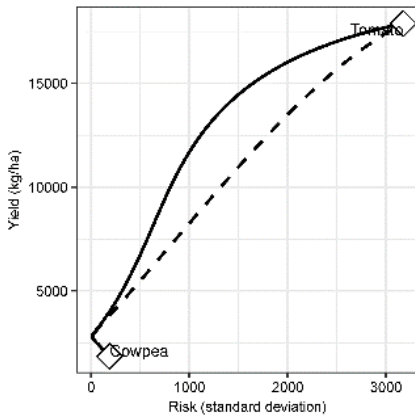
(Bai et al. 2016)_Apricot_Peanut
LER= 1.35 | rho_AB= 1 | beta= 1.67



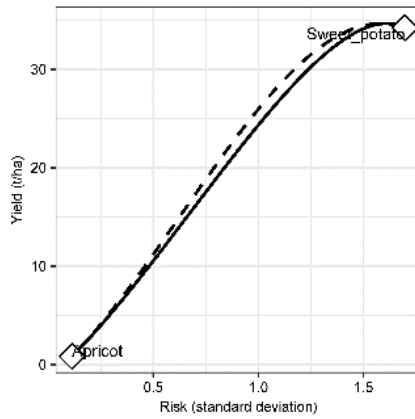
(Bomford 2009)_Tomato_Basil
LER= 1.07 | rho_AB= -1 | beta= 0.77



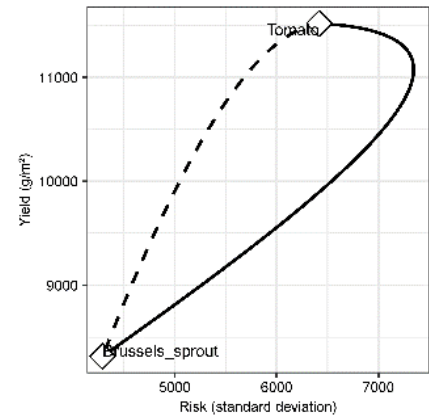
(Adeniyi 2011)_Tomato_Cowpea
LER= 1.11 | rho_AB= -1 | beta= 0.61



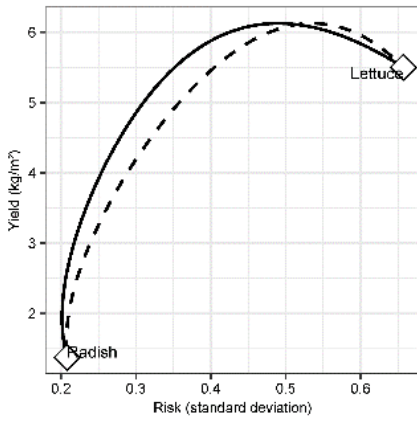
(Bai et al. 2016)_Apricot_Sweet_potato
LER= 1.33 | rho_AB= 1 | beta= 1.06



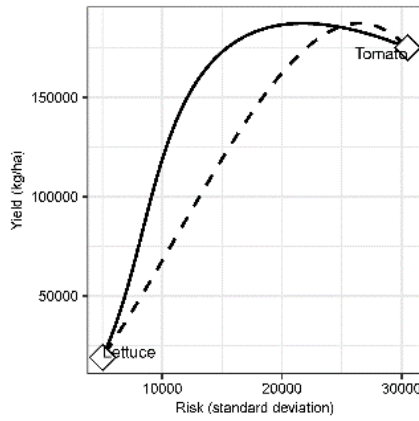
(Bomford 2009)_Tomato_Brussels_sprout
LER= 1.06 | rho_AB= 1 | beta= 1.32



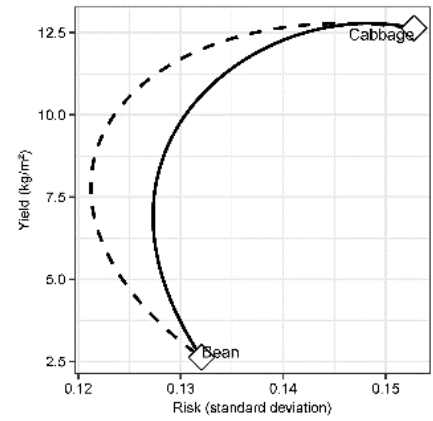
(Cecilio Filho et al. 2007)_Lettuce_Radish
 $LER= 1.48 \mid \rho_{o_AB}= 0.23 \mid \beta= 0.87$



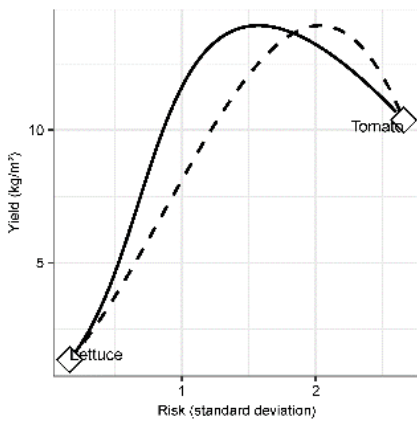
(Cecilio Filho et al. 2011)_Tomato_Lettuce
 $LER= 1.46 \mid \rho_{o_AB}= 0.85 \mid \beta= 0.66$



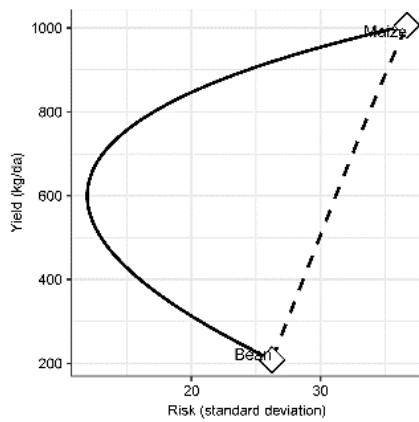
(Guvenc and Yildirim 2006)_Cabbage_Bean
 $LER= 1.27 \mid \rho_{o_AB}= 0.49 \mid \beta= 1.06$



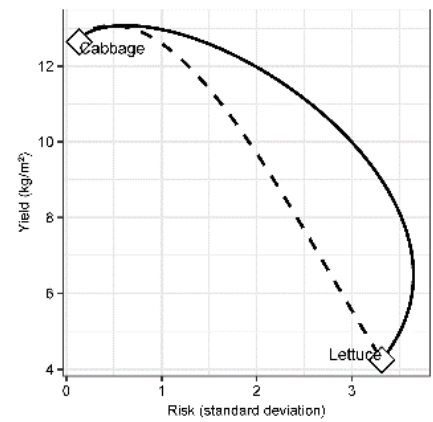
(Cecilio Filho et al. 2010)_Lettuce_Tomato
 $LER= 1.96 \mid \rho_{o_AB}= 1 \mid \beta= 0.7$



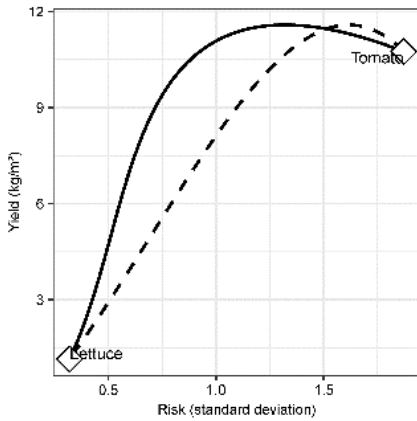
(Çiftçi et al. 2006)_Bean_Maize
 $LER= 1.02 \mid \rho_{o_AB}= 1 \mid \beta= 0.38$



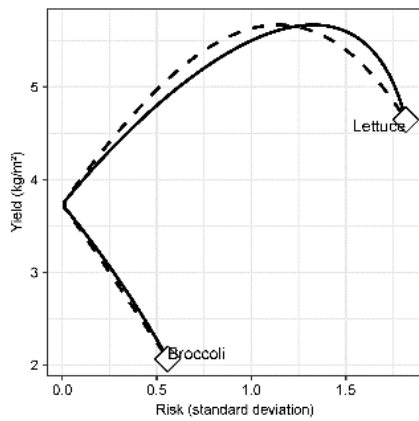
(Guvenc and Yildirim 2006)_Cabbage_Lettuce
 $LER= 1.29 \mid \rho_{o_AB}= 0.02 \mid \beta= 1.58$



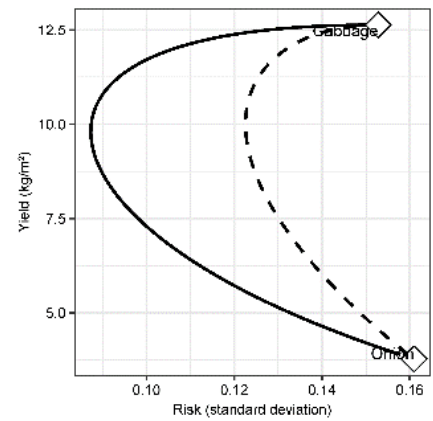
(Cecilio Filho et al. 2010)_Tomato_Lettuce
 $LER= 1.48 \mid \rho_{o_AB}= 0.83 \mid \beta= 0.65$



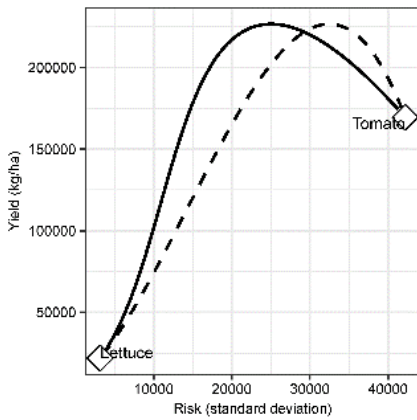
(Demir and Polat 2011)_Broccoli_Lettuce
 $LER= 1.55 \mid \rho_{o_AB}= -1 \mid \beta= 1.2$



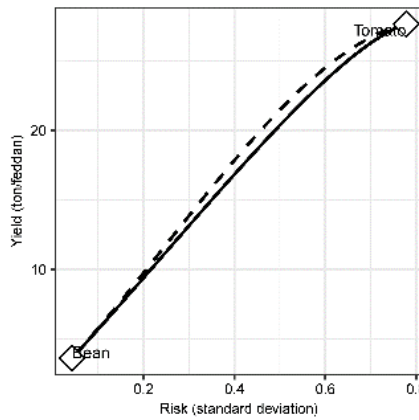
(Guvenc and Yildirim 2006)_Cabbage_Onion
 $LER= 1.18 \mid \rho_{o_AB}= 0.22 \mid \beta= 0.71$



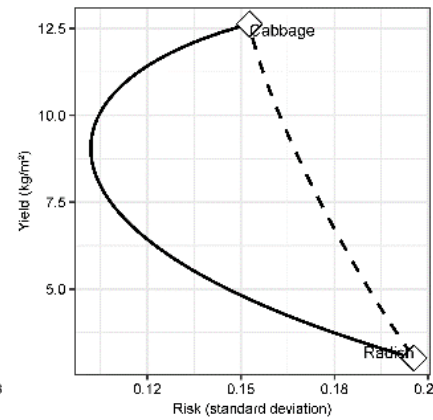
(Cecilio Filho et al. 2011)_Lettuce_Tomato
 $LER= 1.95 \mid \rho_{o_AB}= 0.99 \mid \beta= 0.69$

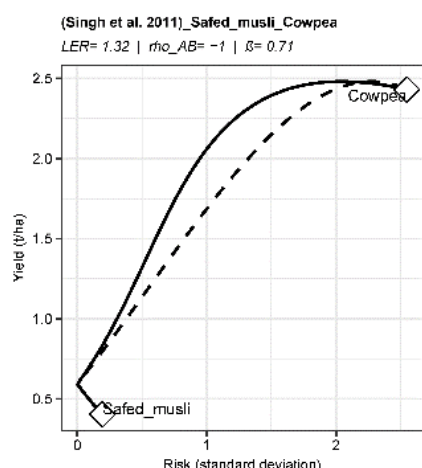
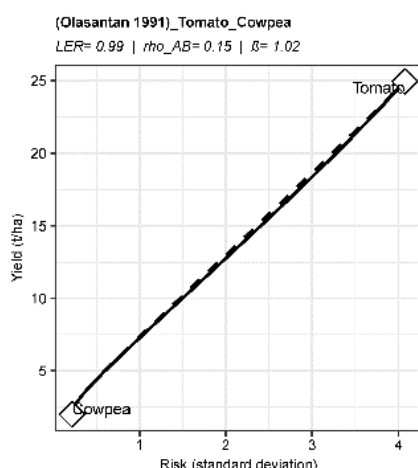
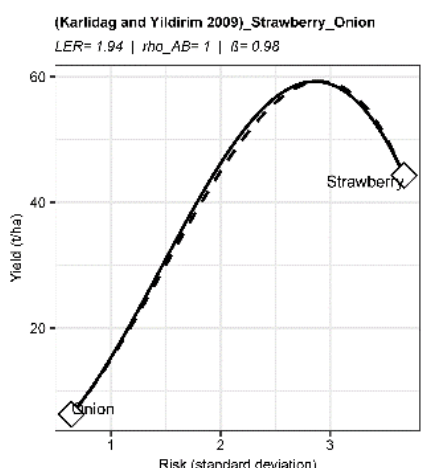
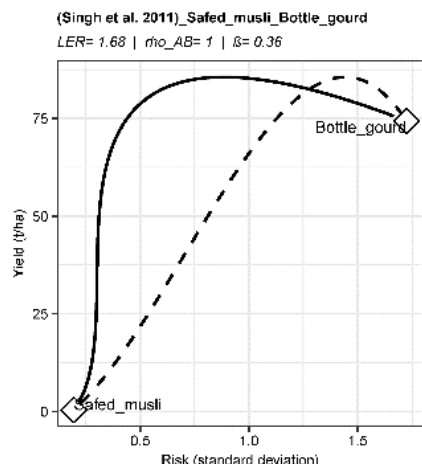
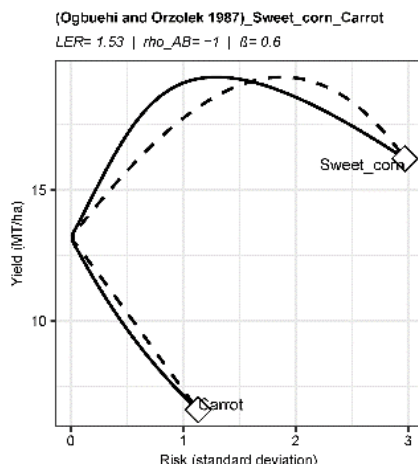
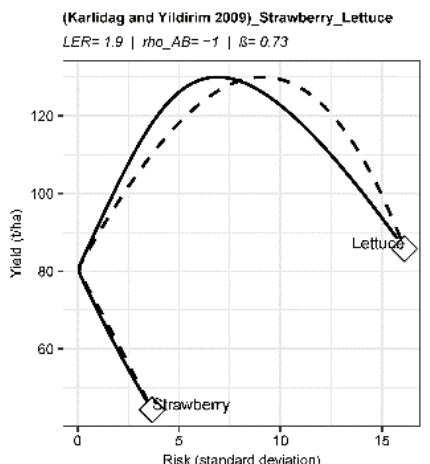
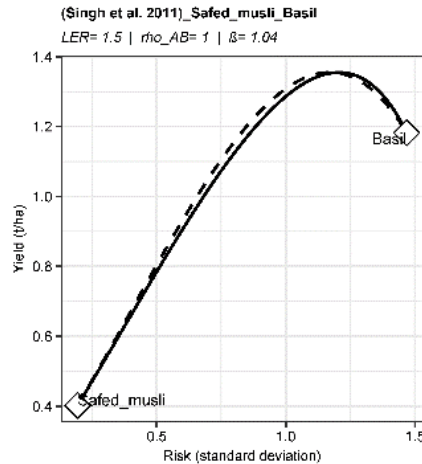
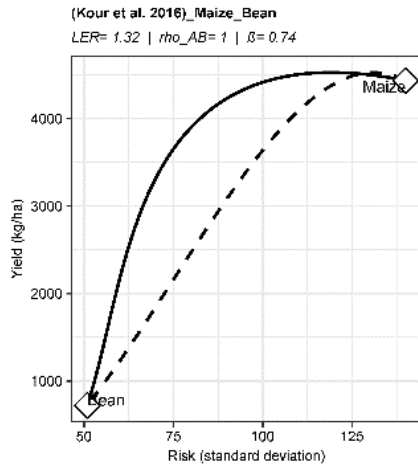
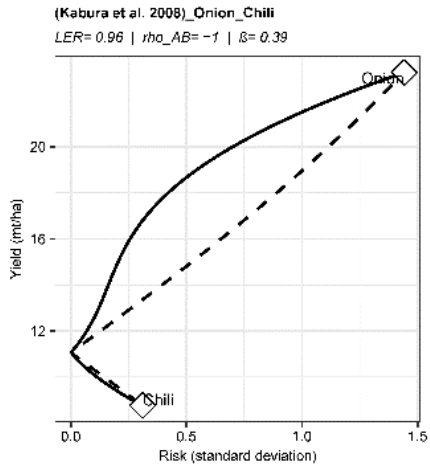
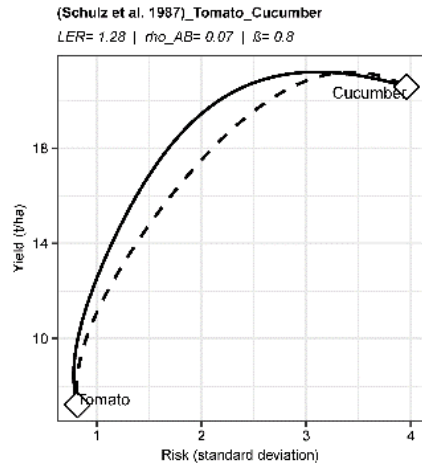
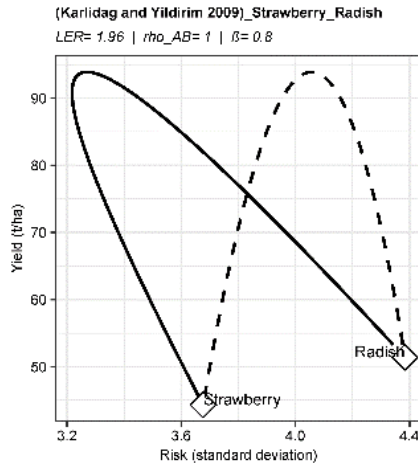
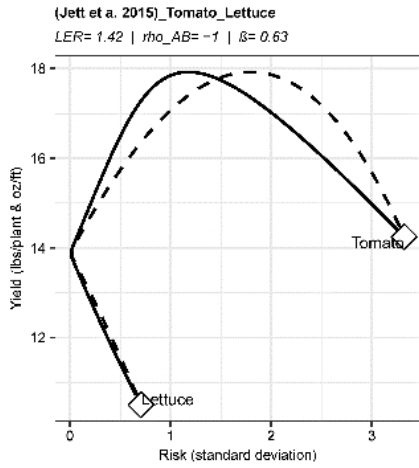


(El-Gaid et al. 2014)_Tomato_Bean
 $LER= 1.17 \mid \rho_{o_AB}= 1 \mid \beta= 1.07$

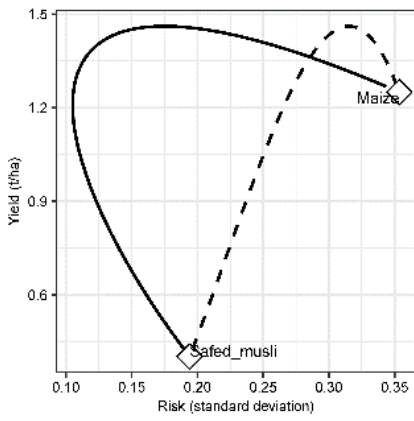


(Guvenc and Yildirim 2006)_Cabbage_Radish
 $LER= 1.08 \mid \rho_{o_AB}= 0.8 \mid \beta= 0.6$

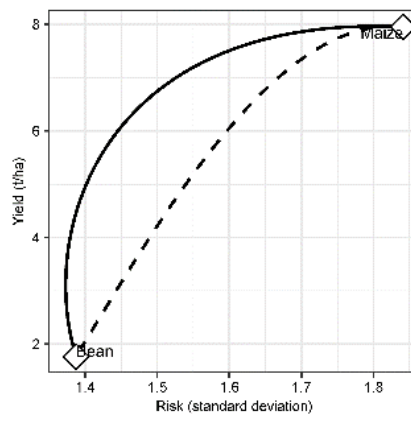




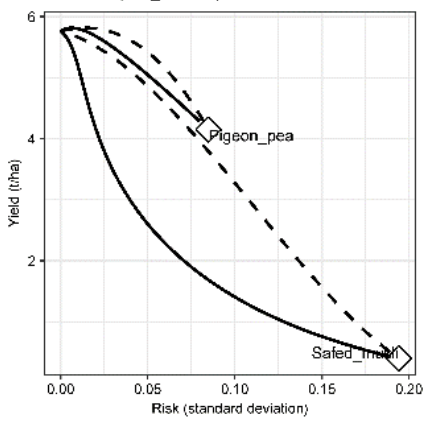
(Singh et al. 2011)_Safed_musli_Maize
 $LER= 1.54$ | $\rho_{AB}= 1$ | $\beta= 0.39$



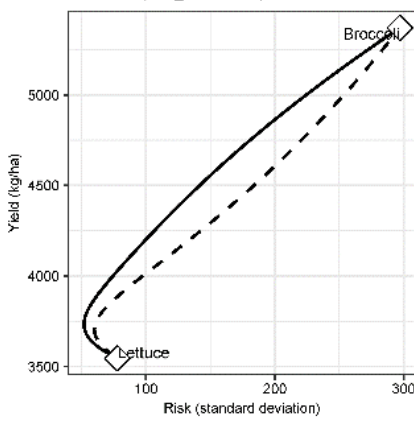
(Temesgen et al. 2015)_Maize_Bean
 $LER= 1.22$ | $\rho_{AB}= 0.94$ | $\beta= 0.91$



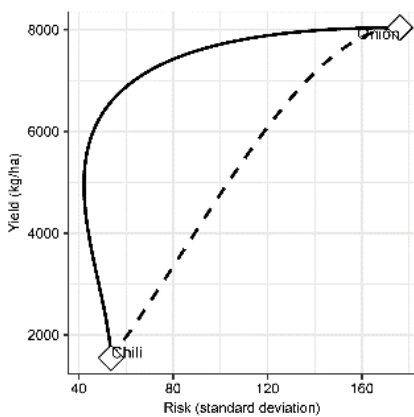
(Singh et al. 2011)_Safed_musli_Pigeon_pea
 $LER= 2.08$ | $\rho_{AB}= -1$ | $\beta= 0.26$



(Stavridou et al. 2012)_Broccoli_Lettuce
 $LER= 0.94$ | $\rho_{AB}= -0.47$ | $\beta= 0.75$



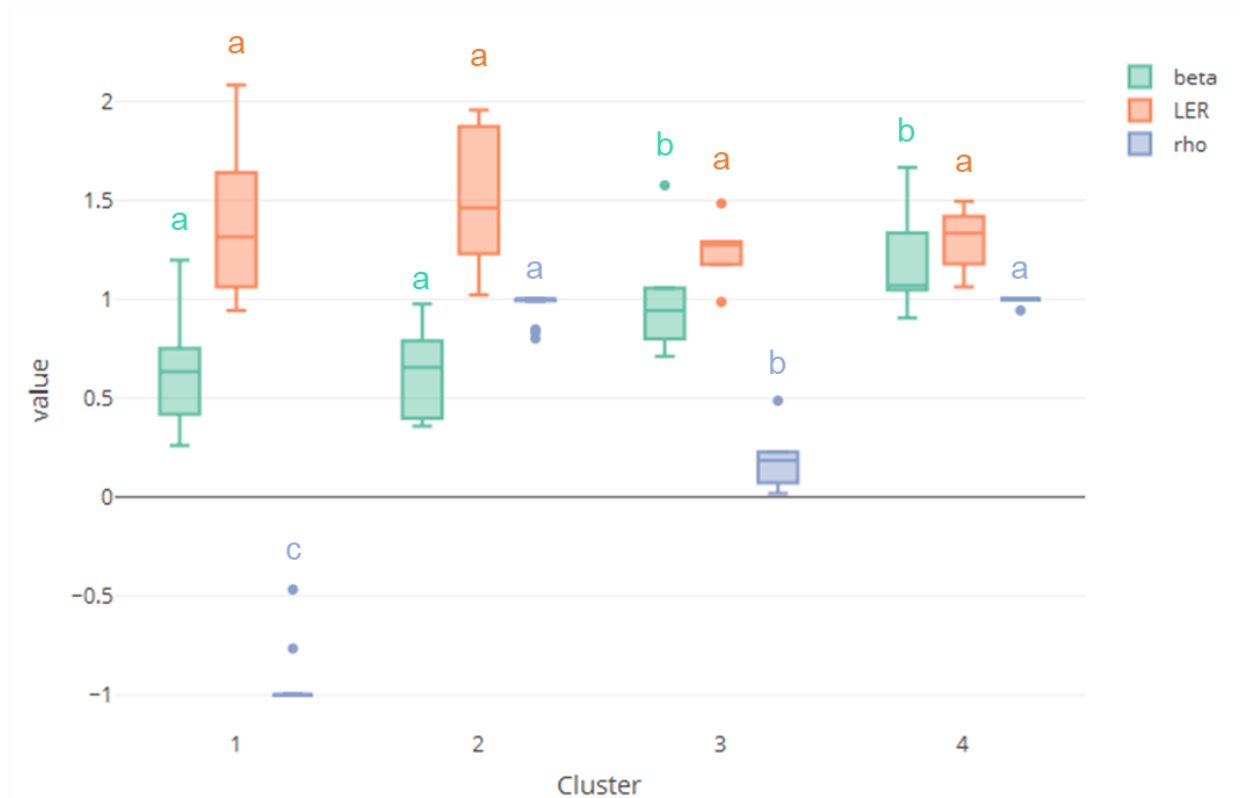
(Tarafer et al. 2003)_Chili_Onion
 $LER= 1.2$ | $\rho_{AB}= 1$ | $\beta= 0.39$



Summary of parameters of the studies investigated

paper	country	crop_A	crop_B	mean_yield_crop_A	mean_yield_crop_B	yield_unit	standard_dev_crop_A	standard_dev_crop_B	nb_samples	time_frames	mean LER	rho	beta
(Abou-Hussein et al. 2005)_Bean_Lettuce	Egypt	Bean	Lettuce	4,88	11,98	t/ha	0,39	0,96	2	2003-2004	1,46	1,00	0,89
(Abou-Hussein et al. 2005)_Bean_Onion	Egypt	Bean	Onion	4,88	4,93	t/ha	0,39	0,40	2	2003-2004	1,43	1,00	0,84
(Adeniyi 2011)_Okra_Cowpea	Nigeria	Okra	Cowpea	7590,41	1850,53	kg/ha	442,42	135,57	6	2007-2008	1,06	1,00	0,43
(Adeniyi 2011)_Tomato_Cowpea	Nigeria	Tomato	Cowpea	17882,35	1839,27	kg/ha	3175,66	188,96	6	2007-2008	1,11	-1,00	0,61
(Adeniyi 2011)_Tomato_Okra	Nigeria	Tomato	Okra	16354,15	6957,83	kg/ha	2042,77	320,79	6	2007-2008	1,04	-1,00	0,43
(Bai et al. 2016)_Apricot_Millet	China	Apricot	Millet	0,82	5,59	t/ha	0,11	0,75	2	2012-2013	1,44	1,00	1,34
(Bai et al. 2016)_Apricot_Peanut	China	Apricot	Peanut	0,82	2,95	t/ha	0,11	0,24	2	2012-2013	1,35	1,00	1,67
(Bai et al. 2016)_Apricot_Sweet_potato	China	Apricot	Sweet_potato	0,82	34,20	t/ha	0,11	1,70	2	2012-2013	1,33	1,00	1,06
(Blazewicz-Wozniak and Wach 2011)_Carrot_Parsley	Poland	Carrot	Parsley	3,23	1,43	kg/m ²	0,31	0,66	3	2004-2006	2,08	-0,77	0,40
(Bomford 2009)_Brussels_sprout_Basil	USA	Brussels_sprout	Basil	8316,00	5827,50	g/m ²	4290,72	2211,12	2	2001-2002	1,18	-1,00	0,79
(Bomford 2009)_Tomato_Basil	USA	Tomato	Basil	11519,50	5827,50	g/m ²	6418,41	2211,12	2	2001-2002	1,07	-1,00	0,77
(Bomford 2009)_Tomato_Brussels_sprout	USA	Tomato	Brussels_sprout	11519,50	8316,00	g/m ²	6418,41	4290,72	2	2001-2002	1,06	1,00	1,32
(Cecilio Filho et al. 2007)_Lettuce_Radish	Brazil	Lettuce	Radish	5,50	1,38	kg/m ²	0,66	0,21	6	2004	1,48	0,23	0,87
(Cecilio Filho et al. 2010)_Lettuce_Tomato	Brazil	Lettuce	Tomato	1,35	10,38	kg/m ²	0,16	2,66	8	2009	1,96	1,00	0,70
(Cecilio Filho et al. 2010)_Tomato_Lettuce	Brazil	Tomato	Lettuce	10,75	1,15	kg/m ²	1,87	0,32	8	2009	1,48	0,83	0,65
(Cecilio Filho et al. 2011)_Lettuce_Tomato	Brazil	Lettuce	Tomato	21901,80	169470,53	kg/ha	3165,38	42207,64	8	2003-2004	1,95	0,99	0,69
(Cecilio Filho et al. 2011)_Tomato_Lettuce	Brazil	Tomato	Lettuce	175153,80	18831,87	kg/ha	30503,11	5004,72	8	2003-2004	1,46	0,85	0,66
(Çiftçi et al. 2006)_Bean_Maize	Turkey	Bean	Maize	208,65	1006,05	kg/da	26,23	36,70	6	2001-2003	1,02	1,00	0,38
(Demir and Polat 2011)_Broccoli_Lettuce	Turkey	Broccoli	Lettuce	2,07	4,65	kg/m ²	0,56	1,82	2	2006-2007	1,55	-1,00	1,20
(El-Gaid et al. 2014)_Tomato_Bean	Egypt	Tomato	Bean	27,65	3,64	ton/feddan	0,78	0,04	6	2010-2012	1,17	1,00	1,07
(Guvenc and Yildirim 2006)_Cabbage_Bean	Turkey	Cabbage	Bean	12,63	2,62	kg/m ²	0,15	0,13	3	2000-2002	1,27	0,49	1,06
(Guvenc and Yildirim 2006)_Cabbage_Lettuce	Turkey	Cabbage	Lettuce	12,63	4,25	kg/m ²	0,14	3,31	6	2000-2002	1,29	0,02	1,58
(Guvenc and Yildirim 2006)_Cabbage_Onion	Turkey	Cabbage	Onion	12,63	3,77	kg/m ²	0,15	0,16	3	2000-2002	1,18	0,22	0,71
(Guvenc and Yildirim 2006)_Cabbage_Radish	Turkey	Cabbage	Radish	12,63	3,01	kg/m ²	0,15	0,21	3	2000-2002	1,08	0,80	0,60
(Jett et al. 2015)_Tomato_Lettuce	USA	Tomato	Lettuce	14,25	10,50	lbs/plan t & oz/ft	3,32	0,71	2	2002-2003	1,42	-1,00	0,63
(Kabura et al. 2008)_Onion_Chili	Nigeria	Onion	Chili	23,22	8,78	mt/ha	1,44	0,31	16	2002-2004	0,96	-1,00	0,39
(Karlıdag and Yildirim 2009)_Strawberry_Lettuce	Turkey	Strawberry	Lettuce	44,30	85,80	t/ha	3,68	16,12	2	2005-2006	1,91	-1,00	0,73
(Karlıdag and Yildirim 2009)_Strawberry_Onion	Turkey	Strawberry	Onion	44,30	6,25	t/ha	3,68	0,64	2	2005-2006	1,94	1,00	0,98
(Karlıdag and Yildirim 2009)_Strawberry_Radish	Turkey	Strawberry	Radish	44,30	51,40	t/ha	3,68	4,38	2	2005-2006	1,96	1,00	0,80
(Kour et al. 2016)_Maize_Bean	India	Maize	Bean	4434,00	720,00	kg/ha	140,01	50,91	4	2011-2012	1,32	1,00	0,74
(Olasantan 1991)_Tomato_Cowpea	Nigeria	Tomato	Cowpea	24,95	2,00	t/ha	4,07	0,22	6	1986-1987	0,99	0,15	1,02
(Schulz et al. 1987)_Tomato_Cucumber	#N/A	Tomato	Cucumber	7,22	20,58	t/ha	0,81	3,96	6	#N/A	1,28	0,07	0,80
(Singh et al. 2011)_Safed_musli_Basil	India	Safed_musli	Basil	0,40	1,18	t/ha	0,19	1,47	4	2004-2006	1,50	1,00	1,04
(Singh et al. 2011)_Safed_musli_Bottle_gourd	India	Safed_musli	Bottle_gourd	0,40	74,38	t/ha	0,19	1,73	4	2004-2006	1,68	1,00	0,36
(Singh et al. 2011)_Safed_musli_Cowpea	India	Safed_musli	Cowpea	0,40	2,43	t/ha	0,19	2,55	4	2004-2006	1,32	-1,00	0,71
(Singh et al. 2011)_Safed_musli_Maize	India	Safed_musli	Maize	0,40	1,25	t/ha	0,19	0,35	4	2004-2006	1,54	1,00	0,39
(Singh et al. 2011)_Safed_musli_Pigeon_pea	India	Safed_musli	Pigeon_pea	0,40	4,15	t/ha	0,19	0,08	4	2004-2006	2,08	-1,00	0,26
(Stavridou et al. 2012)_Broccoli_Lettuce	Denmark	Broccoli	Lettuce	5369,75	3546,00	kg/ha	296,93	77,77	4	2009-2010	0,94	-0,47	0,75
(Tarafder et al. 2003)_Chili_Onion	Bangladesh	Chili	Onion	1546,00	8041,50	kg/ha	53,74	176,07	8	1999-2000	1,20	1,00	0,39
(Temesgen et al. 2015)_Maize_Bean	Australia	Maize	Bean	7,95	1,77	t/ha	1,84	1,39	6	2011-2012	1,22	0,94	0,91

Appendix C.5. Results of the cluster analysis and further statistical analysis



Descriptive statistics of the parameters of the reviewed intercropping systems. Clusters displayed with different letters showed significant differences according to Tukey's Honestly Significant Difference ($P \leq 0.05$).

Annexe D. Annexes du Chapitre IV

Appendix D.1. Working time requirements (in hours per hectare) for each crop considered in our study.

Type	Crop	Latin name	Variety	Months											
				1	2	3	4	5	6	7	8	9	10	11	12
Fruit	Apricot	<i>Prunus armeniaca</i>	Kioto	-	45	28	4	158	629	7	6	-	2	2	-
Fruit	Cherry	<i>Prunus avium</i>	Burlat	50	5	9	20	938	2	3	-	-	2	-	80
Fruit	Fig	<i>Ficus carica</i>	Sollies	30	19	10	-	12	16	16	151	391	263	-	30
Fruit	Fig	<i>Ficus carica</i>	Noire de Caromb	2	4	14	5	6	8	641	6	639	1	-	-
Fruit	Olive	<i>Olea europaea</i>	Aglandau	-	-	53	29	6	4	8	6	4	2	100	141
Fruit	Pear	<i>Pyrus communis</i>	Conference	34	4	11	5	20	8	26	3	153	18	8	43
Fruit	Pear	<i>Pyrus communis</i>	Guyot	1	5	6	32	7	8	130	125	2	8	-	120
Fruit	Apple	<i>Malus pumila</i>	Golden	162	4	3	42	23	163	13	4	334	6	-	-
Fruit	Apple	<i>Malus pumila</i>	Topaz	32	3	12	7	21	9	66	4	303	16	8	43
Fruit	Apple	<i>Malus pumila</i>	Royal Gala	32	6	5	37	20	249	19	255	40	4	2	40
Fruit	Table grape	<i>Vitis vinifera</i>	Alphonse Lavallee	3	65	12	-	6	54	100	118	189	206	3	2
Fruit	Table grape	<i>Vitis vinifera</i>	Muscat de Hambourg	68	10	2	5	55	100	114	156	206	-	-	3
Vegetable	Asparagus	<i>Asparagus officinalis</i>	Grolim	-	6	2	4	11	200	200	169	9	4	4	-
Vegetable	Eggplant	<i>Solanum melongena</i> L.	Black Pearl	-	-	175	269	240	548	502	501	445	334	155	-
Vegetable	Carrot	<i>Daucus carota</i> subsp. <i>Sativus</i>	Napoli	-	-	-	-	-	27	10	135	161	13	1	212
Vegetable	Cabbage	<i>Brassica oleracea</i> var. <i>capitata</i>	Impala	-	-	-	-	-	23	50	22	16	97	-	-
Vegetable	Savoy cabbage	<i>Brassica oleracea</i> var. <i>sabauda</i> L.	Rigoletto	-	-	-	-	-	19	107	18	20	102	7	102
Vegetable	Squash	<i>Cucurbita moschata</i>	Musquee de Provence	-	-	-	16	40	4	5	5	115	-	-	-
Vegetable	Zucchini	<i>Cucurbita pepo</i> var. <i>cylindrica</i>	Zelia	-	1	-	-	90	12	311	307	125	-	-	-
Vegetable	Lettuce	<i>Lactuca sativa</i>	Analora/Impression	2	16	185	24	664	-	-	-	1	-	-	-
Vegetable	Lettuce	<i>Lactuca sativa</i>	Batavia kissmy	20	-	-	-	-	-	-	-	39	266	16	540
Vegetable	Melon	<i>Cucumis melo</i>	Godiva	-	4	11	145	27	17	255	35	4	-	-	-
Vegetable	Leek	<i>Allium ampeloprasum</i>	Tadorna	40	40	1	-	-	5	78	27	1	18	31	40
Vegetable	Pepper	<i>Capsicum annuum</i> L.	Almuden	-	-	191	304	249	411	399	383	314	190	190	-
Vegetable	Potato	<i>Solanum tuberosum</i>	Mona Lisa	-	-	11	2	2	3	2	64	-	2	-	-
Vegetable	Tomato	<i>Solanum lycopersicum</i>	Kanavaro	-	26	143	296	557	705	586	411	235	326	-	-

Annexe E. Annexes du Chapitre V

Appendix E.1. Data used in the model

Type	Crop	Latin name	Variety	Workload requirements (h/month ³)												yield(Kg/ha)	price(€/Kg)	revenue(€/ha)	expenses(€/ha)	harvest_% of_expenses	gross_margin(€/ha)	
				1	2	3	4	5	6	7	8	9	10	11	12							
Fruit	Apricot	Prunus armeniaca	Kioto		45	28	4	158	629	7	6		2	2		20000	2,00	40000	21656	43	18344	
Fruit	Cherry	Prunus avium	Burlat	50	5	9	20	938	2	3			2		0	7000	3,75	22750	21557	64	1193	
Fruit	Pear	Pyrus communis	Conference	34	4	11	5	20	8	26	3	153	18	8	3	10000	1,48	13000	10518	19	2482	
Fruit	Pear	Pyrus communis	Guyot	1	5	6	32	7	8	130	125	2	8		20	15000	1,18	16500	12505	30	3995	
Fruit	Apple	Malus pumila	Golden	162	4	3	42	23	163	13	4	334	6			35000	1,00	35000	18633	23	16367	
Fruit	Apple	Malus pumila	Topaz	32	3	12	7	21	9	66	4	303	16	8	3	20000	1,10	22000	15818	26	6182	
Fruit	Apple	Malus pumila	Royal Gala	32	6	5	37	20	249	19	255	40	4	2	0	25000	1,05	26250	18512	20	7738	
Fruit	Prune	Prunus domestica L.	Président	30	30	35	7	58	18	6	6	406	0	0	0	20000	1,04	16800	14434	41	2366	
Fruit	Peach	Prunus persica L.	Coraline	102	108	10	209	9	152	8	6	4	0	2		10000	2,50	25000	10061	21	14939	
Fruit	Peach	Prunus persica L.	Big Top	84	86	12	129	11	9	268	7	7	4	2		17000	2,20	37400	10823	17	26577	
Vegetable	Asparagus	Asparagus officinalis	Grolim		6	2	4	11	200	200	169	9	4	4		3000	6,00	18000	13662	-	4338	
Vegetable	Carrot	Daucus carota subsp. Sativus	Napoli						27	10	135	161	13	1	12	30000	0,63	18750	11709	-	7041	
Vegetable	Cabbage	Brassica oleracea var. capitata	Impala						23	50	22	16	97			13000	1,40	18200	11441	-	6759	
Vegetable	Savoy cabbage	Brassica oleracea var. sabauda L.	Rigoletto						19	107	18	20	102	7	02	13000	1,40	18200	13058	-	5142	
Vegetable	Squash	Cucurbita moschata	Musquee de Provence				16	40	4	5	5	115				32500	0,85	27625	6929	-	20696	
Vegetable	Zucchini	Cucurbita pepo var. cylindrica	Zelia		1			90	12	311	307	125				40000	1,00	40000	26700	-	13300	
Vegetable	Zucchini	Cucurbita pepo var. cylindrica	Kopana		233	42	702	570	536	62						75000	1,03	76875	74500	-	2375	
Vegetable	Spinach greenhouse	Spinacia oleracea	Meerkat	30	710								335	35	693	0	40000	2,55	102000	85400	-	16600
Vegetable	Beans	Phaseolus vulgaris L.	Pongo			457	19	55	2075	2044	156					22500	6,00	135000	129000	-	6000	
Vegetable	Lettuce	Lactuca sativa	Analora/Impression	2	16	185	24	664					1			77100	0,48	36623	30651	-	5972	
Vegetable	Lettuce	Lactuca sativa	Batavia kissmy	20									39	266	16	40	85000	0,50	42500	41988	-	512
Vegetable	Lamb's lettuce	Valerianella locusta	Trophy	540	25								58	122	127	65	13500	6,80	91800	69688	-	22112
Vegetable	Melon	Cucumis melo	Godiva		4	11	145	27	17	255	35	4				20000	1,30	26000	18291	-	7709	
Vegetable	Melon early	Cucumis melo	Godiva	13	60	142	202	84	328	4	36					30000	1,74	52200	46488	-	5712	
Vegetable	Leek	Allium ampeloprasum	Tadorna	40	40	1			5	78	27	1	18	31	0	25200	1,65	41580	23104	-	18476	
Vegetable	Pepper	Capsicum annum L.	Almuden			191	304	249	411	399	383	314	190	190		55000	2,00	110000	104690	-	5310	
Vegetable	Potato	Solanum tuberosum	Mona Lisa			11	2	2	3	2	64			2		22500	0,60	13500	7198	-	6302	

Appendix E.2. Formula and parameters for fruit tree dynamics

Fruit tree dynamics have been described based on experts' knowledge in a collective workshop. Each fruit tree species was characterized according to three management options: (i) **optimal** investment corresponds to the systematic prioritization of trees in the system management, so that they develop optimally; (ii) **minimal** investment refers to the systematic prioritization of market gardening and the remaining workload is dedicated to trees; (iii) the **intermediate** scenario stands for an in-between situation where tree operations are not done perfectly or are staggered in time.

The resulting fruit tree dynamics were fitted using Nonlinear Least Squares method (Bates and Watts, 1988) and the fitted curves have been assumed to have a sigmoidal shape (Yin et al., 2003) as follows:

$$f(x) = \frac{1}{1 + e^{-a(x-b)}}$$

Scenarios and corresponding parameters

Species	Scenario	a	b	c
Apple	1: optimal	1.00	1.47	4.79
	2: minimal	0.00	0.00	0.00
	3: intermediate	1.00	0.66	6.13
Peach	1: optimal	1.00	1.89	4.17
	2: minimal	0.00	0.00	0.00
	3: intermediate	0.748	5.59	3.87
Apricot	1: optimal	1.00	0.89	6.01
	2: minimal	0.56	1.26	4.76
	3: intermediate	0.78	0.91	5.50
Prune	1: optimal	1.00	2.27	5.29
	2: minimal	0.50	1.48	5.35
	3: intermediate	0.75	1.91	5.31
Pear	1: optimal	1.00	1.14	5.96
	2: minimal	0.00	0.00	0.00
	3: intermediate	0.57	0.90	6.38
Cherry	1: optimal	1.00	1.54	4.19
	2: minimal	0.59	1.36	4.01
	3: intermediate	0.79	1.31	4.26

Annexe F. Horticultural agroforestry systems: a modelling framework to combine diversification and association effects

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Link to the proceedings: https://www.repository.utl.pt/bitstream/10400.5/15589/1/REP-CEF-EURAF-conference_book.pdf

Reference:

Paut, R., Sabatier, R., Tchamitchian, M., 2018. Horticultural agroforestry systems: a modelling framework to combine diversification and association effects, in: 4th European Agroforestry Conference. Agroforestry as Sustainable Land Use. Nijmegen, The Netherlands, pp. 437–441.

1. Introduction

In a context of increasing environmental awareness and evolving relationships between farmers and consumers, new farming organizations have emerged in the last decades thus creating innovative agro-ecological systems (Wezel et al., 2014). One of these systems, known as mixed horticultural system, which corresponds to the intercropping of fruit trees and vegetables is attracting a growing interest in Europe, especially among new entrants into farming (Sieffert et al., 2014; Warlop, 2016).

From the agronomic perspective, this type of system presents two major advantages: (i) firstly, it reduces the overall risk on production through a *diversification effect* (Isbell et al., 2017; Letourneau et al., 2011; Ratnadass et al., 2012) (ii) secondly, it benefits from positive interactions between crops through an *association effect* (Iverson et al., 2014; Vandermeer, 1989). The risk reduction arising from diversification which is a well-studied mechanism in the field of economy has been formalized in the Modern Portfolio Theory (Markowitz, 2010, 1952; Shapira et al., 2009). Yet, this theory, primarily established to design a portfolio of assets in Finance, does not take in account for assets that interact together such as crops in associations. On the other hand, the effect of crop association on production is covered in agricultural sciences by the concept of Land Equivalent Ratio (LER) that provides a standardized basis to assess intercropping system performance. However, this approach is still limited since it does not account for the effect of diversification on risk reduction. Our objective was therefore to combine these two theoretical approaches in a unified framework to formalize the effect of intercropping on both production and risk. After presenting the model linking diversification and association effects, we apply this unified framework on examples based on a literature review.

2. Material and methods

2.1. Formalizing the effect of *association*: the Land Equivalent Ratio

When two crops are cultivated simultaneously on the same surface, interactions between the two crops may lead to an overall production different from the weighted sum of the production of each crop cultivated in monoculture. This association effect is classically assessed in the literature by the so-called Land Equivalent Ratio (Mead and Willey, 1980; Vandermeer, 1989). For a given proportion (k) of crop A in the association with crop B, the value of the LER_k corresponds to the area that would be needed to produce the same amount of crops in two separate monocultures. LER_k is formalized as follows:

$$LER_k = LER_k^A + LER_{1-k}^B = \frac{Y_k^A}{S_A} + \frac{Y_{1-k}^B}{S_B} \quad (20)$$

where Y_k^i is the yield of crop i cultivated in intercropping, and S_i represents the yield of a monoculture of crop i .

An LER greater than 1 means that the intercropping system mixing crop A and crop B produces more than their respective monoculture for the same cultivated area.

2.2 Formalizing the effect of diversification: the Modern Portfolio Theory

The Modern Portfolio Theory (Markowitz, 2010, 1952) formalizes how risk can be reduced in a context of assets diversification. The general idea behind this theory is that when assets are combined in a portfolio and when asset returns are not perfectly correlated, the portfolio risk is reduced compared to single assets portfolio. Applied to agriculture, a diversified portfolio becomes a combination of several crops within a farm.

According to this theory, the **expected return** of a portfolio P is the weighted sum of each individual assets in the portfolio:

$$E(R_P) = \sum_i w_i E(R_i) \quad (21)$$

with w_i the weight of crop i (that is, the proportion of crop “ i ” in the portfolio) and $E(R_i)$ the expected yield of crop i

On the other hand, the **risk** of a portfolio is measured by the standard deviation, σ_P :

$$\sigma_P^2 = \sum_i \sum_j w_i w_j \sigma_{ij} \quad (22)$$

with σ_{ij} the standard deviation of yield for crop i when $i = j$, and the covariance of crop i and j when $i \neq j$

The MPT has already been used in agriculture (Castro et al., 2015; Knoke et al., 2015) but always considering farms as portfolios of non-interacting crops. When applying MPT to agroforestry systems, the challenge is to integrate the effects of interaction between associated crops on the yield of intercropped cultures.

2.3. Combining MPT and LER

Combining both Modern Portfolio Theory and Land Equivalent Ratio requires improving Eq. (21) so as to account for interactions between the two crops:

$$E_k(R_P) = E(R_A)LER_k^A + E(R_B)LER_k^B \quad (23)$$

with $E(R_i)$ the expected yield of crop i and LER_k^A the partial LER of crop A at the proportion of k in the portfolio

According to the MPT, a portfolio yield is the weighted sum of the yields of the monocultures and its risk is lower than the weighted sum of the risk of the two monocultures (Figure 1, solid line). In contrast, when the MPT is combined with the LER framework, yield of the intercropping differs from the weighted sum of the yields of the two monocultures (Figure 1, dotted line).

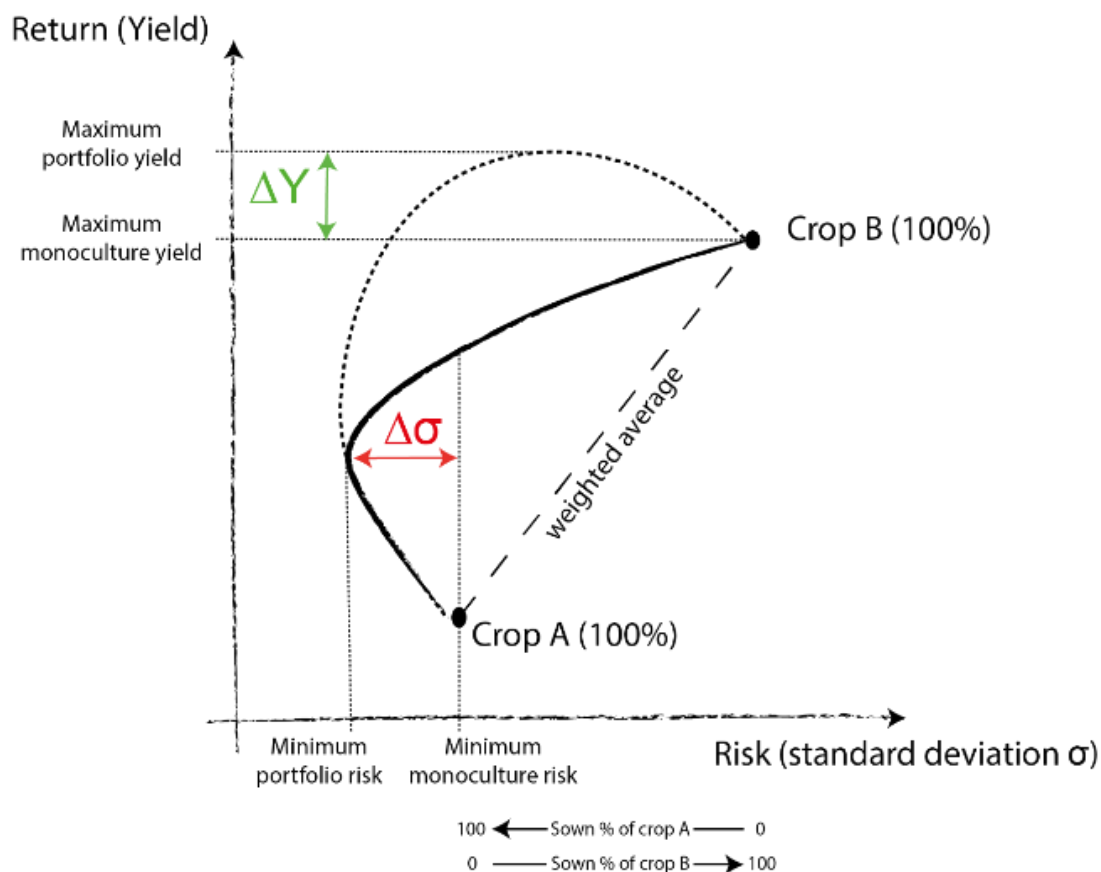


Fig. 1. Possible return and risk combinations for a theoretical agroforestry system. The solid curve represents the risk and yield of the crop portfolio for different proportions of crop A and B in a situation where only the diversification effect is considered (formalized by MPT). The dotted curve represents the risk and yield of the crop portfolio for different proportions of crop A and B in a situation where both the diversification effect and the association effects are considered (formalized by MPT and LER). The dashed line represents what would be the weighted average of risks and returns.

2.4. Application of this new framework

We then applied this framework to realistic situations of intercropping. Based on a literature review of temperate intercropping experiments, we identified 38 articles assessing 277 measures of LER: 8 articles referring to tree-vegetable associations and 30 referring to vegetable-vegetable associations. Out of these 38 articles, only 24 gave sufficient information to evaluate average yields and standard deviations for the two crops in monoculture and in association. Unfortunately, none of these concerned tree-vegetable associations in temperate areas and we

therefore could not apply our framework to European Agroforestry systems. We nevertheless assessed the production-risk relationship for two examples of vegetable-vegetable intercropping systems in temperate climates and a tropical fruit-based agroforestry system, so as to illustrate the functional forms that production risk relationships could take in agroforestry systems. Computations were performed with the R software.

3. Results

3.1. Characteristics of fruits and vegetables intercropping systems

A review of intercropping studies involving vegetables and/or fruits was carried out, resulting in 277 LER measures (often several experiments per study). On average, intercropping was more efficient than monocropping, since 251 out of the 277 calculated LER values were larger than 1. The median LER was 1.28 and the mean 1.36. However, the standard deviation on LER was 0.36, suggesting a high variability in LERs depending on crop species, treatments and experimental designs (Figure 2).

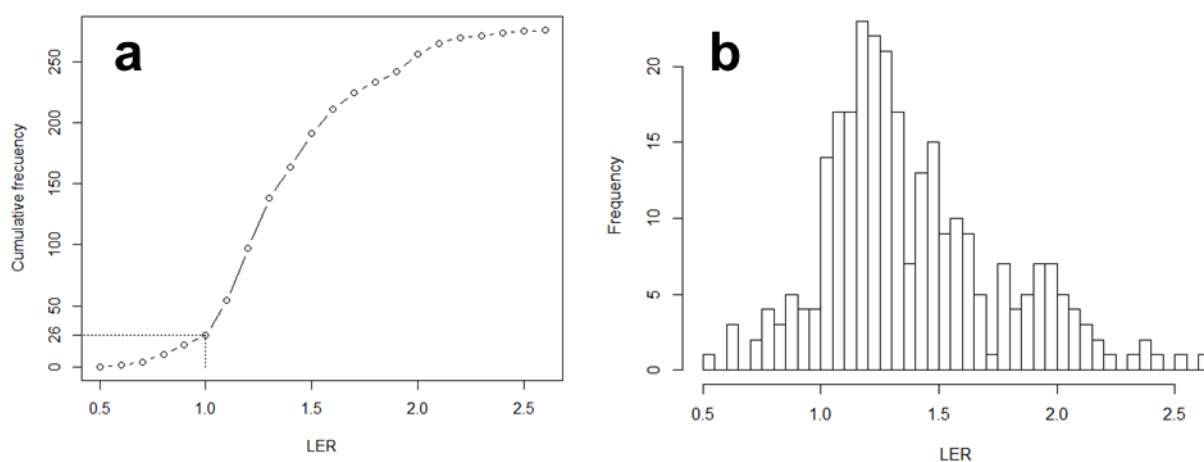


Fig. 2. Cumulative frequencies (a) and frequency distribution (b) of land equivalent ratios (LER) for fruits and vegetables intercropping.

3.2. Illustration with 3 cases from literature

For illustrative purpose, the model combining MPT and LER was run on 3 studies for which sufficient data was available. Among the reviewed papers, the risk-return combination curves took two possible functional shapes. The first functional form appears when a low yield - low risk crop is combined with a high yield - high risk crop (Fig. 3a; 15 of the 24 studies). In the example given here (cabbage-bean intercropping), diversification led to a strong reduction in risk

and association made it possible to reach the lowest level of risk for a yield similar to the one obtained with cabbage only. The second functional form is obtained when a high yield - low risk crop is combined with a low yield - high risk crop (Fig. 3b; 9 of the 24 studies). Interestingly, in this functional form, adding a high-risk / low-yield crop to a low-risk / high-yield monoculture is still beneficial in terms of risk reduction. In the example given here (carrot- parsley intercropping), risk reduction was moderate and yield improvement was particularly high. The only agroforestry systems for which we found sufficient data in the literature is the coffee – banana system (Fig. 3c). It corresponds to the first functional form. In this particular example, risk reduction is marginal but yield improvement can be important. The main difference with the cabbage-bean association is that in the coffee banana system, no combination of the two crops makes it possible to reach at the same time both a lower risk and a higher yield than the monocultures.

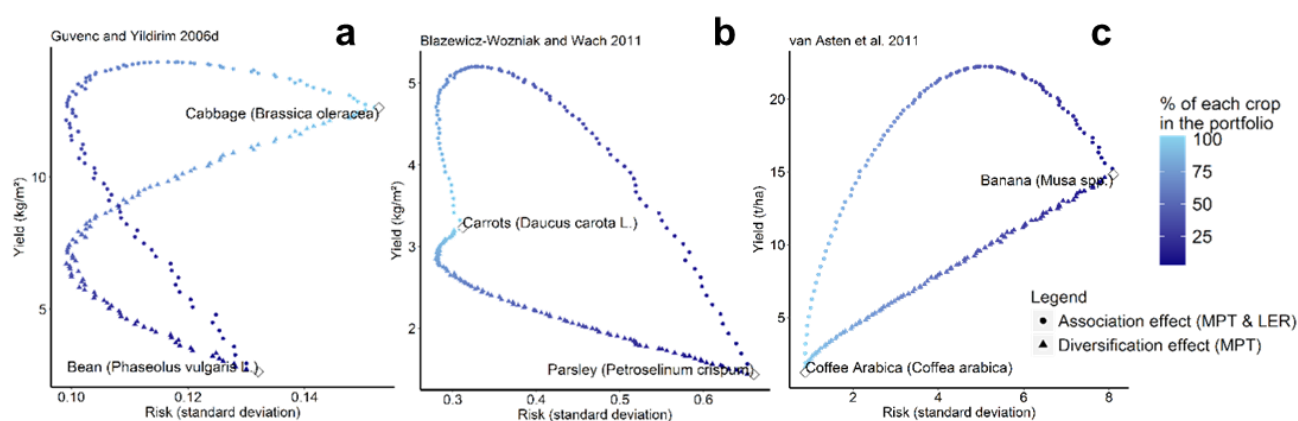


Fig. 3. Risk-return combinations observed for the two types of interactions. (a) a low yield - low risk crop is associated with a high yield - high risk crop, (b) a high yield - low risk crop is associated with a low yield - high risk crop. (c) fruit-based agroforestry system where a low yield - low risk crop is associated with a high yield - high risk crop. Dots (●) represent the performances of intercropping systems for different proportions of crop A and B in the case where only the diversification effect is considered, triangles (▲) represent the performances of intercropping systems for different proportions of crop A and B in the case where both the diversification effect and the association effect are considered.

4. Discussion

The two perspectives examined here were Modern Portfolio Theory, and Land Equivalent Ratio. The former quantifies the effect of diversification on risk, the latter measures the effect of association on production. This research has merged both approaches in a combined framework in order to assess horticultural-agroforestry system performances. The results show how some fruit and vegetable combinations can outperform monoculture in both the risk and

production dimensions. In other words, that it is possible to reduce the overall risk related to production while maintaining or even increasing the global yield thanks to the association of fruits and vegetables. Even though application of this framework to real situations was limited in this study (due to the scarcity of literature data), our results indicate that a two dimensional analysis (risk and return) of agroforestry systems adds insight into the assessment of such systems. Further evaluations of yield and associated standard deviations in a wide variety of agroforestry systems are now needed to evaluate the conditions in which such benefits can be expected. It would be especially interesting to extend this approach to more diversified systems. From the theoretical point of view, extension of the framework to situations with more than two crops is straightforward and does not present any mathematical difficulty. The issue once again lies in the availability of data since (to our knowledge) no study have evaluated yield and standard deviations of more than 2 crops in associations compared to monoculture.

Besides the issue of data availability on production, a further limitation of our study is that we limited our analysis to crop production. However, crop productivity does not directly reflect economic profitability. To further enhance and improve our model, more information on production costs and returns (especially in intercropping systems) would also be necessary (Betters, 1988).

Finally, this study only accounts for the effect of association on production and does not consider the effect of crop association on risk. While many studies have focused on the effect of crop association on overall production, the particular issue of production variability in agroforestry systems remains unstudied (Blandon, 2004; Mead and Willey, 1980). A consensus seems to emerge on the fact that crop association can decrease the risk associated with each crop (Rao and Singh, 1990; Vandermeer and Schultz, 1990) but this effect has rarely been quantified. Therefore, our hypothesis that the individual risk associated to each crop remains unchanged under intercropping can be considered as a conservative hypothesis; and integrating an effect of association on risk is likely to strengthen our conclusion that crop association benefits both production and risk reduction.

Acknowledgments

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Annexe G. How to reconcile short-term and long-term objectives in agroforestry systems? An application of viability theory to Mixed Horticultural Systems

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This work was presented at the DiverIMPACTS¹⁵ European Conference on Crop Diversification, September 18-21 September 2019, Budapest, Hungary.

Link: <https://zenodo.org/record/3516329#.XcQ6o1dKiUk>

Reference: Paut, R., Sabatier, R., Tchamitchian, M., 2019. How to reconcile short-term and long-term objectives in agroforestry systems? An application of viability theory to Mixed Orchard-Market Gardening Systems, in: European Conference on Crop Diversification. Budapest, Hungary.

1. Introduction

The dual productive and environmental challenge that agriculture is facing has led to the emergence of new farming models based on agro-ecological paradigms (Altieri, 2004; Wezel et al., 2014). These systems are built on greater biological diversity that combines cultivated and natural elements within the agroecosystem. One of these systems, known as Mixed Horticultural

¹⁵ DiverIMPACTS is a Horizon 2020 project (Grant No 727482). Diversification through Rotation, Intercropping, Multiple Cropping, Promoted with Actors and value-chains towards Sustainability.

Systems (MHS), corresponds to the intercropping of fruit trees and vegetables. This system is attracting a growing interest in Europe, especially among new farmers (Léger et al., 2018; Warlop, 2016). It represents a diversification strategy that goes further an increasing number of crops, since it adds a functional diversity provided by trees. However, the management of MHS systems is particularly challenging for two main reasons. The first is linked to their complexity, since they add up the intrinsic difficulties of two very demanding systems -fruit trees and vegetables-. The second limitation is related to the fact that such systems involve, even more than for single-species systems, a need for prioritization and trade-offs between objectives and constraints. The simultaneous management of short-term market gardening and long-term orchard, with their own dynamics, can be very complex and jeopardize the long-term viability of the enterprise. The objective of the present study is therefore to provide a modelling framework for the analysis of agroforestry systems that combine annual and perennial crops.

2. Materials and Methods

In the present study, we rely on the framework of the Viability Theory (VT) to assess the management conditions that make it possible to conciliate long-term and short-term dynamics of vegetable and fruit trees. VT is a mathematical framework developed by Aubin (1991) that studies the evolution of dynamical systems under constraints. Its recent applications to natural resource management has proved to be particularly relevant in the fields of fisheries, silviculture or livestock (Sabatier et al., 2017). In the present study, we apply viability theory to explore different management strategies in MHS systems.

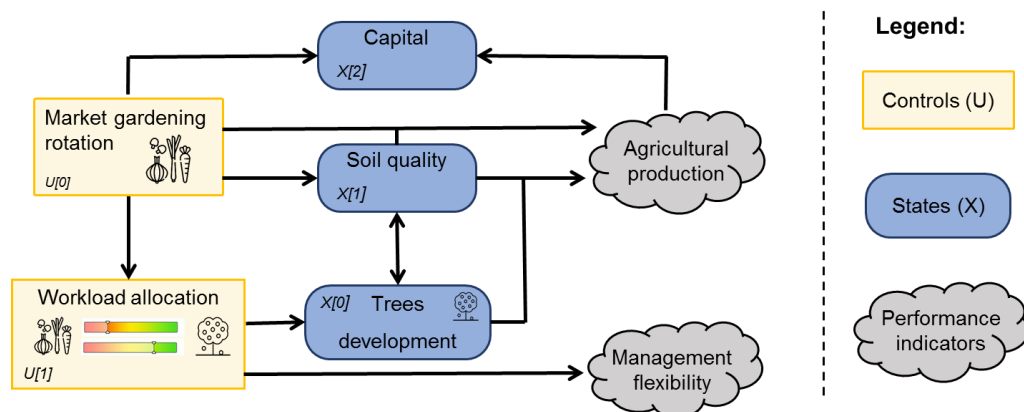


Fig. 1. Conceptual model representation

This framework makes it possible to identify a set of viable management options that maintain the system within a set of constraints over time. It is based on states (X) and controls

(U). States describe the agroecosystem and can vary over time (Fig. 1). Controls represent the levers available for farmers to steer their cropping system, e.g. the choice of vegetables rotation or the workload allocation between fruit trees and market gardening. In our case study, we compare a short-term strategy aiming to promote vegetable production with a long-term strategy that gives priority to the establishment of fruit trees. To do so, we analyze the dynamics of MHS systems as a function of the workload allocation between the two component enterprises (fruit trees and vegetables).

3. Results

The Net Present Values (NPVs) showed that the short-term strategy (Fig. 2a) obtained a greater annual economic profitability during the first years. Indeed in the early years, the costs of planting and operating fruit trees led to a decrease in NPV, but from the sixth year onwards, this loss was offset and the long-term strategy (Fig. 2b) became more effective. Besides, the cumulative NPVs over the whole period indicates that long-term strategy is globally more profitable, indicating that in the long run, a strategy favoring fruit trees establishment might be desirable.

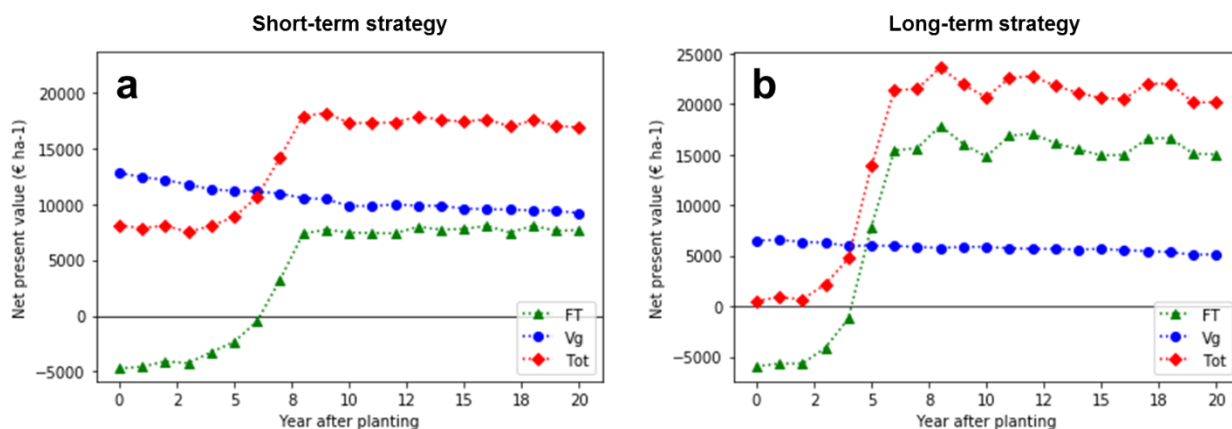


Fig. 2. Evolution of fruit trees (FT), vegetables (Veg) and total (Tot) net present values of a simulated mixed horticultural system over time, as a function of two management strategies: (a) a short-term strategy favoring vegetables production over fruit trees growth; (b) a long-term strategy through the prioritization of fruit trees growth.

4. Discussion and Conclusions

Using this dynamic modelling approach based on viability algorithms, we simulated management decisions that respected the socio-ecological constraints of farmers. This makes it

possible to identify optimal management strategies for both vegetables and fruit trees, and to assess their impact on the long-term dynamics of the system. Results showed that the strategy of promoting tree growth led to better long-term profitability. On the other hand, it requires for farmers being able to cope with several consecutive years of lower performance for trees establishment. The present work also points out the necessary trade-offs generated by the system's complexity (integrating the role of ecological and heuristic uncertainties). Besides, there is still little literature on system components dynamics (e.g. fruit trees-vegetables interactions) which were mainly hypothesized. This raises the need for further research on Mixed Horticultural Systems biological processes.

Annexe H. Complementarities or complexity? The case study of Horticultural Agroforestry Systems

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Reference: Paut, R., Boury-Esnault, A., Sabatier, R., Tchamitchian, M., 2019. Complementarities or complexity? The case study of Horticultural Agroforestry Systems. In: 4th World Congress on Agroforestry. Strengthening links between science, society and policy. 20-22 may 2019, Montpellier, France.

Abstract

Among agroforestry systems, the intercropping of fruits and market gardening (Horticultural Agroforestry System – HAS) is innovative and attracts more and more new entrants to farming (Burgess et al. 2018; Léger et al. 2018). Although HAS meet environmental and social challenges, particularly with regard to diversified and local food consumption, their management is challenging because of species diversity and the complexity of fruit and vegetable management practices (Lauri et al. 2016). The present study aims to understand how labor organization and management practices are impacted by the agroforestry configuration. A framework co-developped with farmers was implemented to record workload in market gardening and orchard activities. Regular follow-ups and semi-structured interviews in 9 farms made it possible to acquire data on workload for fruit trees and vegetable management practices and to highlight frictions points between these two activities. The results reveal (i) an increase in the overall workload induced by the management of two activities; (ii) numerous friction points between orchard and market gardening management practices (Fig. 1); (iii) innovative strategies developed by farmers to address this increasing complexity. Often very promising on paper, HAS are sometimes more difficult to set up in the field (Eksvärd 2016). The present work points out

the main antagonisms related to the simultaneous implementation of fruits and vegetables in an agroforestry design.

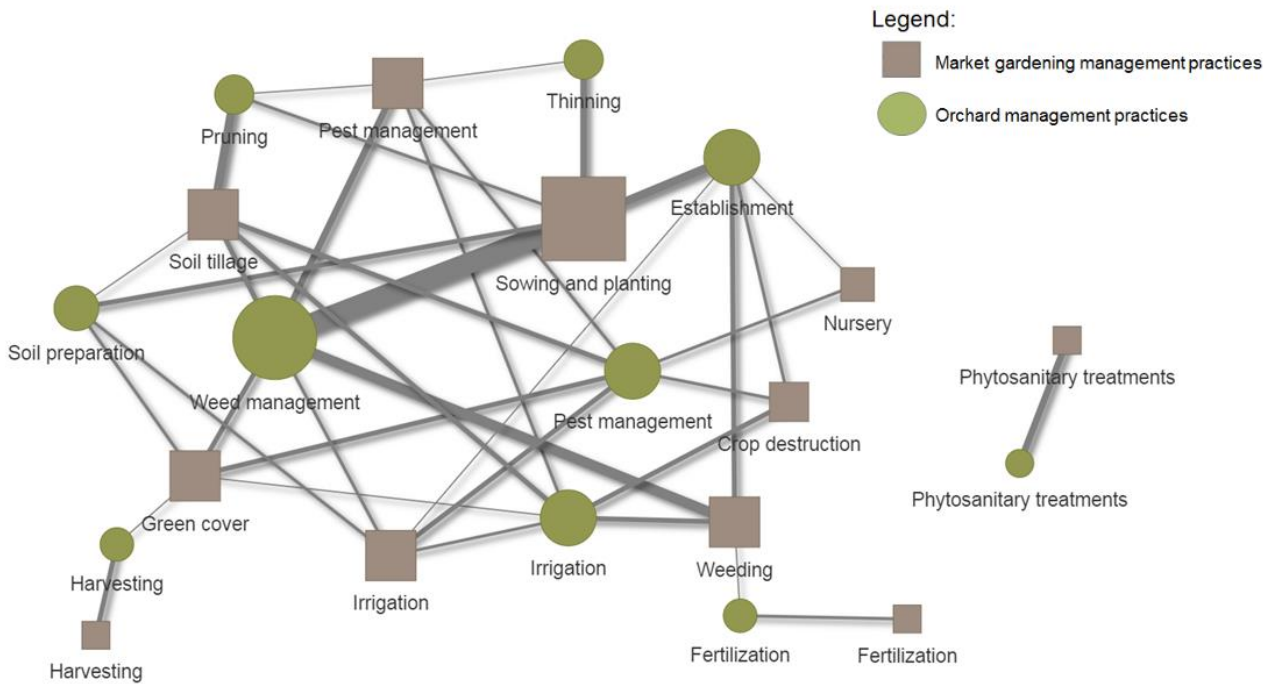


Fig. 1. Network of “friction points” between orchard and market gardening management practices. Square nodes (■) represent market gardening management practices; circle nodes (●) represent orchard management practices. Node size is proportional to the number of interactions in which they are involved. Edges thickness is proportional to the intensity of the interaction between two nodes (number of occurrence among farmers).

Keywords: Fruit-trees, Market gardening, Management practices, Intercropping, Horticulture.

Annexe I. Co-design and on-farm experimentation of practices combining conservation agriculture and agroforestry

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This work was presented at the 4th World Congress on Agroforestry. Strengthening links between science, society and policy. 20-22 may 2019, Montpellier, France.

Abstract

Agroforestry (AF) studies tend not to take much into consideration the different options available for the management of crops per se, generally taking into account classical techniques. However, in these single farming systems, reduced or no-tillage methods using mulch or cover-crops defined as Direct seed Mulch based Cropping systems (DMC) are gaining momentum. According to recent studies, DMC systems result under specific conditions in an enhancement of biological activity of soils and optimization of soil-plant-microorganisms interactions which in turn can enhance the resistance of crops towards plant pathogens. DMC systems have however been rarely combined with AF systems. A straightforward explanation lies in the high level of expertise needed to follow each of the two approaches, which makes their combination highly complex. But more fundamental issues such as the difficulties to manage root competition between trees and vegetables without ploughing are also at stake. The objectives of our work is (1) the co-design and co-implementation with farmers of DMC and AF systems, (2) the study on how these systems and their combination affect the farming system in its whole and (3) the continuous diffusion of the results of this study. We focus on a co-design which is a result from a thorough collaboration between the farmers and our partners which are AF structures and

experts in different fields. We started our work in 2016 and are currently collaborating with a network of 34 farms (arable crops, breeding and horti- culture) in the South-East of France which are using or developing DMC and/or AF systems (e.g. vegetable-orchards, agroforestry in arable crops) since 2007 and up. Ndoli (2018) has already shown that under specific conditions the combination of DMC and AF systems can lead to a reduced productivity as in the case of maize grown under trees. Hence, one of our aims is to identify technical and design options optimizing the combined management of crops and trees in DMC systems and allowing the success of the farming system in the long run. We direct this identification into an iterative process with the co-design of the farms. The co-design of the DMC and AF systems is implemented based on the diagnosis of the farming system at various levels associated to the farmer's objectives. On-farm experiments are then processed by the farmers in order to test the viability of the design. The ADAF carries out with the farmer and in relation with the technical partners the monitoring and evaluation of various parameters which assess the agronomic, environmental and socio-economic per- formances of the farm as well as the soil and crops conditions. Focus is also made, through a systemic approach, on the specific linkage between crop culture and tree management (e.g. workforce repartition and adaptation in vegetable-orchards).

Keywords: co-design, conservation agriculture, on-farm experimentation, systemic approach, participatory development.

Résumé. Les vergers-maraichers sont des systèmes mixtes agroforestiers qui visent à optimiser l'utilisation des ressources spatiales et temporelles en produisant des fruits et des légumes sur la même parcelle. De ce point de vue, ces systèmes semblent en mesure de répondre au double enjeu productif et environnemental auquel l'agriculture est confrontée aujourd'hui. Néanmoins, les vergers-maraichers sont caractérisés par une grande complexité structurale et organisationnelle, car ils combinent deux ateliers très exigeants possédant des dynamiques contrastées. Dans cette optique, les conditions permettant d'obtenir un compromis entre résilience des performances et complexification de la gestion du système nécessitent d'être identifiées. L'objectif de ma thèse est donc de caractériser les compromis entre les bénéfices attendus de ces systèmes et les difficultés engendrées par leur complexité structurale et organisationnelle. La démarche de recherche s'appuie sur le développement de plusieurs modèles qui mobilisent alternativement (i) la théorie du portefeuille ; (ii) le concept de Surface Equivalente Assolée ; (iii) la modélisation dynamique de type états-contrôles. Ces outils de modélisation sont complétés par une approche compréhensive au travers d'entretiens semi-directifs réalisés auprès de 15 agriculteurs du sud-est de la France. La combinaison de ces différentes approches met en évidence quatre résultats principaux. (i) Les effets de la diversification dans un contexte horticole peuvent permettre de réduire la variabilité de la production globale jusqu'à 77% ; (ii) l'association de cultures, en plus d'augmenter le rendement global, réduit davantage le risque ; (iii) la part relative de l'arboriculture et du maraichage dans l'assolement, couplée à l'allocation du temps de travail entre ces deux ateliers sont des éléments déterminants dans la gestion à long terme de la dynamique du système ; (iv) enfin, gérer la complexité liée à la diversité des cultures et à leur agencement agroforestier implique une reconfiguration des pratiques de gestion. L'ensemble de ces résultats met en évidence que la conduite de ces systèmes permet d'arbitrer entre les différentes dimensions étudiées : réduction des risques, synergies entre cultures, différences de dynamiques entre arboriculture et maraichage, mais également, impact de la configuration agroforestière sur les pratiques agricoles. Ces travaux de thèse permettent ainsi de mieux caractériser les compromis entre les bénéfices attendus des vergers-maraichers et la complexité de leur mise en œuvre.

Mots clefs : Agroforesterie ; verger-maraicher ; horticulture ; agroécologie ; théorie du portefeuille ; risque

Abstract. Mixed fruit tree-vegetable systems (MFV) are agroforestry systems that aim to optimize the use of spatial and temporal resources by producing fruits and vegetables on the same plot. In this respect, these systems seem to be able to meet the dual productive and environmental challenges that agriculture faces today. Nevertheless, MFV systems are characterized by great structural and organizational complexity as they combine two very demanding enterprises with contrasting dynamics. In this context, the conditions that enable to achieve a compromise between resilient performance and the increasing system management complexity need to be identified. The objective of my thesis is therefore to characterize the trade-offs between the expected benefits of MFV systems and the difficulties generated by their structural and organizational complexity. The research approach is based on the development of several models that alternatively mobilize (i) portfolio theory; (ii) the concept of Land Equivalent Ratio; (iii) dynamic states-controls modeling. These modeling methods are complemented with a comprehensive approach through semi-directive interviews conducted with 15 farmers in south-eastern France. The combination of these different approaches highlights four main results. (i) The effects of diversification in a horticultural context can reduce overall yield variability by up to 77%. (ii) Intercropping, in addition to increasing the overall yield, further reduces risk. (iii) The relative share of fruit trees and vegetables in crop rotation, coupled with the allocation of workload between these two enterprises are determining elements for the long-term management of the system dynamics. (iv) Finally, managing the complexity associated with crop diversity and agroforestry arrangement implies a reconfiguration of the system's management practices. All these findings show that the management of these systems makes it possible to arbitrate and steer the system between the different dimensions studied: risk reduction, crop synergies, differences in dynamics between fruit trees and vegetables, but also the impact of the agroforestry configuration on management practices. This thesis work thus provides a better understanding of the trade-offs between the expected benefits of MFV systems and the challenges of their implementation.

Keywords: Agroforestry; mixed fruit tree-vegetable systems; horticulture; agroecology; portfolio theory; risk