Performance environnementale de fermes maraîchères en agriculture biologique

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THÈSE DE DOCTORAT DE

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Ecole doctorale Ecologie, Géosciences, Agronomie et Alimentation
Spécialité : « *Sciences Agronomiques* »

Par
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Thèse présentée et soutenue à Rennes, le 17/05/2022
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Résumé

En France, le maraichage en agriculture biologique est un secteur dynamique, composé de fermes présentant différents niveaux d'agroécologie laissant supposer une potentielle bifurcation entre des fermes biologiques « conventionnalisées » reposant sur l'utilisation d'intrants, et des fermes « agroécologiques » valorisant les ressources de l'écosystème. Cette hétérogénéité interroge sur la diversité potentielle des impacts environnementaux associés. S'appuyant sur des données essentiellement qualitatives collectées auprès de 165 fermes et sur un cadre d'analyse conceptuel, la thèse propose une caractérisation de la diversité des fermes et identifie quatre types : 1) les microfermes diversifiées et utilisant peu d'intrants ; 2) les maraîchers diversifiés de taille moyenne ; 3) les producteurs spécialisés dans la culture sous abri ; et 4) les maraîchers spécialisés dans la culture de plein champ. Les caractéristiques des fermes et leur variabilité confirment l'existante de deux pôles « conventionnalisées » et « agroécologiques », tout en montrant qu'il s'agit d'une vision simplificatrice, la majorité des fermes se trouvant entre ces deux pôles.

Afin d'évaluer les performances environnementales de ces systèmes maraichers, l'analyse du cycle de vie (ACV) a été mobilisée. Les fermes complexes, cultivant une grande diversité de légumes en les associant sur de petites surfaces dans une approche agroécologique systémique, posent des défis à cette méthode dans la prise en compte de leurs impacts sur la biodiversité et les interactions spatiales et temporelles sur lesquelles elles reposent. En adaptant le système expert SALCA-BD, j'ai comparé des fermes par rapport à leur impact sur la biodiversité, et mis en évidence l'importance des habitats semi-naturels pour la biodiversité. SALCA-BD permet une évaluation détaillée de l'impact sur la biodiversité qui peut servir de base pour développer des méthodes d'évaluation combinant impacts globaux et locaux dans un cadre d'ACV.

Une approche système de l'ACV a été employée. Cette approche aborde la ferme comme un tout produisant différents produits et où tous les intrants, opérations, et émissions sont rapportés à la production annuelle totale. Cette optique correspond à la logique de l'agroécologie, où beaucoup d'intrants sont raisonnés à l'échelle de la ferme et non à la culture, et où les cultures sont complémentaires les unes des autres. Préférée à une ACV par culture, l'approche système prend en compte les interactions au sein du système, et permet de comparer les systèmes entre eux. D'un point de vue pratique, elle est adaptée au format des données souvent disponibles dans les fermes diversifiées et évite des allocations.

L’application de cette approche de l’ACV à trois fermes contrastées a permis l’analyse des forces et faiblesses de ces fermes vis-à-vis de l’environnement, faisant apparaître de grandes différences entre les systèmes dans leurs principaux postes d’impact. Avec l’utilisation de plusieurs catégories d’impact et unités fonctionnelles, aucune ferme ne ressort clairement meilleure qu’une autre pour l’environnement. Exprimé par unité de surface, la ferme de plein champ, plus extensive, a le moins d’impact et la ferme spécialisée sous tunnel a le plus d’impact, quelle que soit la catégorie d’impact. En revanche, quand les impacts sont exprimés par kg de produit ou par la valeur des produits (en Euro) les différences entre les trois fermes sont plus faibles. La comparaison des systèmes doit se faire en gardant à l’esprit que les fermes ont des productions différentes et complémentaires. Les interactions et complémentarités entre ces modèles méritent d’être étudiées.

Enfin, l’application de l’ACV système a permis d’identifier des perspectives de développement méthodologiques pour mieux estimer les émissions de nitrate, pour harmoniser l’évaluation des impacts environnementaux des fertilisants organiques et pour intégrer la question de la pollution par les (micro)plastiques.

Abstract

In France, the organic vegetable production sector is dynamic, composed of farms with different levels of agroecology, suggesting a bifurcation between "conventionalized" organic farms based on input use, and "agroecological" farms using the resources of the ecosystem. This heterogeneity raises questions about the potential diversity of associated environmental impacts. Based on qualitative data collected on 165 farms and a conceptual analysis framework, this thesis proposes a characterization of farm diversity and identifies four types: 1) diversified, low-input microfarms; 2) diversified, medium-sized market gardeners; 3) producers specialised in cultivation under shelter; and 4) large market gardeners specialised in open field cultivation. The characteristics of the farms and their variability confirm the existence of two poles, "conventionalized" and "agro-ecological", which should be considered as a conceptual perspective with two poles and a gradient of farms between them.

To assess the environmental performance of these vegetable systems, life cycle assessment (LCA) was used. Complex farms, growing a wide variety of vegetables by combining them on small areas in a systemic agroecological approach, challenges this method regarding their impacts on biodiversity and the spatial and temporal interactions on which they rely. By adapting the SALCA-BD expert system, I compared the farms' impact on biodiversity, and highlighted the importance of semi-natural habitats for biodiversity. SALCA-BD allows a detailed assessment of the impact on biodiversity which can serve as a basis for developing assessment methods that combine global and local impacts in an LCA framework.

A system LCA approach was used. This approach considers the farm as a whole producing different products, all inputs, operations, and emissions are related to the total annual production. It corresponds to the logic of agroecology, where many inputs are reasoned at the farm scale rather than the crop level, and where crops complement each other. The system LCA approach, which is preferred to a crop LCA, considers the interactions occurring within the system and allows the comparison of systems. From a practical point of view, it is adapted to the data format often available on diversified farms and avoids allocation.

The application of system LCA to three contrasting farms allowed the analysis of their strengths and weaknesses with respect to their environmental impacts, revealing large differences between the systems in their main impact contributors. Using of several impact categories and functional units, no one farm stood out as clearly better for the environment. Expressed per unit area, the extensive open-field farm had the lowest impact, and the specialized tunnel farm had the highest impact, regardless of impact category. However, when impacts were expressed per kg product or per product value

(Euro), differences between the three farms were smaller. The comparison of the systems must be done keeping in mind that the farms have different and complementary productions. The interactions and complementarities between these models deserve to be studied.

Finally, the application of the system LCA allowed to identify prospects for methodological development to better assess nitrate emissions, to harmonize the assessment of the environmental impacts of organic fertilizers and to integrate the issue of pollution by (micro)plastics.

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AB	Agriculture biologique
ACV	Analyse du cycle de vie
AHC	Agglomerative hierarchical clustering
ANRT	Association Nationale Recherche Technologie
BD	Biodiversité ou *biodiversity*
CAP	Common Agricultural Policy
CC	Changement climatique ou *climate change*
CED	Demande cumulative en énergie ou *cumulative energy demand*
CF	Characterization factors
CH_4	Méthane ou *methane*
CIFRE	Convention industrielle de formation par la recherche
CO_2 eq.	CO_2 équivalent
CO_2	Dioxyde de carbone ou *carbon dioxid*
CTIFL	Centre technique interprofessionnel des fruits et légumes
EMEP	European Monitoring and Evaluation Programme
EU	European Union
FAMD	Factor Analysis of Mixed Data
FiBL	Forschungsinstitut für Biologischen Landbau
FNAB	Fédération nationale de l’agriculture biologique
FU	Functional unit
GH	Greenhouse
ICV	Inventaire du cycle de vie
IFOAM	Fédération internationale des mouvements d'agriculture biologique
INRAE	Institut national de recherche pour l'agriculture, l'alimentation et l'environnement.
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ISG	Indicator species groups
ISO	Organisation internationale de normalisation ou international organization for standardization

ITAB	Institut technique de l'agriculture biologique
LCA	Life cycle assessment
LCI	Life cycle inventories
MCA	Multiple correspondence analysis
ME	Eutrophisation marine ou *marine eutrophication*
MF	Microferme ou *microfarm*
N	Azote ou *nitrogen*
N_2O	Protoxyde d'azote ou *nitrous oxide*
NH_3	Ammoniac ou *ammonia*
NO	Oxide nitrique ou nitric oxide
NO_3	Nitrate
OAT	One at a time
OF	Open-field (dans le chapitre 3)
OF	Organic farming (sauf dans le chapitre 3)
OP	Ferme de plein champ ou outdoor production
PCA	Principal component analysis
PRO	Produits résiduaires organiques
SALCA-BD	Swiss agricultural life cycle assessment - biodiversity
SETAC	Society of Environmental Toxicology and Chemistry
SNH	Semi-natural habitats
SP	Ferme spécialisée en culture sous tunnel ou *sheltered production*
SQCB	Sustainability Quick Check Tool for Biofuels
UAA	Utilised agricultural area
UF	Unité fonctionnelles
UMR SADAPT	Unité mixte de recherche Science Action Développement - Activités Produits Territoires
UMR SAS	Unité mixte de recherche Sol Agro et hydrosystèmes Spatialisation
UNEP	Programme des Nations Unies pour l’environnement
VPS	Vegetable production systems

Avant-propos

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Chapitre 1. Introduction générale

1. L'agriculture biologique et le maraichage

1.1. L'agriculture biologique, un mouvement hétérogène depuis ses origines

Les origines de l'agriculture biologique remontent aux années 1920, en réaction à l'industrialisation de l'agriculture (de Silguy, 1997[1]). Différentes approches émergent en Europe, donnant lieu à des courants variés. L'anthroposophie, philosophie ésotérique créée par l'autrichien Rudolf Steiner liant la terre et le cosmos et développée dans son cours aux agriculteurs (Steiner, 1924), est à l'origine de l'agriculture biodynamique, portée par Pfeiffer en Allemagne notamment (Pfeiffer, 1938). L'agriculture organique, inspirée des thèses d'Howard (1940), met l'humus et la fertilité des sols au centre de sa réflexion, et conteste l'usage d'engrais de synthèse. En Suisse, l'agriculture organo-biologique fondée par un homme politique et sa femme, Hans et Maria Müller et un médecin, Hans Peter Rusch, adoptait une vision économique et sociale en visant l'autonomie des producteurs. Au Japon, Masanobu Fukuoka développe dans les années 1930 l'agriculture naturelle ou sauvage, reposant sur l'absence de labour, d'engrais chimiques ou de compost préparé, de désherbage et de recours à la chimie (Fukuoka et al., 1975).

En France, l'agriculture biologique se développe dans les années 1950, d'un côté à l'initiative d'une association de médecins et homéopathes avec une approche alimentation et santé, et d'un autre côté à l'initiative d'agriculteurs, liés à la *Soil association* créée en Angleterre en 1946 dans la suite des travaux d'Howard, soucieux du rôle de l'humus dans le maintien de la fertilité des sols. En 1963, Jean Boucher et Raoul Le Maire mettent au point un fertilisant à base d'algues, le lithothamne, qu'ils commercialisent. En réaction à cette approche mercantile, le mouvement Nature et Progrès voit le jour en 1964, contestant la société de consommation et l'économie productiviste.

En 1972 à Versailles est créée l'IFOAM, Fédération internationale des mouvements d'agriculture biologique, qui favorise le rassemblement de structures ayant diverses approches idéologiques et techniques. En France, les différents mouvements se regroupent en 1975 et créent la fédération nationale de l'agriculture biologique, la FNAB. La période qui suit vise à faire sortir l'agriculture biologique de la confidentialité et à obtenir une reconnaissance officielle. C'est chose faite en 1980 par la loi n° 80-502 d'orientation agricole qui, sans utiliser le mot agriculture biologique (AB), reconnait que « les cahiers des charges définissant les conditions de production de l'agriculture n'utilisant pas de produits chimiques de synthèse peuvent être homologués par arrêté du ministre de l'agriculture »

[1] Cet ouvrage m'a servi de référence principale pour documenter l'approche historique de l'agriculture biologique.

(JORF, 1980). Cependant cette définition restrictive ne satisfait pas pleinement les acteurs de l'AB qui revendiquent une approche holistique, intégrant les questions de préservation des agro-écosystèmes, les cycles biologiques et l'activité biologique des sols (Lockeretz, 2007).

Les premiers cahiers des charges sont rédigés dans les années 1980 et le label « AB » certifiant les produits issus de l'agriculture biologique voit le jour en 1985. En 1991, le premier règlement européen parait (European Commission, 1991) et reconnait le rôle de l'AB dans la protection de l'environnement. Un nouveau règlement paraît en 2007 (European Commission, 2007) afin d'harmoniser les règlements bio à l'échelle de l'Union Européenne. Depuis 2009, le cahier des charges français disparaît au profit de la réglementation européenne.

Entre temps, l'AB s'est considérablement développée en France, passant de 3500 fermes en 1995 à plus de 10 000 en 2001 (Agence Bio, 2007). Après une phase de stagnation jusqu'en 2005, la croissance reprend, le nombre de fermes en AB passe la barre des 20 000 en 2010 et celle des 50 000 en 2020 (Agence Bio, 2021). Le marché du bio a suivi la même tendance pour atteindre 11,9 milliards d'euros en 2019, dont 55 % sont vendus dans les supermarchés généralistes, 28 % dans les magasins bio et 11 % en vente directe (Agence Bio, 2020). Le cahier des charges européen ne convient pas à tous les acteurs, jugé trop peu exigent par rapport au cahier des charges français, et ouvrant la porte à des pratiques ne correspondant pas à l'esprit de l'AB. Pour Nature et Progrès, avec ce règlement, « l'agriculture biologique entre dans une phase de récupération qui la réduit à une promesse commerciale » (Nature & Progrès, 2017). La FNAB s'oppose également à la suppression du label français, et crée en réaction le label Bio Cohérence qui « complète le règlement européen pour rester fidèle aux fondamentaux de la bio » (Bio Cohérence, 2022), se dotant d'une charte et d'un cahier des charges.

L'histoire de l'agriculture biologique en France met en évidence ses influences multiples et son hétérogénéité. Son développement rapide et le marché grandissant entrainent (et sont causées par) l'arrivée d'acteurs agroindustriels qui rompent avec l'approche historique. Cette industrialisation de la production biologique est décrite en Californie par Buck et al. (1997), qui introduisent le terme de « conventionnalisation », et peut inclure la mise en œuvre d'économies d'échelle avec des fermes plus grandes, le recours accru à l'achat d'intrants (e.g. machines, engrais, aliments pour animaux) ou encore la mécanisation du processus de production (Darnhofer et al., 2010). L'idée que cette conventionnalisation ne touche qu'une partie des agriculteurs, l'autre maintenant une pratique « artisanale » de l'AB, alimente l'hypothèse de la bifurcation (Darnhofer et al., 2010) et trouve un écho auprès du grand public avec l'idée d'une AB « à deux vitesses » (Bolis, 2017). Pour Rosset et Altieri (1997), l'approche holistique de l'AB est menacée par son adoption par « le Capital ». Ils opposent une

AB agroécologique, définie comme "une approche qui va au-delà de l'utilisation d'intrants alternatifs pour développer des agroécosystèmes intégrés avec une dépendance minimale aux intrants externes", à l'AB reposant sur la substitution d'intrants, piloté par le secteur agroalimentaire.

1.2. Le maraichage biologique en France : héritage des pionniers, bifurcation et nouveaux courants

Le maraichage biologique suit la même tendance que l'AB dans son ensemble. Porté par des pionniers dans les années 1980 (Bio de Provence, 2012), le secteur français des légumes biologiques a connu une forte croissance ces dernières années, en raison des conversions d'exploitations conventionnelles et de nouveaux entrants (FRAB, 2019). En 2001, 1,5% des surfaces cultivées en légumes étaient en AB, contre 9,4% en 2020 (Agence Bio, 2021[2]). Le débat autour de la conventionnalisation s'invite également dans le maraichage. Navarrete et al. (2015) observent le contraste entre des maraichers spécialisés ayant adopté une organisation du travail et une commercialisation plutôt industrielle, bénéficiant d'économies d'échelle, et des fermes de petite taille, fortement diversifiées. Elles soulignent qu'une partie des exploitations biologiques issues de fermes conventionnelles, spécialisées dans un petit nombre de légumes, reste spécialisée après la conversion, tandis que d'autres évoluent vers un système agricole plus diversifié. Lefevre et al. (2020) soulignent les difficultés à maintenir des pratiques agroécologiques en matière de protection phytosanitaire tout en répondant aux exigences des filières commerciales, notamment des circuits longs, impliquant des compromis dans les pratiques agricoles. En 2019, le débat sur l'autorisation ou non des serres chauffées en AB en France a cristallisé les oppositions entre les bio « historiques » et les acteurs conventionnalisés, par exemple des organisations de producteurs ou des coopératives, ayant une section bio (Lecocq, 2019; Schaub, 2019). Le label Bio Cohérence a fait le choix d'interdire les serres chauffées alors que la réglementation l'autorise partiellement.

Toutefois, cette opposition ne doit pas masquer que le maraichage bio est hétérogène, et qu'un discours dichotomique postulant « un espace des possibles limité à deux situations polaires au sein des systèmes alimentaires alternatifs, les initiatives « petites et alternatives » et les initiatives « grandes et conventionnalisées » (Velly et al., 2016) est simpliste.

Depuis une dizaine d'années, une nouvelle tendance se popularise : les microfermes. En France le mouvement démarre suite à la médiatisation de la ferme du Bec-Hellouin (Hervé-Gruyer et Hervé-Gruyer, 2014), inspirée de la permaculture dont les performances économiques ont été suivies par un

[2] En plus du rapport, l'agence bio met à disposition les chiffres bruts : https://www.agencebio.org/wp-content/uploads/2021/07/FigTab_DPjuillet2021.xlsx

chercheur d'AgroParisTech/INRAE (Guégan et Leger, 2015). Ces microfermes, cultivant une grande diversité de légumes, au moins 30, sur une petite surface, au plus 1,5 ha cultivés par équivalent temps plein, s'inscrivent dans un contre-pied à l'agriculture dominante, à la standardisation des produits et la société de consommation, dans une approche rappelant celles des pionniers de l'AB (Morel, 2016). L'émergence des microfermes n'est pas le fruit d'un mouvement coordonné et unifié. Les initiatives puisent leur inspiration, philosophie et/ou technique, dans plusieurs travaux antérieurs.

La permaculture, concept développée depuis 1978 en Australie par Mollison et Holmgren (1978), dont se revendique la ferme de Bec-Hellouin, se définit comme un « cadre conceptuel organisateur qui utilise la pensée systémique et des principes de design pour concevoir des paysages durables qui imitent les motifs et les relations observées dans la nature afin de répondre aux besoins locaux en alimentation, énergie, fibres et aux autres besoins matériels et immatériels » (Morel, 2016).

Le maraichage bio-intensif est apparu aux Etats-Unis, lui-même inspiré par les maraichers parisiens du XIXème siècle. Développé dans les années 1970 par Jeavons (2001) surtout à l'échelle d'une production autonome non commerciale, le mouvement a pris de l'ampleur avec Elliot Coleman aux Etats-Unis et Jean-Martin Fortier au Canada, dont l'ouvrage du jardinier-maraicher (Fortier, 2012) a eu un grand écho en France. Fortier définit le maraichage bio-intensif comme « une méthode horticole qui cherche à maximiser le rendement d'une surface en culture avec le souci de conserver, voire d'améliorer, la qualité des sols » et lui donne une dimension commerciale avec le but d'« en vivre, mais surtout bien en vivre ». Ces démarches sont détaillées dans la thèse « Viabilité des microfermes maraîchères biologiques. Une étude inductive combinant méthodes qualitatives et modélisation » (Morel, 2016).

En France, le mouvement du maraichage sur sol vivant est créé en 2012, sous l'inspiration de l'agriculture de conservation, rejetant le labour et le travail du sol profond. Si l'objectif annoncé « de produire des légumes de qualité tout en ayant un impact positif sur l'environnement ainsi qu'en maintenant ses fermes viables, économiquement et humainement parlant » (Maraichage Sol Vivant, 2021) est multidimensionnel, les leviers proposés sont d'ordre technique et mettent en avant des sols peu travaillés et couverts en permanence. Ces fermes sont de petite taille, souvent moins de 3 ha, avec un chiffre d'affaire modeste, souvent entre 30 000 et 100 000€ (Maraichage Sol Vivant, 2017; Maraichage Sol Vivant Normandie Ile de France, 2017).

Si elles diffèrent par leurs inspirations, ces initiatives alternatives radicales ont en commun de questionner le modèle dominant (Morel, 2016). Leurs promoteurs mettent en avant de fortes aspirations sociales et environnementales (Morel et Leger, 2016), se traduisant par des pratiques telles que la fertilisation par des composts et fumiers locaux voire autoproduits, une grande biodiversité cultivée et spontanée entretenue pour favoriser les régulations biologiques, peu de produits de traitement, un travail du sol minimal, l'usage de paillis végétaux et des circuits commerciaux alternatifs. Ces pratiques sont constatées dans l'enquête que j'ai réalisée, et que je présente dans le chapitre 2, pour la plupart des agriculteurs se déclarant d'une « agriculture "alternative" (permaculture et autres courants) ». Toutefois l'enquête suggère que toutes les pratiques ne sont pas mises en place sur toutes les fermes « alternatives », ou pas dans les mêmes proportions. Ces fermes, que l'on peut qualifier d'agroécologiques, ne constituent pas un ensemble monolithique.

1.3. L'agroécologie, une science, un mouvement social, des pratiques agricoles

Le terme agroécologie fait référence à la fois à un domaine scientifique, un mouvement social et des pratiques agricoles (Wezel et al., 2009). Dans son acception scientifique, l'agroécologie étudie, diagnostique et propose des modes de gestion alternatives, à faible niveau d'intrants, des agroécosystèmes (Altieri, 1989), dans une vision systémique (Meynard, 2017). Le champ d'étude a évolué de la parcelle à la ferme ou l'agroécosystème, et englobe parfois désormais le système alimentaire dans son ensemble. Plusieurs définitions existent, reflétant des visions plus ou moins englobantes et des approches plutôt conceptuelles et pluridisciplinaires ou plutôt agronomiques, orientées vers la pratique (Wezel et al., 2009). L'agroécologie en tant que mouvement social fait référence à une volonté paysanne et militante orientée vers une agriculture durable, autonome et à petite échelle (Wezel et al., 2009). Ces mouvements n'utilisent pas forcément eux-mêmes le terme d'agroécologie pour se décrire.

L'agroécologie comme pratique agricole concerne des modes de production utilisant peu d'intrants et mobilisant (et préservant) les ressources du milieu et les processus biologiques (Caquet et al., 2020) pour favoriser les régulations naturelles de l'agroécosystème, dans une approche systémique de la ferme, différente d'une approche simpliste du type « un problème, un intrant » (Meynard, 2017). Par définition les techniques diffèrent selon les cultures et les contextes pédo-climatiques. En maraichage, les principales techniques concernent par exemple la rotation des cultures, le paillis, les engrais verts, le maintien d'habitats semi-naturels sur la ferme pour favoriser les régulations biologiques.

Dans la thèse, je mobilise le concept d'agroécologie essentiellement dans son approche pratique. Dans le chapitre 2, je m'intéresse à des systèmes qui mettent en place des pratiques agroécologiques, que j'analyse sous l'angle des régulations biologiques et ressources du milieu pour limiter les intrants, dans une approche holistique. J'intègre également la dimension du système alimentaire en m'intéressant aux circuits de commercialisation pour caractériser et distinguer les systèmes. Ces deux dimensions me permettent d'utiliser le cadre d'analyse de Thérond et al. (2017), qui caractérise les formes d'agriculture dans leur relation aux pratiques agroécologiques et leur ancrage territorial.

2. Maraichage et environnement

2.1. Les limites planétaires

Les activités humaines ont un impact environnemental majeur, et à toutes les échelles, y compris l'échelle globale, à tel point qu'on appelle désormais l'ère géologique actuelle l'anthropocène (Crutzen et Stoermer, 2000), pour souligner le rôle central de l'homme dans la géologie et l'écologie. Les atteintes à l'environnement sont nombreuses et de natures diverses. Plus récemment, Rockström et al. (2009) puis Steffen et al. (2015) développent le concept de limites planétaires, à l'intérieur desquelles l'humanité peut s'épanouir en sécurité. Ils en identifient neuf, en quantifient sept et estiment que l'humanité a déjà dépassé plusieurs de ces limites : l'érosion de la biodiversité, les flux géochimiques en azote et phosphore, le changement climatique et le changement d'occupation des sols[3].

Les études sur les limites planétaires avaient identifié la pollution chimique en 2009 sans proposer une quantification de cette limite (Rockström et al., 2009). En 2022, Persson et al. (2022) ont quantifié cette limite planétaire, renommée nouvelles entités (*novel entities*), et estimé que l'humanité l'avait déjà dépassée. Au sein des nouvelles entités, les auteurs avertissent que le plastique, mentionné par Rockström et al. (2009) sans insistance, était élevé au rang de sujet très préoccupant, notamment du fait des microplastiques. Le sujet des microplastiques prend de l'importance dans la littérature scientifique et dans les médias depuis une dizaine d'années (Henderson et Green, 2020) reflétant une préoccupation environnementale grandissante.

Parmi les activités en cause dans le dépassement des limites planétaires, l'agriculture tient une place avérée (FAO, 2002). La FAO cible particulièrement les impacts de l'agriculture sur le changement climatique, la pollution de l'eau par les nitrates et phosphates (eutrophisation) et les pesticides, l'acidification et l'érosion de la biodiversité.

A la lumière du concept des limites planétaires, l'enjeu n'est pas uniquement d'optimiser pour produire des biens dont chaque unité consomme ou pollue moins, mais de réduire la pollution globale à un niveau supportable par la planète.

[3] Rockström et al. (2009) utilisent le terme *land-system change* et réfèrent à la diminution des biomes terrestres assurant une régulation du climat par des échanges d'eau, d'énergies avec l'atmosphère, dont le principal moteur est l'extension et l'intensification de l'agriculture. Steffen et al. (2015) actualisent cette définition et considère, comme indicateur, non plus l'extension des surfaces agricoles mais les surfaces restantes en forêt, en tant que principal biome terrestre impliqué dans la régulation du climat.

2.2. Maraichage et environnement

Les fruits et légumes génèrent 10% de l'empreinte carbone[4] moyenne de l'alimentation en France en 2019, (Carbone 4 et MyCO2, 2022), avec 240 kg CO_2 eq. / personne. C'est en dessous de la contribution de la viande (39%) et du lait et des œufs (17%) à l'empreinte carbone, mais devant les autres produits végétaux. La culture de légumes requiert une fertilisation élevée, avec des risques de fuite de nitrates ou phosphates dans les eaux, contribuant à l'impact d'eutrophisation (Agostini et al., 2010; Schenk, 2006). Le paillage plastique des légumes est une source importante de microplastiques (Bläsing et Amelung, 2018; Campanale et al., 2022) car il est fin et difficile à retirer du sol (Qi et al., 2020), et les fruits et légumes contiennent des concentrations préoccupantes de microplastiques (Oliveri Conti et al., 2020). En agriculture conventionnelle les légumes sont des cultures fortement traitées, à des doses variables selon les types de légumes. Les moins traités sont les choux, qui en 2018 en France ont reçu en moyenne 2,8 traitements (indice de fréquence de traitement), contre 11,2 pour les tomates de pleine terre qui sont les plus traitées (Agreste, 2020).

Plusieurs scénarios prospectifs et recommandations officielles envisagent une augmentation des légumes dans l'alimentation future. Pour des raisons de santé, le programme national nutrition santé 2019-2023 recommande d'augmenter la consommation de légumes (Ministère des solidarités et de la santé, 2019). Dans le régime sain et environnementalement durable défini par l'étude EAT-Lancet (Willett et al., 2019) les légumes occupent également une grande part de la consommation. La production de légumes étant appelée à augmenter, la question de ses impacts environnementaux et de leurs réductions est posée.

L'agriculture biologique se revendique comme une voie permettant de diminuer les dommages environnementaux de l'agriculture, par des pratiques respectueuses de l'environnement, de la biodiversité et des ressources naturelles. De façon plus marquée encore, les maraichers inspirés de courants alternatifs mettent en avant la question environnementale dans le choix de leur modèle agricole. Les principes agroécologiques qui sous-tendent l'AB créent un lien fonctionnel fort entre l'agriculture et son écosystème, puisqu'elle s'appuie sur les régulations naturelles qu'il permet.

Il est dès lors légitime de questionner les performances environnementales de ces fermes par des méthodes permettant d'évaluer les impacts, au-delà des moyens et principes conceptuels.

[4] L'empreinte carbone est une notion liée à l'impact sur le climat. Elle correspond à la quantité de gaz à effet de serre émise par une activité anthropique, incluant l'ensemble du cycle de l'activité. L'empreinte carbone de l'alimentation française est constituée par les émissions de la production nationale (hors exportations) et les émissions de la production étrangère importée en France.

3. L'analyse du cycle de vie, méthode quantitative et multicritère d'évaluation environnementale

Plusieurs méthodes d'évaluation environnementale des activités agricoles existent, dont l'analyse peut reposer sur différents stades de la chaine de causalité liant les pratiques agricoles (causes) aux impacts environnementaux (effets) (Payraudeau et van der Werf, 2005). Certaines méthodes s'appuient ainsi sur des indicateurs au niveau des moyens (e.g. la quantité de fertilisant), d'autres évaluent les flux de polluants générés par l'activité agricole (e.g. les émissions de nitrates). D'autres enfin quantifient les impacts associés à ces flux. Certaines méthodes se concentrent sur un impact en particulier (e.g. l'empreinte carbone) alors que d'autres sont multicritères et couvrent une large gamme d'impacts environnementaux. Parmi ces dernières, on peut citer la méthode Sustainability Assessment and Monitoring RouTine (SMART) (Schader et al., 2016), développée par le FiBL en suivant le guide Sustainability Assessment of Food and Agriculture System (SAFA) (FAO, 2014) et qui évalue la durabilité environnementale, économique, sociale et de gouvernance. La durabilité environnementale est évaluée sur plusieurs critères : l'atmosphère, l'eau, la terre, les matériaux, l'énergie, la biodiversité et le bien-être animal. Pour chacun de ces critères, l'outil donne un résultat sous forme de pourcentage par rapport à un objectif de durabilité fixé par la méthode. Dans leur comparaison de 12 méthodes, van der Werf et Petit (2002) concluent que, bien que moins faciles à mettre en œuvre, les méthodes utilisant des indicateurs d'impacts sont préférables car plus proches de l'objectif d'évaluation. Ils préconisent également les méthodes utilisant une large gamme d'indicateurs permettant une approche multicritère, couvrant les échelles locales et globales, et exprimant les résultats sous forme de valeurs (plutôt que de scores sans unité) par unité de produit et par unité de surface. L'analyse du cycle de vie (ACV) correspond à ces critères. C'est par ailleurs une méthode utilisée mondialement pour évaluer des produits agricoles. Elle est l'objet de nombreuses recherches visant à améliorer la fiabilité et la complétude de la méthode (UNEP/SETAC, 2017), y compris à l'UMR SAS où plusieurs chercheurs travaillent sur les questions de développement méthodologique de l'ACV.

3.1. Définition et principes de l'ACV

L'ACV est une méthode d'analyse environnementale standardisée (ISO, 2006a, 2006b) permettant d'évaluer les impacts environnementaux d'un produit ou service, prenant en compte l'ensemble de son cycle de vie, depuis l'extraction des matières jusqu'à la fin de vie du produit, en passant par la phase d'utilisation. De façon imagée, on parle souvent d'une évaluation « du berceau à la tombe ». Les impacts sont évalués à partir de l'inventaire des flux de matière et d'énergie entrants (e.g. consommation de diesel, de métaux, d'engrais) et sortants (e.g. émissions de dioxyde de carbone (CO_2)

dans l’air, de nitrates (NO_3) dans l’eau), qui sont agrégés et convertis en impacts. L’ACV est multicritère et permet l’évaluation de plusieurs catégories d’impact, comme le changement climatique, l’eutrophisation marine ou d’eau douce, l’acidification.

D’après la norme qui la définit, l’ACV est mise en œuvre en quatre étapes interconnectées :

1. La définition des objectifs et du champ de l’étude. Cette phase permet de caractériser le système étudié, sa (ou ses) fonction(s), ses limites, les flux de référence.

2. L’inventaire du cycle de vie (ICV). Cette étape permet d’inventorier l’ensemble des flux de ressources consommées et les substances polluantes émises lors du cycle de vie du produit.

3. L’évaluation de l’impact du cycle de vie. Les impacts potentiels sur l’environnement sont calculés à partir des données d’inventaire qui sont agrégées dans différentes catégories d’impact et converties en impacts ou dommages potentiels sur l’environnement grâce à des facteurs de caractérisation.

4. Interprétation des résultats. Cette phase essentielle permet de discuter les résultats, les incertitudes, d’identifier les contributions relatives des processus ou phases du cycle de vie.

L’ACV attributionnelle, mobilisée dans cette thèse, décrit les flux de matière ou d’énergie lié au cycle de vie du système analysé, dans une situation de *statu quo* (Finnveden et al., 2009). Elle permet d'identifier les intrants, étapes du cycle de vie et impacts responsables d’une part importante des impacts totaux (*hotspots*), ciblant ainsi des leviers pour diminuer l’impact et servant d’étape préalable à la conception de nouveaux systèmes de production (Jolliet et al., 2010). L’ACV permet également la comparaison de produits, processus ou systèmes, ayant des fonctions semblables. Elle peut servir à orienter les décisions mais ne permet pas d’en évaluer les conséquences. Pour cela, l'ACV conséquentielle doit être mobilisée, elle évalue les conséquences environnementales d'une décision en décrivant la manière dont les flux changent en réponse à cette décision (Schaubroeck et al., 2021). L’ACV attributionnelle permet de réponde à des questions du type « Quels sont les intrants générant le plus grand impact environnemental ? » ou « De ces deux produits, lequel a le moins d’impact sur le changement climatique », mais pas « Quel produit faut-il privilégier pour diminuer l’impact sur l’environnement ? » car cette question introduit un processus de décision, dont les conséquences ne sauraient être évaluées par l’ACV attributionnelle.

3.2. L'ACV en agriculture

Dans le cas des ACV agricoles, on considère souvent un champ d'étude allant du berceau à la porte de la ferme, incluant donc les émissions et consommations de ressources liées à l'activité de la ferme dans ce qui constitue le « système de premier plan » (e.g. gaz émis au champ suite aux épandages d'engrais, émissions liées à la combustion du carburant par les tracteurs) et les émissions et consommations associées à la fabrication des intrants (e.g. énergie consommée pour - et émissions générée par - la fabrication d'engrais ou de bâches plastiques) dans ce qui constitue le « système d'arrière-plan ». En se focalisant sur l'activité agricole, cette définition du système présente un intérêt pour l'agronome. Le transport, le packaging et/ou la transformation peuvent être inclus pour élargir le champ d'étude jusqu'au consommateur (e.g. Eide, 2002; Markussen et al., 2014).

De nombreuses évaluations sont réalisées sur des produits agricoles individuels, par exemple le lait (Salou et al., 2017), la pomme (Basset-Mens et al., 2016) ou les haricots (Abeliotis et al., 2013), même si souvent, les fermes ne produisent pas qu'un seul produit. Concernant les productions végétales annuelles, les cultures sont souvent pensées en rotation au sein d'un système de culture, avec des interactions possibles (par exemple pour les fertilisants), posant un défi à l'évaluation d'un produit isolément des autres productions du système de culture. Goglio et al. (2018) décrivent plusieurs approches permettant de réaliser l'ACV « produit » d'une production végétale. L'approche « culture par culture » considère chaque culture séparément de celles qui suivent et précèdent. Elle est simple à mettre en œuvre car elle ne nécessite pas de données hors des pratiques liées à la culture, mais elle ne reflète pas les interactions entre cultures (e.g. l'utilisation du reliquat d'azote par la culture suivante). Dans les approches « allocation », les intrants et sortants sont inventoriés à l'échelle de la rotation et alloués à la culture évaluée selon des critères objectifs à déterminer. Elles conservent l'intégrité du système mais les règles d'allocation entre les produits du système (e.g. du blé et des betteraves) sont complexes à établir, et de manière générale, l'allocation doit être évitée autant que possible (ISO, 2006b). Les approches « combinées » considèrent un certain nombre d'effets temporels de la succession de culture (e.g. effet du précédent cultural), mais demandent beaucoup de temps et de données, et ne sont pas adaptés aux associations de cultures.

Goglio et al. (2018) décrivent également une approche permettant de réaliser l'ACV « système » d'un système de production (e.g. un système de culture) dans son ensemble, et non plus un produit. L'approche décrite, qu'ils appellent « système de culture » considère le système de culture comme un ensemble produisant plusieurs produits. Les impacts sont exprimés pour l'ensemble du système, dans une unité commune aux produits (e.g. masse, énergie, valeur monétaire). Cela permet de prendre en compte les interactions qui ont lieu au sein du système, et permet de comparer des systèmes entre eux, mais ne permet pas d'obtenir des résultats pour une culture ou un produit en particulier.

3.3. Le choix des catégories d'impact

Par son approche multicritère, l'ACV permet une évaluation sur un grand nombre de catégories d'impact. Selon l'objet étudié, toutes les catégories d'impact n'ont pas la même pertinence. Leur choix doit refléter les questions environnementales liées à l'objet étudié (ISO, 2006b).

Les ACV agricoles incluent généralement l'impact des émissions de gaz à effet de serre sur le changement climatique. Il s'agit d'un sujet majeur pour lequel l'impact de l'agriculture est avéré, les secteur contribuant à 19% des émissions en France (Citepa, 2021). C'est par ailleurs une limite planétaire que Rockström et al. (2009) estiment outrepassée. Les principales substances impliquées dans les impacts sur le changement climatique sont le dioxyde de carbone (CO_2), le méthane (CH_4) et le protoxyde d'azote (N_2O). Les émissions des différentes substances sont agrégées dans une unité commune, le kg CO_2-équivalent, à l'aide des facteurs de caractérisation de l'IPCC (2014).

Autre limite planétaire que l'humanité a franchie, est celle de l'eutrophisation liée à un excès de nutriments dans les eaux, provoquant des modifications de l'écosystème aquatique. Dans le cadre de la thèse, je me suis concentré sur l'eutrophisation marine, malgré l'importance également de l'eutrophisation de l'eau douce. Le ruissellement et le lessivage de l'azote (N) des sols agricoles sont la principale cause d'eutrophisation marine (Le Moal et al., 2019). La méthode ReCiPe (Huijbregts et al., 2016) propose des facteurs de caractérisation, utilisés dans cette thèse, pour agréger les émissions en un impact exprimé en kg N-équivalent.

L'érosion de la biodiversité, pour laquelle l'humanité a dépassé la limite planétaire (Steffen et al., 2015) est rarement prise en compte dans les études d'ACV (Knudsen et al., 2019), bien qu'il s'agisse d'un impact environnemental clé de l'agriculture (Haas et al., 2000) et qu'elle figure haut dans l'agenda politique (United Nations Environment Programme, 2021a). Plusieurs méthodes existent, reposant sur l'utilisation des terres comme principal facteur de perte de biodiversité, sans tenir compte de la gestion des terres, notamment agricoles, de façon détaillée. Koellner et Scholz (2008) et Mueller et al. (2014) proposent des facteurs de caractérisation pour les systèmes agricoles conventionnels et biologiques, au sein d'une classe d'utilisation des sols donnée. Knudsen et al. (2017) proposent des facteurs de caractérisation incluant quatre classes d'utilisation des terres agricoles (prairie de monocotylédones, prairie mixte, cultures arables, haies) gérées selon des pratiques conventionnelles ou biologiques. La méthode proposée par Chaudhary et al. (2015), recommandée par The Life Cycle Initiative[5] (UNEP/SETAC, 2017) et depuis actualisée par Chaudhary et Brooks (2018) en introduisant trois niveaux d'intensité d'utilisation des terres, fournit des facteurs de caractérisation pour 804 écorégions et six classes d'utilisation des terres (dont les cultures annuelles, les cultures permanentes et les prairies). Cette méthode a été provisoirement recommandée pour l'analyse des *hotspots* uniquement, mais pas pour les comparaisons de systèmes. Le system expert SALCA-BD (Jeanneret et al., 2014) permet d'intégrer la biodiversité dans une ACV agricole en considérant de façon détaillée les habitats présents sur une ferme et les pratiques qui y sont appliquées, mais ne propose pas de facteurs de caractérisation. À ce jour, il n'y existe pas de méthode faisant consensus pour évaluer les impacts sur la biodiversité (UNEP/SETAC, 2017), et les méthodes existantes, hormis SALCA-BD, ne permettent pas de comparer des fermes ayant les mêmes cultures et le même mode de production agricole (biologique ou conventionnel). Pourtant, l'érosion de la biodiversité est un sujet clé pour évaluer les systèmes agricoles en AB, notamment pour les systèmes les plus agroécologiques préservant et reposant sur la biodiversité (van der Werf et al., 2020).

4. Une problématique à deux niveaux

4.1. La diversité des fermes et ses implications sur leurs performances environnementales

Le maraichage biologique est un secteur hétérogène et dynamique, composé de pionniers de l'AB, de maraichers convertis à l'AB, et de microfermes d'émergence plus récente revendiquant des approches agroécologiques. Dans un contexte de demande croissante et d'un marché qui s'organise à une échelle désormais industrielle, la question de la conventionnalisation d'une partie des maraichers adoptant des pratiques inspirées de l'agriculture conventionnelle émerge, amenant à l'hypothèse d'une bifurcation, avec d'un côté un modèle agricole de fermes spécialisées et reposant largement sur des intrants, et de l'autre des fermes complexes à la production diversifiée, reposant sur les principes de l'agroécologie dans une approche systémique. Ce constat amène à s'interroger sur les performances environnementales de fermes maraichères biologiques contrastées, présentant différents degrés d'agroécologie. Dans quelle mesure le degré d'agroécologie des fermes influence leurs performances environnementales ? Ce premier niveau de problématique doit permettre d'apporter des

[5] The Life Cycle Initiative, partenariat international porté par le programme des Nations Unies pour l'environnement (UNEP) et la Society of Environmental Toxicology and Chemistry (SETAC), a publié un guide identifiant les meilleures méthodes actuellement disponibles.

connaissances sur la durabilité environnementale du maraichage biologique, dans un cadre de potentielle bifurcation de l'AB.

4.2. L'évaluation environnementale de systèmes agroécologiques complexes

Le premier niveau de problématique amène à des questions de méthode, à la question de comment évaluer les performances environnementales de systèmes agroécologiques complexes. En effet, l'analyse du cycle de vie permet d'évaluer les impacts environnementaux, mais les fermes complexes, cultivant une grande diversité de légumes en les associant sur de petites surfaces dans une approche agroécologique systémique, posent des défis à l'ACV dans la prise en compte des impacts sur la biodiversité et des interactions spatiales et temporelles au sein des systèmes agroécologiques. Ce deuxième niveau de problématique implique un développement méthodologique lié à la manière d'aborder la complexité par l'ACV, dans le cas de fermes maraichères agroécologiques.

5. Questions de recherche

A partir de ces deux niveaux de problématique, les questions de recherche de ma thèse sont :

- Comment caractériser la diversité des fermes maraichères bio au regard de leur fonctionnement agroécologique ?
- Comment évaluer et comparer les impacts environnementaux de fermes maraichères bio dans le cadre de l'ACV, en intégrant leur complexité et la nécessité de considérer la dimension biodiversité au cœur de l'agriculture biologique ?
- Quelles sont les performances environnementales de fermes maraîchères biologiques contrastées par leur fonctionnement agroécologique ?

Chapitre 2. Caractérisation de la diversité des fermes maraichères biologiques

Conventionalised vs. agroecological practices on organic vegetable farms: investigating the influence of farm structure in a bifurcation perspective

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Abstract

CONTEXT: According to the bifurcation hypothesis, a gap may be growing between "agroecological" organic farms, which rely mostly on ecosystem services, and "conventionalised" ones, which rely more on external inputs, related to contrasting evolutions in farm structure (e.g. size, specialisation) and supply chains.

OBJECTIVE: The objectives of this study were to 1) analyse the diversity of organic vegetable farming systems in France, 2) investigate the extent to which bifurcation can be observed among organic vegetable farms in France and 3) investigate the extent to which structural factors that can reflect bifurcation (e.g. profiles of "new organic farmers", marketing channels, farm size) are related to conventionalised or agroecological OF.

METHODS: We developed a farm typology based on Factor Analysis of Mixed Data (FAMD) and agglomerative hierarchical clustering (AHC) using information obtained from an online survey with 165 complete answers. We used composite indexes that aggregated primary indicators to compare the biotechnical and socio-economic dimensions of farms among clusters.

RESULTS AND CONCLUSIONS: The diversity that exists in organic vegetable farms, with large differences among farm clusters, can be interpreted as a snapshot sign of bifurcation, which is a temporal process, and support hypotheses that relate farming structure to farming practices in this perspective. Our study suggests that 1) the dichotomy that contrasts "agroecological" to "conventionalised" organic farms should be considered as a conceptual perspective with two poles and a gradient of farms between them; 2) farms that were created as organic tended to be more agroecological than farms that were converted from conventional farming; 3) new entrants to organic farming had the best agroecological performances; 4) the best agroecological performances were associated with short supply chains, although good agroecological performances did occur with some long supply chains; and 5) the smallest farms were more likely to implement agroecological practices, but farm size did not have the same influence on all agroecological practices.

SIGNIFICANCE: These findings confirm the influence of structural factors that reflect bifurcation of the degree of conventionalisation or agroecology of organic vegetable farming. For a given set of structural factors (i.e. farmer profile, farm size and supply chain), however, agroecological performances varied greatly. This suggests levels of freedom to develop more agroecological organic practices for a given farm size or supply chain that should be further investigated.

Keywords

Agroecology; horticulture; farming diversity; conventionalisation hypothesis; small farms; adoption

Highlights

- Organic vegetable farms showed a range of farm structure, related to practices with different levels of agroecology
- The smallest farms were the most agroecological, while the most conventionalised practices were associated with a large percentage of sheltered area
- Large farms were less agroecological on average, but some had agroecological performances similar to those of smaller farms
- The coexistence of agroecological and conventionalised farms may result from bifurcation, where the role of new entrants needs further research

1. Introduction

Organic agriculture is characterised by the prohibition of synthetic chemical fertilisers and pesticides. Beyond these certified standards, the overall principles which support organic farming (OF) are the use of natural resources by managing biological processes of ecological systems, and limited use of non-renewable resources and off-farm inputs (European Commission, 2007). However, the hypothesis of “conventionalisation” of OF, defined as “the introduction of farming practices that undermine the principles of organic farming” (Darnhofer et al., 2010) suggests that the mainstreaming of OF may increase the reliance of some organic farms on external inputs. Conventionalisation may also be related to a more industrial management approach and economic model, which contrasts with the small-scale family farming historically supported by OF (Howard, 1940; Lockeretz, 2007). OF based on applying a limited set of organic principles can be opposed to OF based on agroecological principles (Gliessman, 2013). Rosset and Altieri (1997) opposed agroecological OF, defined as “an approach that goes beyond the use of alternative inputs to develop integrated agroecosystems with minimal dependence on external, off-farm inputs”, to OF based on input substitution, driven by the agribusiness sector. The contrast between these models, hereafter referred to as “agroecological” and “conventionalised” organic systems, supports the “bifurcation hypothesis” (Darnhofer et al., 2010).

Beyond academic discussions about the relevance of this hypothesis, the bifurcation of OF is a controversial topic in civil society. This is especially true in France, where the media reveal a growing concern about “two-speed” OF (Bolis, 2017) and doubts of consumers about the true sustainability behind the organic label. These concerns are related to the rapid growth of OF in the country. In the past five years, the area of organic production in France has doubled, reaching 2.3 million ha, which represented 8.5% of French agricultural land in 2019. The organic market has followed the same trend to reach 11.9 billion € in 2019, 55% of which is sold in generalist supermarkets, 28% in organic shops and 11% by direct selling (Agence Bio, 2020). France represents 15% of the European Union’s (EU’s) OF area and 23% of the EU’s organic product market (Agence Bio, 2019). The EU Common Agricultural Policy (CAP) supports OF, having given it 6.3 billion € from 2014-2020 (1.5% of the CAP budget). In France, organic vegetable production is the sector that receives the largest subsidies from the CAP per hectare: 900 € and 600 € for conversion and maintenance, respectively (Senat, 2019). Within these global dynamics, the French organic vegetable sector has grown strongly in recent years, due to conversions of conventional farms and new entrants (FRAB, 2019), and currently represents ca. 8% of the national area of fresh vegetable production (Agence Bio, 2020). In France, the bifurcation debate is increasing for organic vegetables, fed by parallel contrasting trends. On one hand, the strong increase in sales, particularly in supermarkets, may favour larger and more specialised farms and become an incentive for large conventional vegetable farms to convert to OF. On the other, the country has seen a recent and growing development of “microfarms” created mainly by new entrants with no agricultural background and strong social and environmental aspirations, characterised by small areas, diversified production, short supply chains and radically alternative practices (e.g. inspired by permaculture) (Morel and Leger, 2016). Although the bifurcation hypothesis refers more to changes in practices on existing organic farms (Darnhofer et al., 2010), the role of these “new organic farmers” in France generates many discussions. At the heart of this societal debate in France, we identify three controversial statements that partly echo some scientific studies:

1) Conversion of large conventional farms in response to the growing organic market would result in conventionalised OF (which somewhat echoes Läpple and Rensburg (2011), who observed that late adopters of OF tend to attach more importance to profit); in contrast, the strong ecological values of new entrants, for whom farming is above all a “life project”, would be materialised in agroecological OF (Morel and Léger, 2016).
2) Conventionalised OF would be involved in long supply chains which conform to dominant industrial rationales, whereas “truly” agroecological OF forms would be part of local short supply chains that value agroecological practices in the perspective of a global food system (Fernandez et al., 2013; Francis et al., 2003; Guzmán et al., 2016; Lamine and Dawson, 2018).
3) Small farms would promote agroecological practices better than larger farms (Netting, 1993; Rosset, 2000); thus, larger farms would be related to conventionalised OF.

The objectives of this study were to 1) analyse the diversity of organic vegetable farming systems in France, 2) investigate the extent to which bifurcation can be observed among organic vegetable farms in France and 3) investigate the extent to which structural factors that can reflect bifurcation are related to conventionalised or agroecological OF. We considered a broad definition of structural factors, which included profiles of “new organic farmers”, marketing channels and farm size (Stanton, 1991). Most studies of conventionalisation and bifurcation have been performed by social scientists who focused on dynamics and structural evolution of farms over time, whereas the relationships between these structural changes and actual farming practices have rarely been investigated (Darnhofer et al., 2010). As agronomists, we did not analyse bifurcation as a temporal process. Instead, we empirically explored a snapshot of the current diversity of organic vegetable farms in France and assessed whether it reflects contrasting OF approaches that could be related to bifurcation. The main novelty of this study is its analysis of the extent to which structural factors that can reflect bifurcation are related to conventionalised or agroecological OF practices on the ground.

To reach these research objectives, we performed the study in mainland France, focussing on the north-west and south-east, which are two contrasting vegetable-producing regions. We developed a farm typology based on Factor Analysis of Mixed Data (FAMD) and agglomerative hierarchical clustering (AHC) using information obtained from an online survey with 165 complete answers. The biotechnical functioning and socio-economic context of the resulting clusters were analysed using composite indexes that we developed based on the conceptual framework of Thérond et al. (2017). To our knowledge, our study is the first quantified application of this framework.

2. Materials and methods

2.1. Building the typology

To explore the diversity of the structure and practices of organic vegetable farms in France, we chose a typological approach (Blanco-Penedo et al., 2019; Kamau et al., 2018; Sierra et al., 2017). The variables chosen to characterise farming systems influence the resulting typology greatly (Alvarez et al., 2018), and the structure of the typology depends on its objective (Perrot and Landais, 1993). We built our typology using a six-step method developed for research or development projects by Alvarez et al. (2014), who described the steps as follows:

1. “Precisely state the objective of the typology
2. Formulate a hypothesis about farming systems diversity
3. Select variables to characterise the farming systems
4. Design a sampling method for collecting data
5. Cluster the farming systems using multivariate statistics
6. Compare the resulting typology to the hypothesis and validate the typology with local experts”

The objective of the typology was to analyse the diversity of organic vegetable farming systems in France using the analytical framework of Thérond et al. (2017), which characterises agricultural systems along two dimensions. The first dimension corresponds to the biotechnical functioning of farming systems and assesses the "balance between external inputs versus ecosystem services". This axis distinguishes chemical-input-based, biological-input-based and biodiversity-based farming systems, the last of which are often associated with an agroecological approach. In our study, biotechnical functioning would therefore be our proxy to assess to which extent OF is conventionalised or agroecological. The second dimension corresponds to the socio-economic context of farming systems and assesses the balance between relationships based on global market prices vs. “territorial embeddedness”, defined by Thérond et al. (2017) as “social, spatial and ecological issues which mitigate purely economic relationships and behaviours centred on global market prices”.

Our hypotheses about farm types reflected the three statements about farm size, marketing channels and farmer profiles that we aimed to investigate. After consulting experts in organic vegetable production and technical guidebooks by organic development institutes (Clus, 2009; Jammes, 2012), we developed the following hypotheses:

1) Large farms are managed more often by previously conventional farmers who recently converted to OF, medium-sized farms are managed by established organic farmers, and the smallest farms are managed by new entrants.

2) The larger the farm, the more external inputs it uses, the fewer types of vegetables it grows and the longer its distance to consumers. We identified the area under shelters as a potential bias to this simple relation, as productivity is higher under shelters than outdoors.
3) Cultivated area is a key criterion to describe a farm's structure, as its size influences its technical functioning (e.g. small farms tend to use land more intensely; crop rotation is likely to differ for different farm sizes) (Carter, 1984; Netting, 1993; Rosset, 2000). Cultivated area is often used as a key criterion in farm typologies (e.g. Adewale et al., 2019; Lopez-Ridaura et al., 2018; Navarrete, 2009; Sierra et al., 2017). We expected the smallest farms to be microfarms (Morel and Leger, 2016) with less than 1 ha and the largest farms to have ca. 30-80 ha.

Given these hypotheses, our typology relied on indicators of farming practices related to the use of external inputs, farm structure including size and farmers' profiles (e.g. farm age, OF since creation or converted) and the farms' socio-economic context.

2.2. Farm data collection

We focused our survey on two contrasting regions of France known for their vegetable production (conventional and organic): the north-west (Brittany, Normandy, Pays de la Loire) and south-east (Provence-Alpes-Côte-d'Azur, Occitanie). The survey included only farms that produced organic vegetables for the fresh market as their main production.

Data were collected using an online survey sent to farmers from April-July 2019. Its questions were chosen to enable us to classify farming systems according to their biotechnical functioning and socio-economic context (Thérond et al., 2017). For organic vegetable farms, Adewale et al. (2016) identified that fuel use, organic fertilisers and soil emissions had strong environmental impacts. They also mentioned that farm size and site-specific soil and climatic conditions influenced carbon footprints. The survey's questions thus focussed on farm structure, farming practices that were likely to influence environmental impacts and socio-economic issues.

The questions were divided into six categories:

- Farm history and geography
  - Farm age
  - Years since the farm was labelled "organic"
  - Location (administrative department)
- Land
  - Utilised agricultural area (UAA) including non-cultivated areas
  - Area cultivated in vegetables, whether outdoors or sheltered (high plastic tunnels or multi-span greenhouses)

- Human and mechanical labour resources
    - Number of people working permanently or temporarily (labour)
    - Number of tractors
- Production
    - Number of different vegetables grown: farmers were asked to count the types of vegetables distinguished by consumers and marketing, regardless of their botanical species (Morel and Leger, 2016). For example, cauliflower and kale are two different vegetables, as are green beans and dried beans. No distinction was made between varieties. Lettuce (e.g. Batavia, oakleaf) counted as one vegetable type. Potatoes and strawberries were counted as vegetables.
    - Other types of production besides vegetables
- Farming practices
    - Type of tillage and tools used
    - Main practices to manage soil fertility
    - Main practices to control weeds
    - Main practices to control pests and diseases
    - Actions to protect or promote local biodiversity
    - Origin of seeds and seedlings
- Economy and selling strategy
    - Marketing supply chains
    - Destination of the vegetables sold (from local to export markets)
    - Annual revenue

The questions about farming practices did not require quantitative responses to make them simple and easy to answer. From a list of practices, farmers were asked which one(s) they used most often. The complete form is available in Supplementary Material.

The online survey was disseminated to the farmers through several networks – specialised in OF or not – including local agricultural development organisations and commercial organisations, to capture as many farm types as possible. Follow-up e-mails and phone calls were made regularly based on the responses collected, to ensure that sampling was as complete as possible (Álvarez et al., 2014). Ultimately, 174 surveys were completed, 165 of which were sufficiently complete. Most of the farmers who answered were located in the two targeted regions, but because of word-of-mouth communication, some farmers in other regions answered the survey (**Fig. 2.1**).

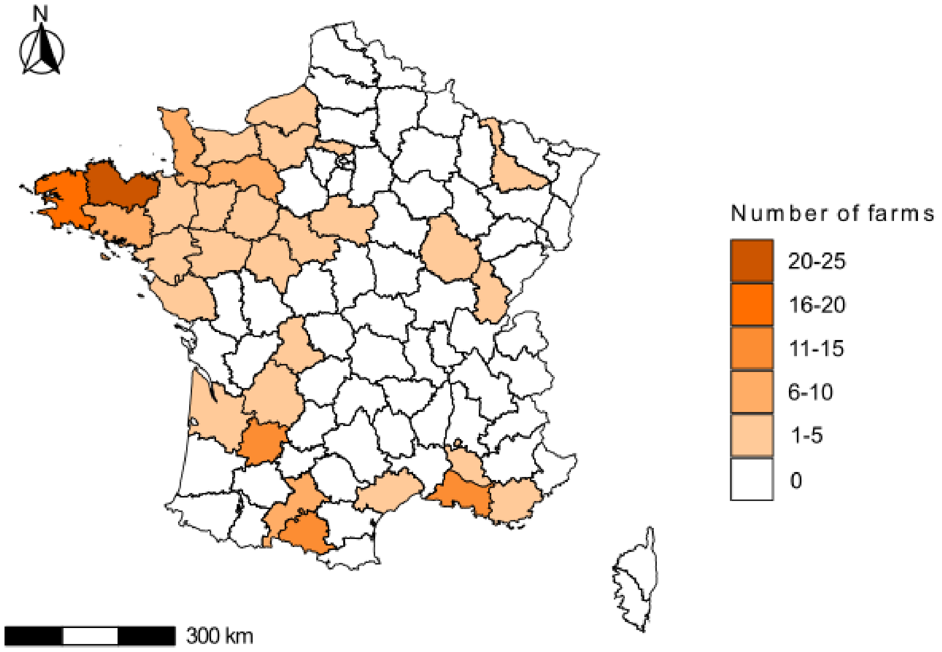

Fig. 2.1. Number of the 165 farms surveyed in each of the administrative departments of mainland France

2.3. Data management and statistical analysis

We created the typology and characterised the farm types in three stages: 1) formatting of the database, including selection of variables and imputation of missing data; 2) FAMD and 3) AHC. The data were summarised in a Microsoft® Excel worksheet and processed with R software v. 3.5.3 (R Core Team, 2019) and RStudio v. 1.1.463 (RStudio Team, 2016).

In stage 1, data that were not directly suitable for analysis were transformed into categorical variables with a limited number of categories. This process resulted in 24 farm variables that were screened for abnormal values using dot charts and for poorly represented categories. No abnormal values were found, and one category with only three farms was merged with the next closest category. In addition, the data revealed 15 missing values, which were few enough to be imputed using the regularised iterative algorithms *estim_ncpFAMD* and *imputeFAMD* (Audigier et al., 2016) in the R package missMDA (Josse and Husson, 2016). We calculated Kendall's rank correlation for each pair of the quantitative variables, none of which was strongly correlated (Kendall's $\tau<0.7$, $p<0.001$). Four categorical variables (willingness to dedicate space to biodiversity on the farm, furthest selling destination, region and alternative farming) were not used in the FAMD because they were redundant or not related directly to farm structure or farming practices (**Table 2.1**). The variables removed were used as supplementary variables to describe the clusters. This process resulted in a database of 165 farms described by 17 variables – nine categorical and eight quantitative – related to farm structure and farming practices, and four supplementary categorical variables (**Table 2.1** et **Table 2.2**).

Table 2.1. Description of the categorical variables used in the Factor Analysis of Mixed Data or to describe the clusters. *(n/a: not applicable)*

Categorical variable	Response	Practices	Used for the FAMD	Composite index (1)	Value for composite index calculation (2)
Tillage	No-tillage	No-tillage is applied on most fields	Yes	Biotechnical functioning	3
	Surface tillage	Surface tillage is applied on most fields			2
	Deep non-inversion tillage	Deep non-inversion tillage is applied on most fields			1
	Ploughing	Ploughing is applied on most fields			0
Fertilisation	Self- or locally produced	Farmer uses mainly green manure, self- or locally produced manure or compost	Yes	Biotechnical functioning	2
	Mixed	Farmer uses both purchased and self-produced fertilisers			1
	Purchased on the market	Farmer uses mainly purchased organic fertilisers such as pellets or industrial compost			0
Weed control	Based on natural techniques	Farmer uses mainly organic mulch, manual or mechanical weeding, including a false seed bed	Yes	Biotechnical functioning	2
	Mixed	Farmer combines both techniques			1
	Based on artificialising the environment	Farmer uses mainly plastic covers or thermal weeding			0
Pest and disease control	Based on local resources	Farmer relies mainly on local biodiversity, banker plants and basic substances	Yes	Biotechnical functioning	2
	Mixed	Farmer combines both techniques			1
	Based on external inputs	Farmer uses mainly purchased products such as copper, sulphur, biocontrol boxes of micro- or macro-organisms			0
Seed and seedling management	Seeds partly self-produced	Farmer produces his/her own seeds, at least partly	Yes	Biotechnical functioning	2
	Seedlings partly self-produced	Farmer buys seeds and grows his/her own seedlings, at least partly			1
	Seeds and seedlings purchased	Farmer buys seeds and seedlings			0
Willingness to dedicate space to biodiversity on the farm	Major	Dedicating space to biodiversity is considered a major issue	No		
	Important	Dedicating space to biodiversity is considered an important issue			
	Unimportant	Dedicating space to biodiversity is not considered an important issue			
Food supply chain	Direct Selling (0 intermediary)	Farmer sells directly to final customers (e.g. baskets, markets)	Yes	Socio-economic context	4
	Direct selling and short mixed	Farmer sells directly and with one intermediary			3
	Short (1 intermediary)	Farmer sells in short food supply chain with one intermediary (local shops)			2
	Long and short mixed	Farmer sells in short and long food supply chains			1
	Long (2+ intermediaries)	Farmer sells in long food supply chain with at least two intermediaries (e.g. wholesaler, supermarkets)			0
Furthest selling destination	Department	Vegetables are sold within the same department (small French administrative division)	No	Socio-economic context	3
	Regional	Vegetables are sold within the same region (larger French administrative division)			2
	National	Vegetables are sold in France			1
	Foreign	Vegetables are sold outside of France			0
Annual revenue in thousand Euros	0-30	Annual revenue is less than 30 000 euros	Yes	n/a	
	30-60	Annual revenue is 30 000-60 000 euros			
	60-100	Annual revenue is 60 000-100 000 euros			
	100-300	Annual revenue is 100 000-300 000 euros			
	300-500	Annual revenue is 300 000-500 000 euros			
	500-1000	Annual revenue is 500 000-1 000 000 euros			
	1000 +	Annual revenue is greater than 1 000 000 euros			
Region	South-east	Farm located in the south-east, including Provence-Alpes-Côte-d'Azur and Languedoc Roussillon	No	n/a	
	North-west	Farm located in the north-west, including Bretagne, Pays-de-la-Loire and Basse-Normandie			
	South-west	Farm located in the south-west, including Aquitaine and Midi-Pyrénées			
	Other	Farm located in any other region			
Conversion to organic farming	Farm created as organic	Farm created as an organic farm	Yes	n/a	
	Farm converted to organic farming	Farm converted to organic farming			
Diversification	Specialised in vegetable production	Farm growing only vegetables (possibly combined with small fruits)	Yes	n/a	
	Diversified in other types of production	Farm growing vegetables and other crops and/or animals			

Alternative farming	Alternative farming	Farmer practices permaculture, agroforestry, associated crops or other form considered as alternative	No	n/a
	Non-alternative farming	Farmer practices traditional vegetable farming		

(1) indicates to which composite index the categorical variable contributed. (2) indicates the value of each variable's response when used to calculate the composite index.

Table 2.2. Medians of the eight quantitative variables used in the Factor Analysis of Mixed Data, agglomerative hierarchical clustering and comparison of the four farm clusters (p-values are given for the Kruskal-Wallis tests). For each variable, a different letter indicates a significant difference according to the pairwise Mann-Whitney U test at p<0.05.

Quantitative variables	Cluster 1 (n = 41)	Cluster 2 (n = 99)	Cluster 3 (n = 9)	Cluster 4 (n= 16)	p-value
Farm age (years)	5 (a)	9 (b)	30 (c)	27.5 (c)	<0.001
Utilised agricultural area (UAA) (ha)	3 (a)	5.2 (b)	6 (b)	38 (c)	<0.001
Outdoor vegetable area (ha)	0.50 (a)	1.70 (b)	2.00 (ab)	14.50 (c)	<0.001
Sheltered vegetable area (ha)	0.05 (a)	0.20 (b)	3.00 (c)	0.07 (ab)	<0.001
Sheltered area as % of vegetable area (1)	8% (a)	10% (a)	67% (c)	1% (b)	<0.001
Labour (full-time equivalent)	1.3 (a)	2.7 (b)	7 (c)	7 (c)	<0.001
Number of tractors	1 (a)	2 (b)	3 (d)	5 (c)	<0.001
Number of types of vegetables	30 (a)	40 (a)	12 (b)	11 (b)	<0.001

(1) Vegetable area is the sum of outdoor and sheltered vegetable area whereas UAA relates to the global farm area.

In stage 2, factor analysis was used to reduce the dimensionality of the data. Because the database contained both categorical and quantitative variables, the analysis required FAMD, which can be considered a combination of principal component analysis (PCA) and multiple correspondence analysis (MCA) (Pagès, 2004). The first six components, which explained 47% of the variance, were retained for the clustering. Each variable was represented the most by one of the first six components.

In stage 3, AHC was performed using the Euclidian distance of the factorial coordinates of the individuals with Ward's (1963) method to identify homogeneous clusters of farms on the first six components. A k-means consolidation was performed, as suggested by Husson et al. (2010). The optimal number of clusters – four – was determined by considering the largest relative loss of inertia (**Fig. 2.2**). The number of clusters was validated by comparing the distribution of variance between within-group (54%) and between-group (46%) inertia.

Once the clusters were identified, the relationship between a cluster's number (1-4) and the categorical or quantitative variables was studied using a chi-square or Kruskal-Wallis test, respectively. For each categorical variable, a hypergeometric test was performed to characterise the clusters by the responses and to test whether the response was over- or under-represented in each cluster. For each quantitative variable, a pairwise Mann-Whitney U test was performed to test the significance (at p<0.05) of differences between medians. The FAMD and AHC were performed using the R package FactoMineR (Le et al., 2008).

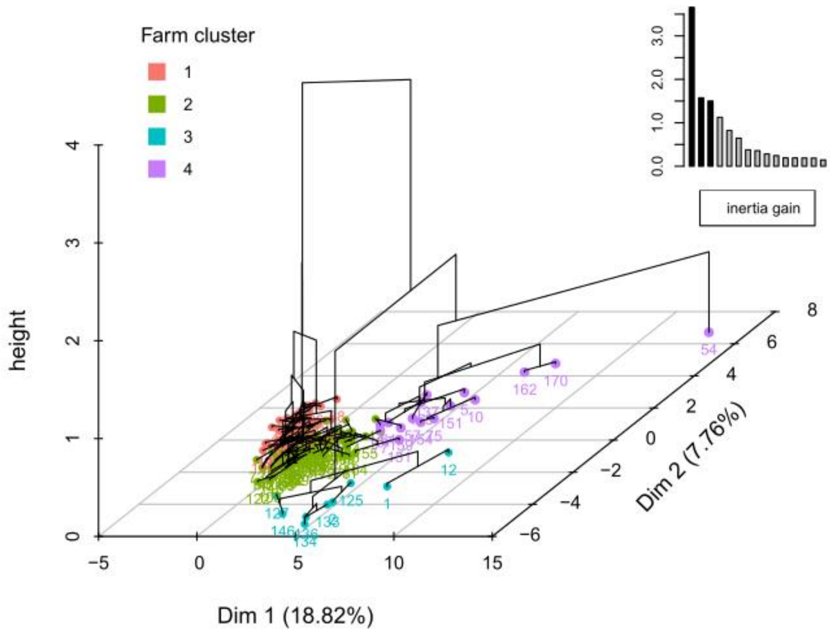

Fig. 2.2. Hierarchical clustering of the four farm clusters on the factor map

2.4. Composite indexes

The conceptual framework of Thérond et al. (2017) has two dimensions (i.e. biotechnical and socio-economic) which are not quantified or based on defined indicators. To position the 165 farms in this framework, we needed to define a quantified index for each dimension.

Two composite indexes were calculated from subsets of indicators to characterise the farms' biotechnical functioning and socio-economic context, and they were used as proxies to quantify the position of each farm in Thérond et al.'s (2017) framework. These indexes were additive combinations of normalised primary indicators (as in Herzog et al. (2006)). Primary indicators were obtained by transforming variables used in the FAMD into quantitative indicators. Unlike principal component methods, which are "neutral", we ranked the intensity of each possible value of each primary indicator (i.e. practices were ranked by their intensity). For example, the variable "Fertilisation" and its three possible responses ("Purchased on the market", "Mixed", and "Self- or locally produced") were transformed into a primary indicator "Fertilisation" with three possible values (0, 1 and 2, respectively).

The composite indexes were calculated by normalising the primary indicators according to Legendre and Legendre (2012) (i.e. scaling them from 0-1 and then averaging them (Eq. (1)):

$$\mathbf{I} = \frac{\sum_{i=1}^{n}\left(\frac{y_i - y_{min}}{y_{max} - y_{min}}\right)}{n} \quad \textbf{(1)}$$

where I is the composite index, y_i the observed value, y_{min} the minimum observed value, y_{max} the maximum observed value and n the number of primary indicators.

The composite indexes, which ranged from 0-1, excluded primary indicators that were strongly correlated with each other (Kendall's rank correlation $\tau > 0.7$). The composite indexes were analysed by farm cluster. They, and the residues after analysis of variance, did not follow a normal distribution, and some clusters had few farms. Clusters were thus compared using a Kruskall-Wallis test. For each index, a pairwise Mann-Whitney U test was performed to test the significance (at $p<0.05$) of differences between medians.

2.4.1. "Biotechnical functioning" composite index: Assessing the role of ecosystem services and external inputs

Ecosystem services provided to an agroecosystem by on-farm biodiversity may allow for a reduction in the use of external inputs (Duru et al., 2015). The contrast between biodiversity-based farming systems, which use ecosystem services substantially, and input-based farming systems defines the vertical axis of Thérond et al.'s (2017) analytical framework. The inputs that may be reduced using ecosystem services are those used for soil fertility and structure, pest and disease management, and water supply (Bommarco et al., 2013). Agricultural practices that promote ecosystem services also include choices of species and varieties (Thérond et al., 2017).

The five primary indicators we used to calculate the composite index of biotechnical functioning were tillage, fertilisation, weed control, pest and disease control, and seed and seedling management, which were derived from the variables of the same name (**Table 2.3**). This composite index ranged from 0 (i.e. external-input-based system) to 1 (i.e. biodiversity-based system). In our study, biotechnical index was thus used as a proxy to estimate the extent to which organic practices were agroecological (towards 1) or conventionalised (towards 0).

Netting (1993) described the relationship between farm size and the use of external inputs, stating that small farmers often use few external inputs. Small farmers have been seen as providing environmental benefits, among other virtues (Rosset, 2000). Thus, we investigated the relationship between farm size and use of external inputs in our dataset. We used a polynomial model to describe the biotechnical index as a function of the logarithm of vegetable area, which was calculated for each farm as the sum of its outdoor vegetable area and sheltered vegetable area. The logarithm was used because of the large number of small farms in the dataset. The model's distribution of residuals and p-values were examined to assess its fit.

2.4.2. "Socio-economic" composite index: Assessing the socio-economic context

Farming systems are parts of food systems, which include practices to produce, process, package and distribute food (i.e. the "food supply chain") (Thérond et al., 2017). "Conventional food systems" are based on complex, industrial and globalised food supply chains centred on global market prices. In contrast, “alternative food systems” are based on local production with different forms of governance and multiple forms of value (e.g. social, ethical). On this horizontal “socio-economic context” axis, Thérond et al. (2017) described four systems: globalised commodity-based food system, circular economy, alternative food system and integrated landscape approach.

The two primary indicators we used to calculate the composite index of socio-economic context were food supply chain (i.e. the number of intermediaries) and furthest selling destination (i.e. the distance from the farm to the point of sale), which were derived from the variables of the same name (**Table 2.3**). The indicators and variables were related but conveyed different information. This composite index ranged from 0 (i.e. systems based on global market prices) to 1 (i.e. systems with high territorial embeddedness). In our study, the socio-economic index was thus used as a proxy to estimate the extent to which the socio-economic context was territorially embedded (towards 1) or connected to the global market (towards 0).

3. Results

3.1. Farm clusters

3.1.1.General characteristics

Four clusters of 41, 99, 9 and 16 farms, respectively, were identified (**Fig. 2.2**). All quantitative variables were significantly related to the cluster variable (**Table 2.1**, Kruskal-Wallis $p < 0.001$). The chi-square tests indicated that all categorical variables but one (diversification) were related to the cluster variable (**Table 2.3**, $p < 0.001$).

The characteristics of the clusters are presented in Tables 2 and 3. UAA and the area of outdoor vegetables increased with cluster number (e.g. UAA had a median value of 3 ha for cluster 1 and of 38 ha for cluster 4). The sheltered vegetable area, however, was largest in cluster 3 (median of 3 ha, compared to 0-0.2 ha for the other clusters). The number of tractors also increased with cluster number. Farming practices varied among clusters, with trends differing depending on the type of practice (**Table 2.3**). As some farms produced products other than vegetables, differences in UAA and the areas grown in vegetables were observed.

For economic variables, there was a clear contrast between the group of clusters 1 and 2, which had a strong preponderance of selling through short supply chains (zero or one intermediary) at a local scale, and the group of clusters 3 and 4, which sold in long supply chains (at least two intermediaries) throughout France or for export. The annual revenue of the farms varied widely but tended to increase with cluster number.

Table 2.3. Distribution of responses to each categorical variable (in percentage of total) for four farm clusters used in the Factor Analysis of Mixed Data, agglomerative hierarchical clustering and chi-square test of homogeneity.
Underlined variables were selected to characterise the clusters. Bold values identify responses that are over-represented in the given cluster compared to the entire sample, whereas underlined values identify those that are under-represented in the given cluster compared to the entire sample (p<0.05).

Variable and responses (p-value of chi-square test (1))	**Cluster 1 (n = 41)**	**Cluster 2 (n = 99)**	**Cluster 3 (n = 9)**	**Cluster 4 (n= 16)**
<u>Tillage (<0.001)</u>				
No-tillage	**44%**	<u>2%</u>	11%	0%
Surface tillage	46%	**55%**	<u>11%</u>	<u>19%</u>
Deep non-inversion tillage	<u>7%</u>	28%	**78%**	31%
Ploughing	<u>2%</u>	15%	0%	**50%**
<u>Fertilisation (<0.001)</u>				
Self- or locally produced	63%	54%	<u>0%</u>	69%
Mixed	22%	27%	33%	31%
Purchased on the market	15%	19%	**67%**	<u>0%</u>
<u>Weed control (<0.001)</u>				
Based on natural techniques	**37%**	<u>1%</u>	0%	0%
Mixed	56%	**74%**	56%	63%
Based on artificialising the environment	<u>7%</u>	25%	44%	38%
<u>Pest and disease control (<0.001)</u>				
Based on local resources	**93%**	<u>34%</u>	<u>0%</u>	<u>19%</u>
Mixed	<u>7%</u>	**49%**	67%	63%
Based on external inputs	<u>0%</u>	16%	33%	19%
Willingness to dedicate space to biodiversity on the farm (<0.001)				
Major	**39%**	26%	11%	<u>6%</u>
Important	61%	52%	33%	63%
Unimportant	<u>0%</u>	22%	**56%**	31%
<u>Seed and seedling management (<0.001)</u>				
Seeds partly self-produced	**51%**	<u>5%</u>	11%	19%
Seedlings at least partly self-produced	49%	**59%**	<u>0%</u>	38%
Seeds and seedlings purchased	<u>0%</u>	36%	**89%**	44%
<u>Food supply chain (<0.001)</u>				
Direct selling (0 intermediary)	**73%**	54%	<u>0%</u>	<u>0%</u>
Direct selling and short mixed	10%	**24%**	0%	19%
Short (1 intermediary)	15%	5%	0%	6%
Long and short mixed	0%	6%	11%	0%
Long (2+ intermediaries)	<u>2%</u>	<u>11%</u>	**89%**	**75%**
Furthest selling destination (<0.001)				
Department	71%	**66%**	<u>0%</u>	<u>13%</u>
Regional	15%	17%	0%	6%
National	15%	15%	33%	**50%**
Foreign	0%	<u>2%</u>	**67%**	**31%**
<u>Annual revenue (k€) (<0.001)</u>				
0-30	**73%**	<u>11%</u>	0%	<u>0%</u>
30-60	17%	18%	0%	0%
60-100	<u>10%</u>	**36%**	0%	<u>0%</u>
100-300	<u>0%</u>	**31%**	44%	19%
300-500	<u>0%</u>	<u>3%</u>	22%	**38%**
500-1000	0%	<u>0%</u>	**33%**	**31%**
1000 +	0%	0%	0%	**13%**
Region (<0.001)				
South-east	**24%**	<u>4%</u>	**89%**	0%
North-west	<u>32%</u>	**69%**	<u>11%</u>	75%
South-west	29%	18%	0%	19%
Other	15%	9%	0%	6%
<u>Conversion to organic farming (<0.001)</u>				
Farm created as organic	**93%**	**84%**	<u>0%</u>	<u>44%</u>
Farm converted to organic farming	<u>7%</u>	<u>16%</u>	**100%**	**56%**
<u>Diversification (0.26)</u>				
Specialised in vegetable production	<u>39%</u>	59%	78%	44%
Diversified in other types of production	**61%**	41%	22%	56%
Alternative farming (<0.001)				
Alternative farming	**90%**	<u>26%</u>	33%	<u>13%</u>
Non-alternative farming	<u>10%</u>	**74%**	67%	**88%**

(1) If clusters differ significantly (P <0.05), they are considered to come from different populations.

3.1.2.Farm cluster descriptions

Cluster 1: Microfarmers for the local market (**Fig. 2.3a**)

Cluster 1 farms had the smallest UAA, outdoor vegetable area and sheltered vegetable area (medians of 3.0, 0.5 and 0.04 ha, respectively), compared to medians for all farms of 5, 1.5 and 0.15 ha, respectively. The median vegetable area was 0.55 ha. They also had less labour (1.3 full-time equivalent (FTE) vs. 2.3) and fewer tractors (1.0 vs. 2.1). With a median of 30 vegetables grown, these farms were diversified, even though 29% of them grew fewer than the 30 types of vegetables needed to fully meet Morel and Leger's (2016) definition of a microfarm. Farmers placed major or high importance on dedicating space for biodiversity. They used external inputs less, practiced significantly more no-tillage than farms in other clusters and practiced little deep tillage (with or without inversion). Weeds, pests and diseases were controlled mainly using natural practices and local resources. Some of their seeds and seedlings were self-produced. Most fertilisation was self- or locally produced, but the percentage did not differ significantly from that of the entire sample. Their annual revenue was low (most less than 30 000 €), and they had high territorial embeddedness, selling to the local market. Most farms (93%) had been organic since their creation, which was recent (median of 5 years), which may help explain the low annual revenue. Some of these farms may not have reached their full development. Most farmers declared that they practiced alternative farming, which Morel and Leger (2016) consider to be a feature of microfarming.

Cluster 2: Medium-sized market gardeners for the local market (**Fig. 2.3b**)

Cluster 2 farms were larger than cluster 1 farms (medians of UAA, outdoor vegetable area and sheltered vegetable area of 5.2, 1.7 and 0.2 ha, respectively) but remained smaller than the farms of clusters 3 and 4. The median vegetable area was 2 ha. More people worked on the farm (median of 2.7 FTE) than on cluster 1 farms, but much fewer than on the farms of clusters 3 and 4. With 40 types of vegetables grown, these farms were highly diversified. Farming practices were mixed between agroecological-based practices and the use of external inputs. Most farmers declared that they practiced non-alternative farming. Most farms had been organic since their creation (84%), which was a period (median of 9 years) longer than that of cluster 1 farms but much shorter than those of cluster 3 and 4 farms (**Table 2.1**). With 99 farms, a wide range of annual revenue (30-300 k€) and mixed practices, this cluster was the most heterogeneous.

Cluster 3: Producers specialised in cultivation under shelters for long food supply chains (**Fig. 2.3c**)

Cluster 3 farms were characterised by a large sheltered vegetable area (median of 3 ha), which occupied ca. two-thirds of the UAA, with a median vegetable area of 6 ha. Labour (median of 7 FTE) was higher than those of clusters 1 and 2. They were specialised, producing a few types of vegetables (median of 12) sold in long supply chains to national and export markets. Annual revenue ranged from 100-1000 k€. Almost all farms were located in the south-east, known as an area for producing vegetables under shelters throughout the year for export. They used inputs for seeds, fertilisation and pest management intensively, and biodiversity was not their main concern. These farms had a long history (median of 30 years) and had all started in conventional farming before converting to organic.

Cluster 4: Large market gardeners specialised in outdoor cultivation for long food supply chains (**Fig. 2.3d**)

Cluster 4 farms were characterised by a large outdoor vegetable area (median of 14.5 ha) and a small sheltered vegetable area (median of 0.07 ha), with a median vegetable area of 15.1 ha. They had more workers (median of 7 FTE), more tractors (median of 5) and produced fewer vegetables (median of 11) than farms in clusters 1 and 2. They ploughed significantly more than farms in other clusters. They used mainly local fertilisers, sometimes combined with purchased fertilisers. Annual revenue ranged from 100 k€ to more than 1000 k€, and they sold in long supply chains to national and export markets. They started farming ca. 27.5 years ago, the majority of them in conventional farming before converting to organic (56%), and declared that they practiced non-alternative farming.

(a) Cluster 1

(b) Cluster 2

(c) Cluster 3

(d) Cluster 4

Fig. 2.3. Photographs of farms of the four clusters (Credit: first author)

3.2. Differences among clusters for biotechnical functioning and socio-economic context

Farm clusters differed in the biotechnical index ($\chi2= 78.241$, df=3, $p<0.001$), which was not surprising, as its components were variables that had influenced the clustering (**Fig. 2.4**). Cluster 1's biotechnical index (median of 0.80) was significantly higher than that of all other clusters. It was followed by clusters 2 and 4 (medians of 0.50 and 0.40, respectively), which did not differ significantly from each other. Cluster 3 had the lowest biotechnical index (median of 0.27), which differed significantly from those of the other clusters. The highest agroecological performances of cluster 1 were related to higher scores for all primary indicators except fertilisation (**Fig. 2.5**). Cluster 4 had the highest score for fertilisation but lowest score for tillage. Farm clusters also differed in the socio-economic index ($\chi2= 52.324$, df=3, $p<0.001$) (**Fig. 2.5**). Clusters 1 and 2 had the highest socio-economic index (medians 1 and 0.88, respectively), which differed significantly from those of clusters 3 and 4 (medians of 0 and 0.17, respectively), which did not differ significantly from each other. The two composite indexes were significantly but weakly correlated (Kendall's $\tau = 0.23$, $p<0.001$).

The 165 farms showed high variability when positioned on a framework defined by the socio-economic index and biotechnical index (**Fig. 2.6**). Microfarms (cluster 1) were in the upper right quadrant of the framework, relying on ecosystem services with a high territorial embeddedness. They were opposite in the framework from cluster 3 farms – specialised in sheltered production – which were in the lower left quadrant, being biological input-based and selling on the global market. Cluster 2 and 4 farms were approximately halfway on the vertical axis but differed on the horizontal axis. Cluster 2 farms were mainly on the right half of the framework, being territorially embedded, whereas cluster 4 farms were on the left half of the framework, with relationships based on global market prices.

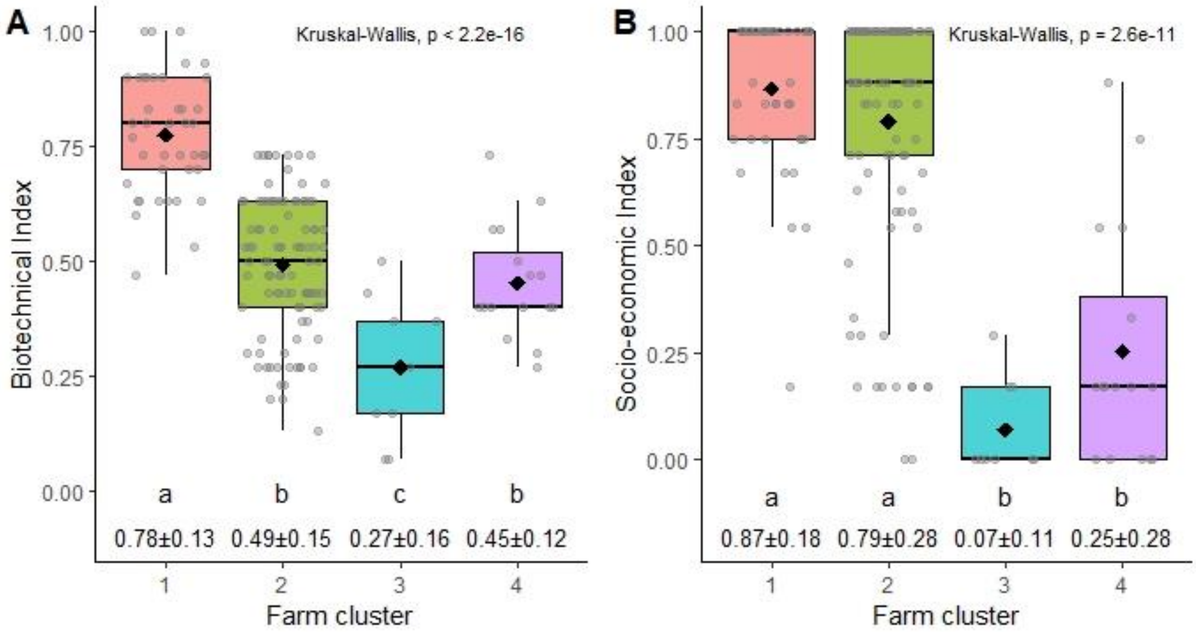

Fig. 2.4. Boxplots of the (A) biotechnical index and (B) socio-economic index for the 165 farms by farm cluster. A horizontal jitter function is used in the graph to visualise farm points more clearly. Medians differed significantly among farm clusters for the biotechnical index (Kruskal-Wallis $\chi 2= 78.241$, df=3, $p<0.001$) and the socio-economic index (Kruskal-Wallis $\chi 2= 52.324$, df=3, $p<0.001$). A different letter indicates a significant difference according to the pairwise Mann-Whitney U test at $p<0.05$. Values below the letters show means (black diamonds) ± standard deviations. Whiskers represent 1.5 times the interquartile range.

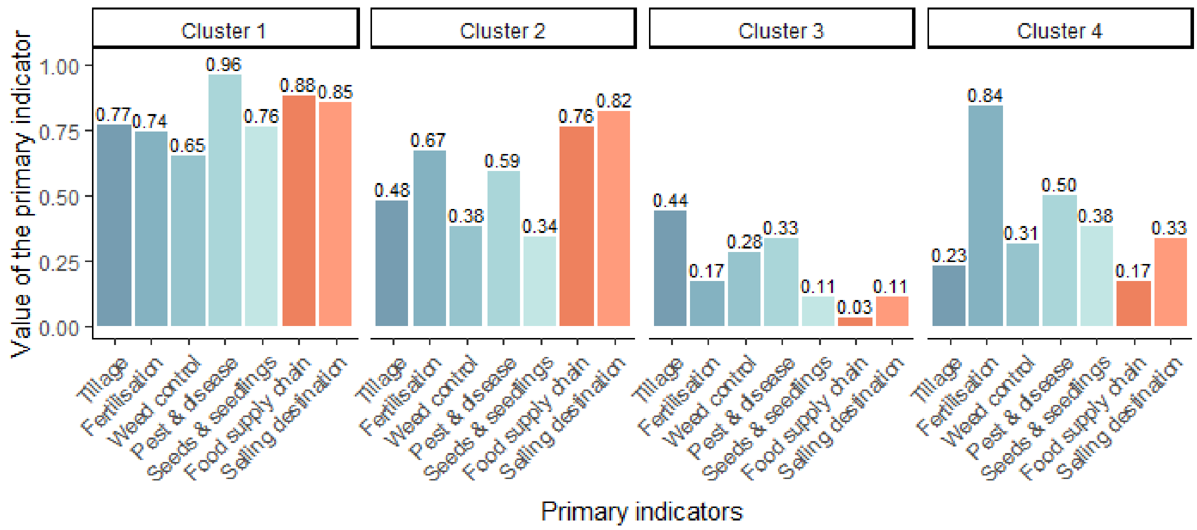

Fig. 2.5. Median scores of the primary indicators used to build the composite indexes of biotechnical functioning (blue) and socio-economic context (red) according to cluster. See Table 2.1 for full names and descriptions of primary indicators.

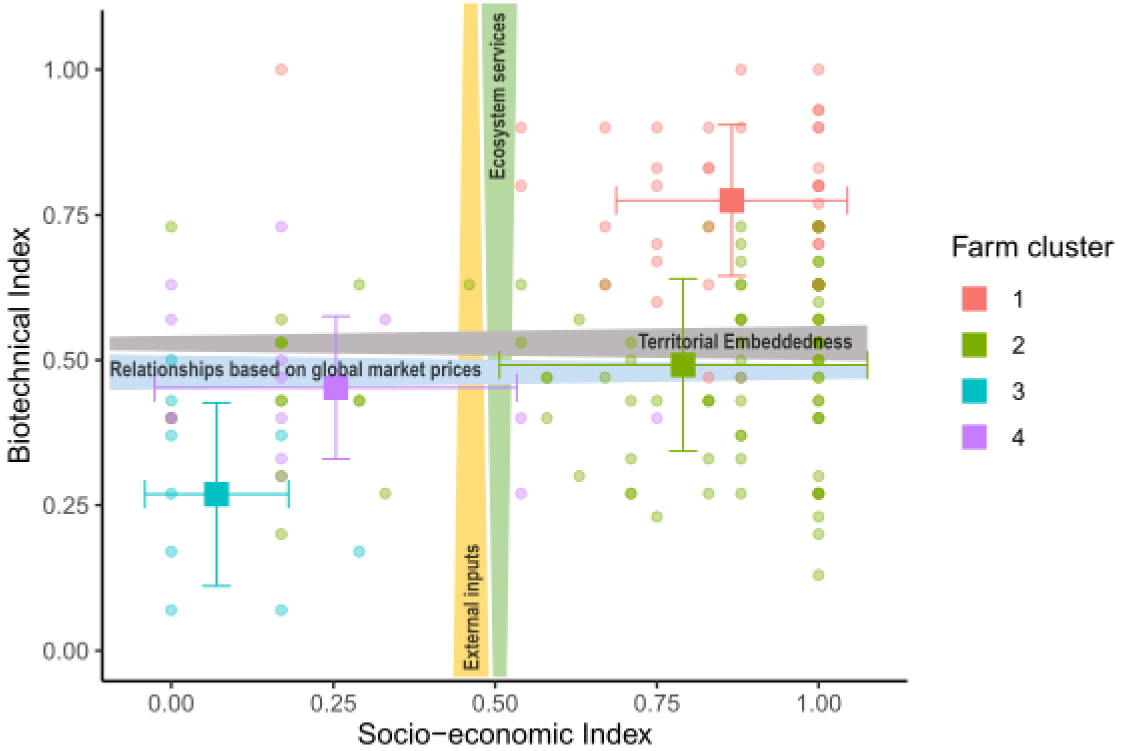

Fig. 2.6. Representation of the 165 farms sorted by farm cluster on a framework defined by the socio-economic index and the biotechnical index.
Darker circles indicate overlapping farms with the same values. Squares represent the mean of each index, whereas error bars represent the standard deviation of the two indexes for each farm cluster. (Thérond et al., 2017)

3.3. Relationship between the vegetable area and the biotechnical index

The regression model that fitted best was a second-order polynomial (**Fig. 2.7**) with three significant coefficients ($p<0.001$):

$$\mathbf{Y = 0.12x^2 - 0.28x + 0.58 \ (2)}$$

where Y is the biotechnical index and x the logarithm (log10) of the vegetable area.

The residuals were normally distributed according to the Shapiro-Wilk test (W = 0.996, p = 0.967). The adjusted R^2 was 0.29. The minimum fitted value of the biotechnical index was reached at log (vegetable area) = 1.18 (i.e. 15 ha).

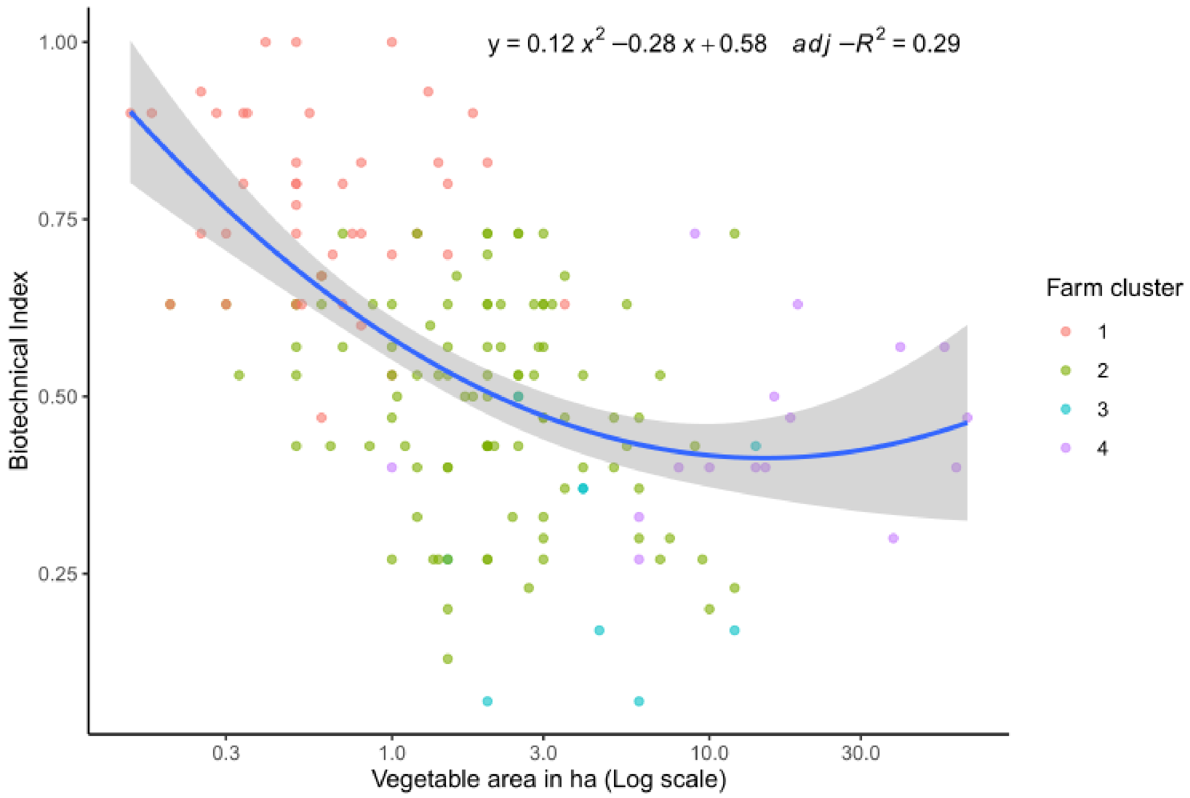

Fig. 2.7. Second-order polynomial regression (blue line) of the biotechnical index as a function of log (vegetable area). The grey zone represents the 95% confidence interval of the regression. Darker circles indicate overlapping farms with the same values.

The biotechnical index decreased for farms from 0-15 ha, especially for smaller farms (ca. < 2-3 ha). For farms larger than ca. 15 ha, the 95% confidence interval was too broad to determine whether the biotechnical index increased or continued to decrease. Only the smallest farms reached the highest values of biotechnical index. The wide distribution of the farms and relatively low adjusted R^2 (0.29) indicated that vegetable area was not the only factor that determined biotechnical functioning.

4. Discussion

4.1. Selection of data and interpretation of the statistical analysis

We collected data from the farmers on a voluntary basis. We aimed to maximise the number and diversity of the farms involved by sending e-mails to farmers and managers of farmers' networks. Despite this communication effort, only willing farmers and managers answered the survey or forwarded it to farmers in their network, respectively. This approach may have resulted in a small sample size for some farm types (e.g. cluster 3). In particular, one farm in cluster 4 lay apart from the other farms in the FAMD factor map (**Fig. 2.2**). This farm was the largest one in the sample (65 ha of outdoor fields, 1.8 ha sheltered, 29 ETP and 19 tractors). It is possible that other organic farms in France have similar characteristics and, had they been included in our sample, would have formed another cluster.

Five of the eight quantitative variables (i.e. UAA, outdoor vegetable area, sheltered vegetable area, labour, and number of tractors) were related to farm size. The strongest correlation was between outdoor vegetable area and number of tractors (Kendall's $\tau = 0.61$, $p<0.001$), which we did not consider strong enough for either of the variables to be discarded. As farm size lay at the core of our hypotheses about farm types, we considered that it was important to include all of these variables.

As expected by the hypotheses, farm size influenced the clustering strongly, with significant differences among the clusters. The differences that we hypothesised existed among farm types in the use of external inputs, the number of types of vegetables and the distance to consumers were confirmed by the analysis (**Table 2.1** and **Table 2.3**). Compared to the hypotheses made *a priori*, clusters 2 and 3 did not differ in UAA (i.e. farm size) but did differ in sheltered vegetable area.

4.2. Comparison with existing typologies and frameworks

A few typologies of organic vegetable farms have been developed in different geographic and institutional contexts. To our knowledge, none of them was based on a factor analysis with the aim of positioning the farms on a framework that combined biotechnical and socio-economic factors. They were based on different criteria, mainly the cultivated area (Drouet et al., 2020; Dumont and Baret, 2017) or economic characteristics (Clus, 2009; Giraudet, 2019; Jammes, 2012; Navarrete, 2009), especially the type of food supply chain (i.e. short, mixed or long), used as a key criterion, but not farming practices, which is a novelty of our study.

In the typology developed in Belgium by Dumont and Baret (2017), vegetable area was the key criteria used to cluster the farms: market gardening on small areas (<2.5 ha), on medium-sized areas (2-10 ha), on large areas (12-38 ha) and vegetables in combination with field crops (>25 ha). This approach is in line with the importance that we placed on area-based variables in our typology. Dumont and Baret (2017) assessed whether their farm categories were agroecological or not based on a definition of "agroecology" which included the use of organic practices and implementation of socio-economic principles (e.g. financial independence by decreasing inputs, geographic proximity to markets, partnership between producers and consumers) (Dumont et al., 2016). They found organic market gardening on small areas and medium-sized areas to be agroecological, whereas larger organic systems were not. This result partially agrees with ours, in which the clusters of the smallest farms (i.e. 1 and 2) had higher biotechnical and socio-economic indexes than those of larger farms (i.e. 3 and 4), albeit not significantly so between clusters 2 and 4 for the biotechnical index. Compared to those of Dumont and Baret (2017), the composite indexes we developed go beyond the binary “agroecological or not” distinction (Dumont and Baret, 2017) by ranking the farms. These indexes summarised and quantified characteristics of the clusters, which allowed us to compare them, capture their main features and assess the variability within each cluster.

4.3. Contribution to the bifurcation debate

4.3.1.The diversity of organic vegetable farms in France: a sign of bifurcation?

Our results highlighted biotechnical and socio-economic heterogeneity among organic vegetable farms. The diversity of farming systems observed, associated with significantly different positions on the two axes of the analytical framework, can be interpreted as evidence of the coexistence of “agroecological” and “conventionalised” OF (Gliessman, 2013) and as a sign of possible bifurcation. Cluster 1 farms, with significantly higher biotechnical indexes, are clearly “agroecological”, whereas cluster 3 farms are the most “conventionalised”. Our study showed a bimodal distribution on the socio-economic axis (i.e. between short and long food supply chains) but no discontinuity on the biotechnical axis. Thus, our study suggests that the dichotomy between “agroecological” and “conventionalised” organic farms should be considered as a conceptual perspective with two poles and a gradient of farms between them.

Trends that support the bifurcation hypothesis have been documented in California for organic vegetables (Buck et al., 1997). Our study, based on a single survey, did not allow us to examine bifurcation as a process. Thus, for the farms in our sample, it remains unclear whether the existing heterogeneity results from past and/or present bifurcation, whether farms in the middle of the gradient tend to move more towards one pole than the other, whether this heterogeneity will continue and thus whether bifurcation is truly occurring in the French context. Addressing these topics would require a historical survey of the past or a follow-up study of the future of these farms. The only historical information we collected was whether each farm had been organic since its creation or converted to OF afterwards.

4.3.2.Role of “new organic farmers” in the bifurcation of farming practices

Most farms in cluster 1 and 2 had been organic since their creation, whereas most farms in cluster 3 and 4 had been converted to OF afterwards. However, cluster 3 and 4 farms generally had been organic longer than cluster 1 and 2 farms (median time since conversion of 11 and 22 vs. 5 and 9 years, respectively) (**Table 2.2**). Thus, comparing “organic since creation” to “converted to OF” seems to make more sense in our study than the classic opposition of early vs. late adoption of OF (Best, 2008; Läpple and Rensburg, 2011).

Best (2008) and Läpple and Van Rensburg (2011) consider farms which have been converted earlier or later to OF. To our knowledge these studies do not integrate or discuss specifically the role and values of farms created by new entrants with strong ecological values and no agricultural background, such as microfarms (Morel and Léger, 2016). Microfarms (cluster 1) or medium-sized vegetable farms (cluster 2) are often newly established on land that used to be part of cereal or livestock farms after the farmer retired. It seems incorrect to consider these new organic farms as "late adopters", as they were organic since their creation. To a certain extent, the strong ecological values of these new entrants may be closer to those of pioneers or early adopters of OF observed in other studies (Best, 2008; Läpple and Van Rensburg, 2011). Conventional farms have a structural (e.g. land, buildings, machines) and technical history which may increase their likelihood of implementing conventionalised practices once converted. Moreover, including agroecological principles in the overall design of the farm may be easier when the farm has been created based on OF principles.

Confirming these hypotheses, most agroecological practices were observed in the youngest farms that had been created as organic (cluster 1), whereas the most conventionalised practices were observed in cluster 3, all of whose farms converted to OF (**Table 2.3**). This tends to confirm that the profile of new organic farmers analysed through the "creation vs. conversion" perspective may play a role in the bifurcation of farming practices and should be investigated and discussed further in bifurcation or conventionalisation studies. However, comparing farms with a contrasting number of years in OF may be biased, because learning occurs over time (Darnhofer et al., 2010; Padel, 2008). For example, idealistic new entrants who start out with radical alternative practices may make conventionalisation trade-offs later to increase economic viability or decrease workload (Dumont and Baret, 2017).

4.3.3. Role of supply chains in the bifurcation of farming practices

The two extreme poles in our study – cluster 1 (with the most agroecological practices, short supply chains and a high socio-economic index) and cluster 3 (with conventionalised practices and long supply chains) – tend to support the assertion that the long supply chains that develop with the mainstreaming of OF may be related to less agroecological practices. This echoes the abundant literature that claims that agroecological practices (which may take more time and be associated with smaller farms with lower production volumes, as discussed later) are more likely to be supported by shorter supply chains that bring more added value to farmers and may reduce environmental impacts (Fernandez et al., 2013; Francis et al., 2003; Guzmán et al., 2016; Lamine and Dawson, 2018). Lower prices in long supply chains would require larger volumes and economies of scale (Mazoyer and

Roudart, 2006) to make a profit, which would favour conventionalised practices. If annual revenue is considered a proxy of production volumes, this explanation is consistent with the observation that cluster 1 farms had the lowest annual revenue, whereas cluster 3 farms had the highest (**Table 2.3**).

This relationship between volume and supply chains was also observed when comparing clusters 2 (lower volumes and short supply chains) and 4 (higher volumes and long supply chains). Their contrasting socio-economic indexes but equivalent biotechnical indexes indicate that farms with long supply chains can reach agroecological performances similar to those of farms with short supply chains, although the best agroecological performances were reached with short supply chains (cluster 1). The most agroecological farms of cluster 4 reached similar biotechnical indexes as some cluster 1 farms (**Fig. 2.4**), which suggests that high agroecological performances in organic vegetable production can be reached with long supply chains and should be investigated further.

4.3.4.Role of farm size in the bifurcation of farming practices

The decrease in biotechnical index as farm vegetable area increased up to 15 ha that was observed in this study reflects the relationship between use of external inputs and farm size that was observed in studies of smallholdings, especially in developing countries (Netting, 1993; Rosset, 2000). Decreasing external costs while relying on local resources and ecosystems to increase self-sufficiency and added value is a common strategy to make a living (or survive) on a small area (van der Ploeg, 2018), which also applies to French microfarmers (Morel et al., 2017).

Developing practices based on ecosystem services to reduce commercial inputs can increase the amount of labour per unit area (Morel et al., 2018). For example, establishing and managing wildlife habitats, growing green manure, composting local organic matter and producing homemade natural pesticides from local plants requires more time than applying commercial fertilisers and pesticides. Implementing agroecological practices also increases uncertainty (Duru et al., 2015) and may thus require more time in order to observe and learn about the specific characteristics and behaviour of agroecosystems. This may explain why agroecological practices may be easier to implement on smaller farms (cluster 1) than on larger farms (other clusters), where the logic of economies of scale reduces the amount of human labour per unit area (Mazoyer and Roudart, 2006).

Acknowledging the importance of farm size should not overlook other factors related to farming structure and strategies. For example, sheltered vegetable production traditionally has higher investment costs, higher production and complex plant-protection issues (Bavec et al., 2017; Lefevre et al., 2020). These factors probably make it more challenging to reduce external inputs in sheltered production.

Moreover, our study suggests that farm size may not have the same influence on all agroecological practices. For example, the largest farms (cluster 4) had the highest score for fertilisation because managing fertility with farm resources involves growing green manure, which requires space. Thus, the larger area of cluster 4 may favour these practices, unlike for the other clusters, in which rapid successions of crops to generate sufficient added value on a smaller area can the possibility of growing green manure (Morel and Leger, 2016). Conversely, cluster 4 may have had the lowest score for tillage because implementing no- or reduced tillage in OF is particularly challenging (Vincent-Caboud et al., 2017). Although some innovations can be explored on smaller areas by increasing labour intensity, developing them at a larger scale may be more difficult.

This discussion opens several research questions for agroecology in general and OF in particular. Can the highest agroecological performances be maintained only at small scales? To what extent does the structure of large organic farms or sheltered production depend on external inputs? This knowledge would be crucial for policy making, as most public subsidies for agriculture, especially OF, are land-based (per ha), which is associated with an increase in farm size (Key and Roberts, 2007) and possibly the conventionalisation of organic farms. Further research could also investigate the high variability within clusters to identify ways to improve agroecological performances.

4.4. From composite indicators to environmental assessment of a diversity of organic vegetable systems

Many studies have compared agronomic (de Ponti et al., 2012; Seufert et al., 2012), environmental (Foteinis and Chatzisymeon, 2016; Salou et al., 2017; van der Werf et al., 2020) or economic (Beltran-Esteve and Reig-Martinez, 2014; Froehlich et al., 2018) performances of OF vs. conventional farming. These studies implicitly considered organic systems as a single, homogeneous group. As our study revealed high biotechnical and socio-economic diversity among organic vegetable production systems, it is not appropriate to consider organic vegetable farms as a homogeneous group.

Some of the main arguments for encouraging agroecological practices, promoting more territorially embedded supply chains and criticising conventionalisation of OF are related to environmental impacts. The biotechnical and socio-economic composite indicators we developed allow to describe the diversity of agroecological practices and involvement in supply chains of organic vegetable farms. However, it remains to be seen whether higher biotechnical or socio-economic indexes result in lower environmental impacts. Composite indexes are the mean of primary indicators that can have contrasting values. In addition, any category of biotechnical or socio-economic indicator that we used may be related to contrasting environmental impacts, depending on the context, specific type of practice or supply chain. To overcome these limits, we will continue this research by performing life cycle assessment (European Commission - Joint Research Centre, 2010) of farms from each cluster to quantify their environmental impacts.

5. Conclusion

Our study, based on 165 farms in France, revealed a heterogeneity of organic vegetable farms that were grouped in four clusters with contrasting size, percentage of vegetable area under shelters, labour force, production diversity, mechanisation, involvement in supply chains, age, time since adoption of OF and farming practices. Methodologically, our study shows the utility of using composite indexes that aggregate primary indicators to position and compare the biotechnical and socio-economic dimensions of farms according to the conceptual framework of Thérond et al. (2017). Including costs in the socio-economic index would have made it stronger, but the available data did not allow this.

Contrasts between microfarms and the larger farms that specialised in cultivation under shelters can be interpreted as sign of bifurcation and support our three assertions that relate farming structure to farming practices. In particular, it calls for the need to consider, through the “creation vs. conversion” perspective, the role of new entrants who create new organic farms in adoption or bifurcation studies, which generally focus on existing farms that convert earlier or later.

The best agroecological performances were associated with short supply chains, although good agroecological performances did occur with some long supply chains. Our study also highlights that the smallest farms were more likely to implement agroecological practices even though farm size did not have the same influence on all agroecological practices.

Overall, our results suggest that:

- The dichotomy that contrasts “agroecological” and “conventionalised” organic farms should be considered as a conceptual perspective with two poles and a gradient of farms between them.
- For farms which lie away from these poles, size, supply chain and type of adoption of organic farming do not fully explain the level of reliance on external inputs *vs.* ecosystem services.
- For vegetable farms, the percentage of vegetable area under shelters should be considered in bifurcation studies in addition to UAA.

The study's main limitation is that it did not consider bifurcation as a dynamic process. This study raises questions to be investigated further, especially about strategies and the potential to develop more agroecological organic practices at a given scale or in a given supply chain. To our knowledge, no study has provided solid data or evidence that relates bifurcation of organic farming systems to impact on the environment. Quantifying environmental impacts of the diversity of organic farms and their practices among and within clusters is the next logical step of our research, as this is an important dimension of debates about the conventionalisation of organic practices.

Acknowledgments

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Transition

Le chapitre 2 a proposé une caractérisation de la diversité des fermes maraichères biologiques en France. Il identifie quatre types : 1) les microfermes diversifiées et utilisant peu d'intrants ; 2) les maraîchers diversifiés de taille moyenne ; 3) les producteurs spécialisés dans la culture sous abri ; et 4) les maraîchers spécialisés dans la culture de plein champ. Les caractéristiques des fermes et leur variabilité confirment l'existence de deux pôles « conventionnalisés » et « agroécologiques », tout en montrant qu'il s'agit d'une vision simplificatrice, la majorité des fermes se trouvant entre ces deux pôles.

Caractériser la diversité est une étape préalable à l'évaluation et à la comparaison des performances environnementales des fermes. Elle permet d'identifier les caractéristiques spécifiques des fermes et les caractéristiques génériques qui les relient fortement aux autres fermes du même type.

Le chapitre 2 a montré que la biodiversité occupe une place centrale dans la réflexion de certains maraichers, qui y expriment la volonté forte de dédier une partie de la ferme pour la favoriser. Pour d'autres maraichers, la biodiversité n'est pas une préoccupation particulière. Ces différences renforcent l'intérêt de disposer d'un outil pour évaluer les fermes sur ce sujet.

Le chapitre 3 présente la démarche d'adaptation de l'outil SALCA-BD aux cultures de légumes.

Chapitre 3. Système expert pour évaluer la biodiversité

Using an expert system to assess biodiversity in life cycle assessment of vegetable crops

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Abstract

Biodiversity loss in agricultural landscapes due to intensification of agriculture and degradation and loss of semi-natural habitats is a major issue that life cycle assessment (LCA) methods intend to address. No current LCA method is able to assess and compare impacts on the biodiversity of vegetable production systems as a function of farming practices and the local context. Based on a literature review and consultation with experts, the SALCA-BD expert system, originally designed to assess impacts on the biodiversity of cropland and grassland at field, rotation, and farm levels, was adapted to vegetable production systems. SALCA-BD is based on an inventory of the habitats found on a farm and a list of practices that can be implemented in these habitats. We distinguished an open field and a greenhouse as two distinct “level I” habitats, as a habitat’s openness favours the exchange of species with surrounding habitats. These two habitats were subdivided into “level II” habitats that corresponded to vegetable crops. Given the many types of vegetables, we used a clustering method to create a few categories that grouped vegetables that had similar potential to host biodiversity. We tested the expert system at field and farm levels using scenarios and a farm case study. We quantified effects of changes to individual practices and practice intensities at the field level on biodiversity. The results highlighted the importance of semi-natural habitats for preserving biodiversity, in addition to low-intensity practices, which indicates that assessment at the farm level is more informative than that at the field level. Because it considers habitats and practices in detail, SALCA-BD is useful for assessing biodiversity at field and farm levels and for comparing farming systems with the same land use and type of management (organic or conventional), which other LCA methods for assessing biodiversity cannot do. As SALCA-BD does not consider impacts of the background system, combining SALCA-BD with comprehensive methods for assessing impacts on biodiversity is a promising perspective for more complete assessment.

Keywords: agriculture, biodiversity indicators, expert system, farming practices, SALCA-BD

1. Introduction

Life cycle assessment (LCA) is a method used worldwide to assess potential impacts of a product , or the system that produces it, on the environment (ISO, 2006b). It allows comprehensive assessment to be performed, which can help compare the environmental profiles of products (Curran, 2014). It is based on a set of impact categories (e.g. climate change, eutrophication, ozone depletion) that cover a broad range of environmental issues. Negative impacts of human activities on biodiversity are recognised as a major environmental issue (IPBES, 2018). In particular, impacts of agriculture on biodiversity have been widely documented, especially due to the organisation of agricultural landscapes and the types and intensities of practices in and around fields (Abdi et al., 2021; FAO, 2019; Karp et al., 2012; Mupepele et al., 2021). Assessing impacts on biodiversity in LCAs of agricultural products is of primary importance (Koellner et al., 2013), and many studies have developed methods for doing so (Curran et al., 2016; Gabel et al., 2016).

Many of these methods are based on estimating impacts of land-use classes alone, with no consideration of land management. Koellner and Scholz (2008) and Mueller et al. (2014) developed characterisation factors (CFs) for impacts of conventional and organic farming systems on biodiversity within a given land-use class based on literature reviews of studies that used different sampling methods. Knudsen et al. (2017) developed CFs based on field data in Europe, including four agricultural land-use classes (i.e. monocotyledon pasture, mixed pasture, arable crops, and hedge) managed under conventional or organic practices. The method developed by Chaudhary et al. (2015), which provided CFs for 804 ecoregions and six land-use classes (i.e. intensive forestry, extensive forestry, annual crops, permanent crops, pasture, and urban) was provisionally recommended by the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC, 2017) for analysing impact hotspots, but not for comparing systems. Chaudhary and Brooks (2018) updated the method by introducing three levels of land-use intensity: minimal, light, and intense. Hayashi (2020) compared impacts estimated by the updated method to field-level biodiversity (species richness) observations of rice production systems in Japan and found inconsistencies between regional- and field-scale species richness of plants and amphibians.

Because none of these methods can compare farms or fields that have the same land use and type of management (organic or conventional), two organic vegetable farms would have the same impact even though they may have practices (Pépin et al., 2021) that impact biodiversity differently. These methods are useful for identifying hotspots of impact on biodiversity but do not provide detailed analysis, particularly of agricultural systems whose farming practices and local characteristics must be considered (Teixeira et al., 2016).

The expert system SALCA-BD (Swiss Agricultural LCA—Biodiversity) (Jeanneret et al., 2014) integrates biodiversity into agricultural LCA as an independent impact category. It assigns coefficients to crop and non-crop habitats that reflect their ability to host terrestrial species diversity, and to farming practices that reflect their impact on biodiversity. The coefficients, combined with the practices selected by the user, result in scores for 11 indicator species groups (ISGs) (i.e. crop flora, grassland flora, birds, small mammals, amphibians, snails, spiders, carabid beetles, butterflies, wild bees, and grasshoppers), which can be aggregated to a single final biodiversity score at field, rotation, and farm levels. The method has been validated with field observations of plants and grasshoppers in grassland (Jeanneret et al., 2014) and of vascular plants, spiders, and wild bees in cropland, grassland, and semi-natural habitats (SNHs) (Lüscher et al., 2017). Unlike other methods that apply CFs based on land use, SALCA-BD focuses on agricultural systems and does not estimate an absolute value for species loss. It is valid for Switzerland and neighbouring regions. SALCA-BD's detailed analysis allows for comparison of fields or farms by considering the practices applied to crops and SNHs. It is useful for assessing farms and identifying and testing impacts of innovative alternatives (e.g. changes in practices or land use) on biodiversity. Because SALCA-BD is focused on on-farm activities (i.e. the foreground system), it does not consider off-farm activities (i.e. the background system), such as the production of imported feed or land occupied by the infrastructure used to transport inputs.

SALCA-BD, initially developed for cropland, grassland, and SNHs, was later adapted to orchards by Van der Meer et al. (2017). In this study, we adapted SALCA-BD to vegetable crops, which had not been included in cropland, by adding habitats and practices specific to vegetable production systems (VPSs). VPSs differ from cropland by the presence of sheltered production in addition to open-field production and, on some farms, the practice of intercropping (i.e. growing two or more vegetables in the same field) (Pépin et al., 2021). To adapt SALCA-BD to VPSs, we first identified the habitats and practices specific to VPSs and estimated their impacts on biodiversity. We then performed sensitivity analyses of the main characteristics of VPSs at the field level. Finally, we applied SALCA-BD to a farm case study.

2. Materials and methods

2.1. The expert system SALCA-BD

SALCA-BD is based on an inventory of farming practices that may be applied to crops and SNHs (**Fig. 3.1**) and includes as many practices as possible that influence biodiversity on a farm (Jeanneret et al., 2014). The inventory lists "level I" habitats (e.g. cropland, grassland, SNHs), which are divided into "level II" habitats (e.g. winter wheat, unproductive pasture, hedgerows). For each habitat, farming practices (e.g. tillage type, tillage depth) are listed, and if needed, subdivided into up to three levels (i.e. I: plant protection, II: insecticide, and III: date of application).

Because habitats have different potentials for hosting each ISG (e.g. an onion field may be more favourable for crop flora than grassland flora), a coefficient ($C_{habitat}$) that expresses this potential that ranges from 0 (lowest) to 10 (highest) is assigned to each habitat. Similarly, because management practices may influence ISGs differently (e.g. tillage influences carabid beetles and birds differently), a coefficient ($C_{management}$) that expresses this influence that ranges from 0 (lowest) to 10 (highest) is assigned to each practice. Each farming practice has several management options that describe how the practice is implemented (e.g. for tillage type: “no tillage”, “ploughing”). Based on an extensive literature review and expert consultations, the direct impact of each management option in a given habitat on populations of each of the 11 ISGs is rated (rating “R”) on a scale from 0-5: 0 (not applicable), 1 (strong decline), 2 (decline), 3 (neutral), 4 (increase), and 5 (strong increase). For instance, the rating of herbicide applications for butterflies considers only mechanical and chemical impacts from direct contact, not indirect impacts due to removing potential host plants.

The final impact score of a practice implemented in a given habitat on a given ISG is calculated as $R \times (C_{habitat} + C_{management})/2$. The average of the impact scores of the practices in a given habitat on a given ISG equals the “ISG score” at the field level. A bonus or malus is applied to the "ISG score" at the field level to capture the influence of soil cover over a one-year period. The “ISG scores” for all 11 ISGs can be aggregated to calculate the impact on biodiversity (i.e. “biodiversity score”) of a given habitat using weights that depend on the position of each ISG in the food web. Lower weights express a higher position of the ISG in the food web (i.e. consumes other ISGs). The biodiversity scores at the field level can be aggregated at rotation or farm levels using the areas of the fields as weights. The ratings and coefficients are listed in SALCA-BD’s “control table”.

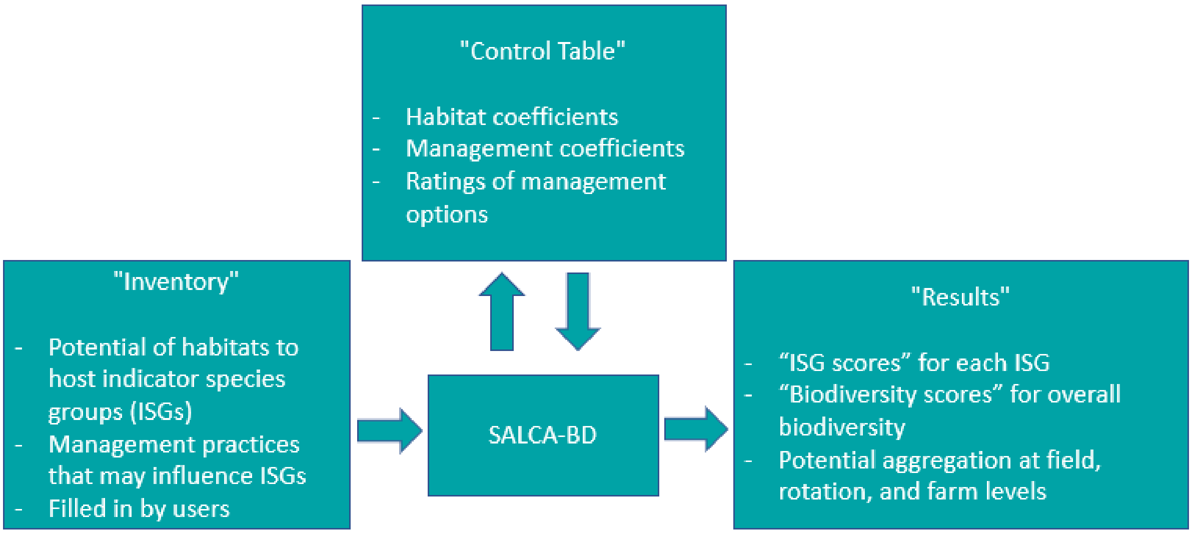

Fig. 3.1. The SALCA-BD framework. Users fill out the inventory file and import the control table into the expert system. The expert system assigns ratings and coefficients from the control table to the data in the inventory in order to calculate final scores.

2.2. Parametrisation of SALCA-BD to VPSs: the inventory and control table

Adapting SALCA-BD to VPSs required modifying the existing inventory and control table. The habitats, farming practices, and management options specific to VPSs were identified through a literature review, consultation with experts in VPSs (Supplementary Material 1), and statistical analysis. The literature review included studies from 1990-2020 in the temperate climate zone from scientific articles and grey literature, including magazine articles, trade-press articles, academic dissertations, institutional reports, book chapters, and conference proceedings (Mahood et al., 2014). The literature data bases used were the Web of Science, Google Scholar, and the online archives of FiBL (Forschungsinstitut für Biologischen Landbau), the Louis Bolk Insitute, and ITAB (Institut Technique en Agriculture Biologique). This step, which yielded 1132 records, took inspiration from a systematic review that parametrised SALCA-BD for orchards (van der Meer et al., 2020).

Level II habitats of cropland in SALCA-BD are crops (e.g. winter wheat, maize). Because VPSs contain many different crops, and little information about biodiversity is vegetable-specific, we defined level II habitats of VPSs as groups of vegetables that had similar potential to host all 11 ISGs. Starting with 40 vegetable crops (excluding perennials), we performed multiple component analysis (MCA), followed by agglomerative hierarchical clustering (AHC), to create a few categories. Each vegetable crop was described by four categorical variables that represented coarse habitat characteristics for biodiversity: height (low, medium, high), soil cover (low, medium, high), crop duration (≤ 5 months, > 5 months), and presence of flowers (yes, no) (Supplementary Material 2). The AHC was based on k-means consolidation of the Euclidian distance of the factorial coordinates of each crop, calculated using Ward's (1963) method. The optimal number of clusters was determined by considering the largest relative loss of inertia.

Once AHC had defined clusters, the relation between cluster number and the categorical variables was studied using a chi-square test. For each variable, a hypergeometric test was performed to characterise the clusters by their responses and to test whether each cluster over- or under-represented the responses. The MCA and AHC were performed using the R package FactoMineR (Lê et al., 2008), R software v. 3.5.3 (R Core Team, 2019), and RStudio v. 1.1.463 (RStudio Team, 2016).

Once the inventory had been created, we defined habitat coefficients, management coefficients, and ratings to build the control table. An initial version was based on findings of the literature review. This version was modified after interviewing experts of the ISGs, who were chosen because they were ecologists specialised in the ISGs, as recommended by Souza et al. (2015).

2.3. Sensitivity analysis

We conducted a one-at-a-time (OAT) sensitivity analysis to study the influence of farming practices and habitats on biodiversity scores at the field level. We analysed different management options of farming practices that were specific to VPSs for four contrasting vegetable categories (level II habitats) in each level I habitat, using wheat as a reference crop, as Jeanneret et al. (2014) did, for a total of 106 scenarios. Management practices that were not analysed in the sensitivity analysis were set to practices that are common on low-intensity organic farms (e.g. fresh manure and compost as fertilisers, low frequency of fertilisation). Biodiversity scores were calculated at the field level and aggregated for all 11 ISGs.

As a system-level sensitivity analysis, we compared two fields of onion cultivated with low- vs. high-intensity practices in each level I habitat that varied in fertilisation, weed control, pest control, and tillage. In the low- or high-intensity scenario, management options were the least or most, respectively, intensive in terms of frequency, quantity, and types of inputs. Biodiversity scores were calculated at the field level for each ISG and aggregated for all 11 ISGs.

2.4. Farm case study

We applied SALCA-BD to an organic vegetable farm in Brittany, France, and calculated the farm-level biodiversity score using two boundaries: (1) cultivated areas only or (2) cultivated areas and SNHs. The farm produced vegetables and rye on 21 ha of open fields in a four-year rotation: potato / rye followed by turnip / cabbages (i.e. cauliflower, green cabbage, Savoy cabbage, Brussels sprouts, kale) / various vegetables (e.g. carrots, onions, squash). Fertilisation consisted of cow and poultry manure applied three out of every four years. Mechanical weeding was performed by tractor, and weeds in carrot crops were controlled by thermal weeding (flame produced using natural gas). Reusable anti-insect netting was used to cover certain vegetables, but there were few other types of pest or disease control. The farm was located in a hedgerow-network landscape. Its SNHs were 0.9 ha of extensive grassland, 2.6 ha of hedgerows around the fields, and 0.3 ha of ruderal area. The farm grew Jerusalem artichoke, which was not in the list of vegetables that we had used for the clustering; thus, we assigned to it the vegetable category whose characteristics were the most similar to its characteristics. The farm also grew potato, which exists in the original SALCA-BD as a level II habitat under cropland. Because this farm cultivated its potato more like a field crop (i.e. mechanised on large areas) than a vegetable, we assigned the expert system's pre-existing potato habitat to it.

3. Results

3.1. Parametrisation of the expert system SALCA-BD for VPSs

To cluster vegetable crops into level II habitats, two basic forms of vegetable production – an open field (OF) and a greenhouse (GH) – needed be distinguished as level I habitats because they differ in their openness and climate (i.e. temperature and humidity). Several types of GHs for vegetable production exist, but only those that could represent a habitat for any ISGs were considered. Soilless GHs were excluded as they are emptied and cleaned in winter, and can be considered as a building, which lies outside the scope of SALCA-BD. Only GHs with sides or ends that can be opened during the year, such as tunnels, bi-tunnels, and multi-span GHs, were considered.

Ultimately, we defined the same level II habitats for OF and GH (**Table 3.1**). The first three components of the MCA, which explained 74% of the variance, were retained for the AHC. Each variable was represented the most by one of the first three components. The AHC identified four clusters. Because vegetables that had the shorter duration and the presence of flowers were separated between two of them, we grouped these vegetables to create a fifth cluster. From the AHC, five categories of annual vegetable habitats that had similar characteristics were created (categories A to E). The chi-square tests indicated that all four categorical variables (i.e. height, soil cover, crop duration, and presence of flowers) were significantly ($p < 0.01$) related to the cluster number of each category. Category A was characterised by low soil cover and grouped vegetables in the Liliaceae family. Category B was characterised by high soil cover and grouped vegetables in the Brassicaceae family along with annual aromatic plants. Category C grouped leafy and root vegetables with medium soil cover, without flowers. Category D grouped tall plants with a longer duration and flowers, which were mainly vegetables in the Solanaceae family and fava bean, but not early potato, which was grouped in category E. Category E was characterised by flowers and grouped vegetables in the Cucurbitaceae family along with beans, peas, and edible flowers. Three perennial vegetable categories were created for artichoke (F), asparagus (G), and strawberry (H), which differ from each other in their soil cover, height, and presence of flowers. A category for intercropped vegetables (I) was created for fields in which multiple vegetables are grown at the same time, which is common on microfarms (Morel and Leger, 2016).

Table 3.1. Vegetable categories as a function of soil cover, height, crop duration, and presence of flowers.
The characteristics of categories A-E were defined by agglomerative hierarchical clustering, and those in bold were significant (chi-square test: $p < 0.01$).

Category	Vegetables	Characteristics
A	shallot, fresh onion, onion, leek, garlic	• medium height • **low cover** • no flowers
B	head cabbage (e.g. Brussels sprouts, Savoy cabbage), leafy cabbage (e.g. kale), cauliflower, broccoli, other cabbage (e.g. Chinese cabbage), annual aromatic herbs	• low-medium height • **high cover** • no flowers
C	beetroot, Swiss chard, bunch radish, carrot, celery, celeriac, salad, mixed leaves, endive, fennel, lamb's lettuce, spinach, turnip, parsnip, radish	• low-medium height • **medium cover** • **no flowers**
D	eggplant, fava bean, pepper, potato, tomato, sweet potato	• **high height** • **longer duration** • **flowers**
E	pumpkin and squash, melon, watermelon, cucumber, courgette, bean, pea, early potato, edible flowers	• low-medium height • medium-high cover • **flowers**
F	artichoke	perennial, medium soil cover
G	asparagus	perennial, low soil cover
H	strawberry	perennial, flowers
I	intercropped vegetables	

Because most farming practices of VPSs (e.g. fertilisation, tillage, sowing) already existed for cropland in the expert system, we used them for VPSs. We added or adapted weed-control practices that were specific to VPSs, such as mulching, manual/mechanical hoeing, and thermal weeding (i.e. flame, steam, or hot water), and their corresponding management options (**Table 3.2**). We also added weed-control practices specific to GHs (on the interior grassy edge). These practices are alternatives to the application of herbicides.

Table 3.2. Habitats, farming practices, and management options in SALCA-BDA for vegetable production systems (VPSs) in the level I habitats of an open field or greenhouse in SALCA-BD. Those in bold are specific to VPSs, whereas those in italics are specific to a greenhouse.

Level II habitat	Level I farming practice	Level II farming practice	Level III farming practices	Management options
Categories A to I Green manure	Fertilisation	-	Date, quantity, type, & technique (e.g. incorporated)	For each practice
	Plant protection	Weed control	**Cover**	**No cover, organic mulch, or synthetic mulch**
			Manual/mechanical hoeing **Thermal weeding**	**Yes or no**
			Selective herbicide Non-selective herbicide	No herbicide, or a percentage of the area (< 25%, 25% to < 50%, 50% to < 75%, or 75-100%)
		Insecticide	Date, quantity, & type	For each practice
		Fungicide	Date, quantity, & type	For each practice
		Biological pest control	Date, quantity, & type	For each practice
		Rodent control	Date, quantity, & type	For each practice
		Mollusc control	Date, quantity, & type	For each practice
	Soil tillage and sowing	-	Date, tillage type, & depth	For each practice
	Irrigation	-	-	Yes or no
	Harvest	-	Date & post-harvest material	For each practice
Interior grassy edge	*Plant protection*	*Weed control*	*Type & frequency*	*For each practice*
	Cutting	-	-	*Yes or no*

3.2. One-at-a-time sensitivity analysis

At habitat level I (cropland, OF, GH), mean aggregated biodiversity scores for white onion, pumpkin, artichoke, and intercropped vegetables in GH were 35%, 35%, 29%, and 27% lower, respectively, than those for winter wheat (**Fig. 3.2**). In OF, only white onion, which had the lowest soil cover, had lower biodiversity scores (-5%) than winter wheat. Pumpkin, artichoke, and intercropped vegetables had higher biodiversity scores than winter wheat, with a mean increase of 2%, 9%, and 17%, respectively. All vegetables had higher biodiversity scores in OF than in GH.

For all crops, biodiversity scores for differing management options followed a similar pattern, in which the options resulting in the highest (no weed control) and lowest scores (non-selective herbicide on 75-100% of the area) differed by 9.6% (intercropped vegetables in OF) to -11.5% (white onion in OF) (**Fig. 3.2**). All weed-control practices had lower biodiversity scores than winter wheat (no weed control), by 5.6% (organic mulch) to 11.4% (non-selective herbicide on 75-100% of the area) for white onion in OF. Synthetic mulch had more negative impact on biodiversity than organic mulch and manual/mechanical hoeing. Selective herbicides had slightly less negative impact on biodiversity than non-selective herbicides.

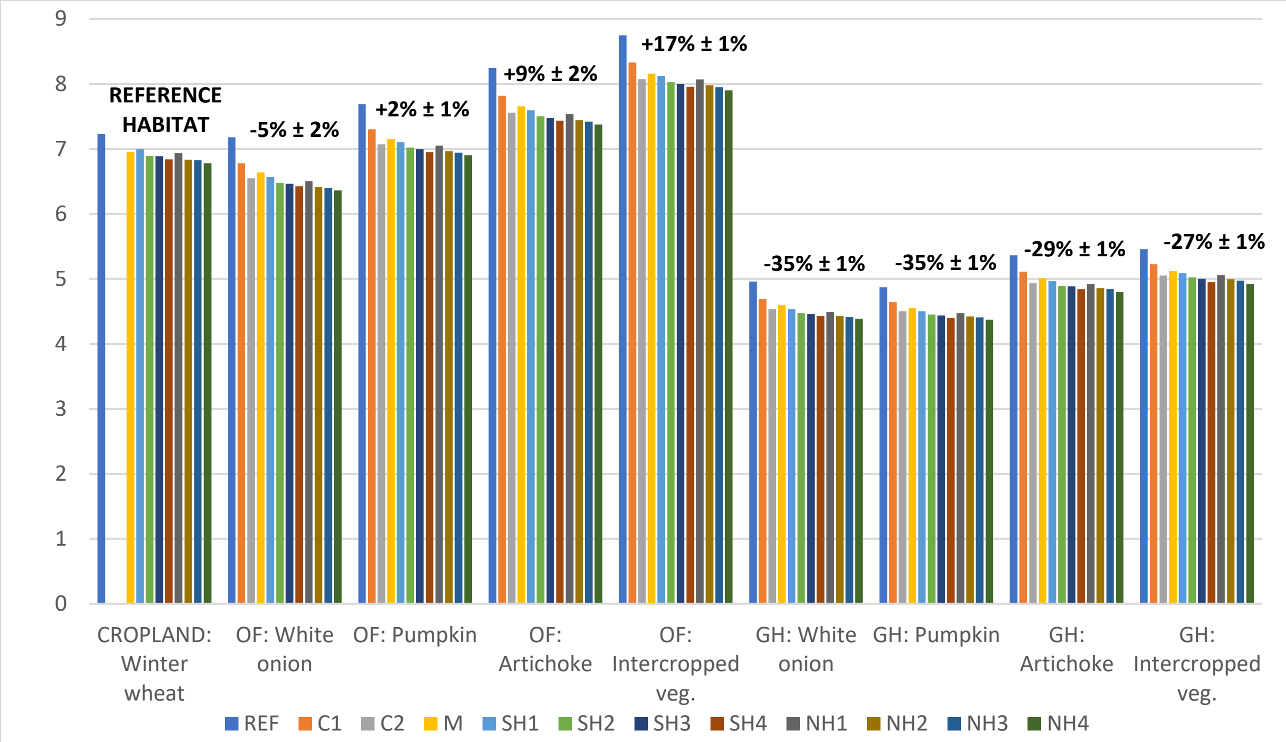

Fig. 3.2. Effect on the biodiversity score of the level I habitat (cropland, open field (OF), greenhouse (GH)), level II habitat (white onion, pumpkin, artichoke, intercropped vegetables) and weed-control practices.
REF (Reference, no weed control), C1 (organic mulch), C2 (synthetic mulch), M (hoeing), SH1 (selective herbicide on < 25% of the area), SH2 (SH on 25% to < 50%), SH3 (SH on 50% to < 75%), SH4 (SH on 75-100%), NH1 (non-selective herbicide on < 25% of the area), NH2 (NH on 25 to < 50%), NH3 (NH on 50% to < 75%), NH4 (NH on 75-100%). Bold text indicates the difference between the mean score of a habitat and the mean score of cropland (the reference). The percentage variability represents the mean (±standard deviation) of the differences between each practice of each level II habitat compared to the same practice in the reference habitat.

3.3. System-level sensitivity analysis

White onion with high-intensity practices (High) had lower biodiversity scores than that with low-intensity practices (Low), in both OF and GH, for each of the ISGs and for the aggregated biodiversity score (**Table 3.3**). Two ISGs in OF (i.e. grassland flora and grasshoppers) and three ISGs in GH (i.e. grassland flora, amphibians, and grasshoppers) had a biodiversity score of 0, which corresponded to the assumptions made that VPSs are not potential habitats for these ISGs. Amphibians (in OF), mammals, snails, and wild bees were the ISGs with the lowest biodiversity scores, and with the smallest relative decrease when comparing High to Low (-40, -6%, -26%, -26%, respectively, in OF; -6%, -26%, -6%, respectively, in GH). Crop flora, birds, and spiders had the highest biodiversity scores in both OF and GH. Birds and spiders were influenced most by management intensity (-54% and -50%, respectively, in OF; -53% and -50%, respectively, in GH). Crop flora differed between the two systems by -32% in OF and -34% in GH.

Table 3.3. Biodiversity scores for white onion grown using low-intensity (Low) or high-intensity (High) practices in an open field or greenhouse for the 11 indicator species groups. Differences represent the percentage change in High's score compared to Low's score.

Indicator species	Open field			Greenhouse		
group	Low	High	**Difference**	Low	High	**Difference**
Field level	7.47	4.71	-37%	5.24	3.30	-37%
Crop flora	24.13	16.41	-32%	16.08	10.61	-34%
Grassland flora	0.00	0.00	-	0.00	0.00	-
Birds	9.06	4.13	-54%	3.75	1.75	-53%
Mammals	4.29	4.03	-6%	2.92	2.75	-6%
Amphibians	2.56	1.55	-40%	0.00	0.00	-
Snails	2.92	2.17	-26%	2.92	2.17	-26%
Spiders	9.85	4.92	-50%	8.10	4.03	-50%
Carabid beetles	7.95	4.66	-41%	7.25	4.39	-39%
Butterflies	5.44	3.12	-43%	3.44	2.00	-42%
Wild bees	3.00	2.21	-26%	3.00	2.21	-26%
Grasshoppers	0.00	0.00	-	0.00	0.00	-

3.4. Farm case study

The farm's score was 7.4 for its cultivated area and 14.6 when including its SNHs (**Fig. 3.3**). At the field level, potato had the lowest score (5.3) and Jerusalem artichoke (assigned to habitat category D) had the highest score (8.6). The ISGs that differed the most between these two crops were crop flora (8.4 and 22.5, respectively), spiders (9.6 and 12.5, respectively), and butterflies (0 and 4.9, respectively) (**Table 3.4**). Crop flora and spiders (many of whose species are ground-dwelling) were negatively influenced by the many tillage operations in potato. Cropland habitats, including potato, were not considered suitable for butterflies, whereas all other vegetables in OF were considered as potential habitat for them. The SNHs had scores from 20.6 (grassland) to 22.7 (hedgerow). ISGs with a high coefficient of variation (i.e. grasshopper, grassland flora, butterflies, wild bees, and amphibians) had different scores for cultivated areas and SNHs. Conversely, ISGs with a low coefficient of variation (i.e. carabid beetles, spiders, crop flora, snails, mammals, and birds) were influenced similarly (positively or negatively) by cultivated areas and SNHs.

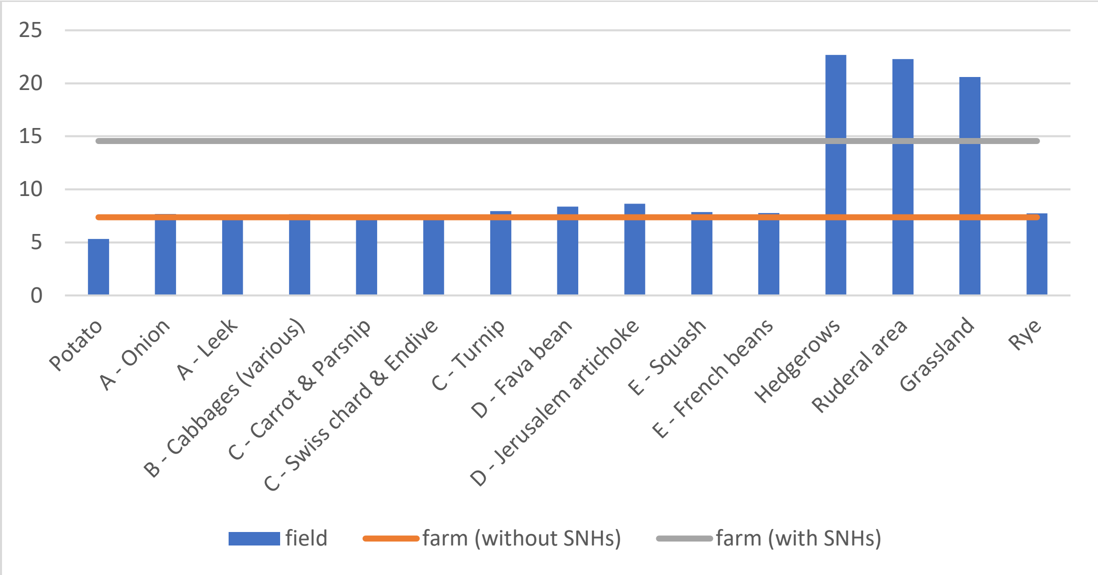

Fig. 3.3. Biodiversity scores for individual crops and semi natural habitats (SNHs) of an organic vegetable farm, and whole-farm results with and without the inclusion of SNHs. The capital letter before the name of each vegetable refers to its category.

Table 3.4. Biodiversity scores at field and indicator species group (ISG) levels of the organic vegetable farm case study. The capital letter before the name of each vegetable refers to its habitat category.

Indicator species group	ISG score	Potato	A - Onion	A - Leek	B - Cabbages (various)	C - Carrot & Parsnip	C - Swiss chard & Endive	C - Turnip	D - Fava bean	D - Jerusalem artichoke	E - Squash	E - French beans	Hedgerows	Ruderal area	Grassland	Rye	Coefficient of variation
Field level		**5.3**	**7.7**	**7.6**	**7.6**	**7.2**	**7.5**	**7.9**	**8.4**	**8.6**	**7.9**	**7.8**	**22.7**	**22.3**	**20.6**	**7.7**	
Crop flora	17.0	8.4	23.2	22.7	18.5	17.1	18.1	19.8	22.1	22.5	18.5	18.1	0.0	27.0	0.0	18.7	47%
Grassland flora	24.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.8	27.0	21.4	0.0	208%
Birds	15.7	11.1	9.8	9.7	11.9	11.0	11.5	12.1	13.8	13.6	12.5	12.5	43.3	30.0	30.4	12.8	60%
Mammals	8.3	6.8	6.6	6.6	6.6	6.5	6.6	6.6	6.6	6.6	6.6	6.6	19.0	22.4	13.0	7.0	57%
Amphibians	3.4	2.1	2.2	2.2	2.2	2.2	2.2	2.3	2.4	2.2	2.2	2.2	10.4	16.6	9.3	2.2	104%
Snails	4.4	2.7	2.7	2.7	4.8	4.7	4.7	4.9	2.5	2.9	4.7	4.7	7.1	10.4	11.0	2.6	55%
Spiders	13.6	9.6	10.3	10.0	11.6	11.1	11.5	11.8	11.4	12.5	11.5	11.3	32.7	17.6	26.4	10.5	48%
Carabid beetles	15.7	11.3	11.3	11.2	13.4	12.5	13.0	13.3	10.8	12.7	11.5	11.5	33.4	21.4	29.4	16.1	45%
Butterflies	11.4	0.0	3.7	3.7	3.6	3.7	3.7	4.3	6.0	4.9	4.9	4.9	41.0	16.0	37.3	0.0	139%
Wild bees	5.7	4.1	2.7	2.7	2.7	2.6	2.7	2.8	5.8	5.4	5.4	5.4	13.6	32.4	24.1	5.6	113%
Grasshoppers	29.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.7	15.2	29.5	0.0	217%

4. Discussion

4.1. Novelties and challenges of adapting SALCA-BD to VPSs

The expert system is based on the concept of a field occupied by a crop or crop rotation. Individual VPSs can grow many vegetables (e.g. ca. 40 on diversified farms) (Pépin et al., 2021). The literature review did not yield information that would have allowed us to define habitat coefficients for all vegetables, and the experts confirmed this point. Because an expert system with too many categories is not user-friendly, clustering vegetables according to their characteristics provided an operational solution for SALCA-BD. Although these clusters already contain 40 vegetables, they can be adapted by adding other vegetables, as we did for Jerusalem artichoke in the case study. Some farms, especially microfarms, have small fields with intercropped vegetables (Morel and Leger, 2016). Because each vegetable covers too little area to perform a meaningful assessment, we created the intercropped vegetable category to represent such a field as a single habitat, whose value to biodiversity is expressed in its habitat coefficients (Pereira et al., 2015; Sokos et al., 2013). To estimate the habitat coefficients of this category, we considered a field with vegetables of different heights, soil cover, durations, and blooming periods, as usually found on small organic farms. The literature and experts did not suggest creating several categories to represent different intercrop compositions. Ultimately, nine vegetable categories were created.

Most of the practices in VPSs were similar to practices in cropland. Only weed control differed greatly, as vegetable farmers commonly cover the soil with organic or synthetic mulch. In terms of impacts on biodiversity, the main advantage of mulching compared to hoeing and thermal weeding is that it disturbs the soil less (Alyokhin et al., 2020). Mechanical hoeing requires machines that may compact the soil and disturb ground-dwelling fauna (Rivers et al., 2016). Thermal weeding is often used along with mechanical weeding to increase the effectiveness of weed control (Fontanelli et al., 2013); however, as the experts confirmed, it can negatively impact local faunal biodiversity.

The literature review did not provide enough detailed information to parametrise every aspect of the inventory and control table. Most studies of impacts of a farming practice on the abundance of an organism focused on pest management, not biodiversity. Fortunately, the interviews with the experts filled knowledge gaps. During these interviews, the challenge consisted of distinguishing direct impacts from and indirect impacts, which was sometimes difficult. For example, the experts considered that hoeing can have a negative impact on birds (rating of 2), not only because it disturbs the birds themselves (a direct impact), but also because it can have negative impacts on the insect prey of birds (an indirect impact).

4.2. Impacts of weed-control practices: sensitivity analysis

The OAT sensitivity analysis indicated that all vegetables are worse for biodiversity when they are in GH instead of OF. For the modified control table, we assumed that increasing openness of a habitat favours the exchange of species with surrounding habitats. The habitat coefficients of OF and GH influence the biodiversity score, and these results are consistent with the expert system's assumption that habitat influences biodiversity more than weed-control practices. Martin et al. (2020), who studied effects of six farming practices, field size, and crop diversity on eight taxonomic groups in farmland in Ontario, Canada, also observed that habitat type, defined by field size and crop diversity, can influence biodiversity as much or more than management practices.

The fact that scores of all level II habitats followed the same pattern as the weed-control practices changed (**Fig. 3.2**) indicates that parametrisation of the expert system for VPSs is consistent with that for cropland. The biodiversity scores of vegetables varied less in GH than in OF because a GH has an inherently lower biodiversity potential than an OF. Indeed, an OF provides more opportunities for species to colonise it from the surroundings than a (partly) closed GH does, as expressed by the habitat coefficient. Intercropped vegetables had the highest biodiversity scores in both OF and GH, which aligned with the habitat coefficients assigned. Intercropped vegetables provide high variability in resources in space and time, which favours, for example, populations of solitary bees (Baños-Picón et al., 2013).

For a given habitat category, biodiversity scores varied little as a function of weed-control practices. Indeed, changing a single practice cannot have a large effect in SALCA-BD due to the small range of its scoring scale (i.e. 1-5). A more specific example is the small difference between the application of selective and non-selective chemical herbicides, for which the scoring scale was even smaller (i.e. 1-3), since no information was found to support a positive effect of any type of herbicide on biodiversity, which excluded ratings of 4 and 5. Synthetic mulch had a more negative impact on biodiversity than organic mulch, based on results of Summers et al. (2010) and Madzaric et al. (2018). They observed that organic mulch in a vegetable field was associated with more spiders than plastic mulch or bare soil was, and that high humidity and moderate temperatures, as found on soil covered with organic mulch, would foster the growth of spider populations.

4.3. Impacts of management intensity: system-level sensitivity analysis

The high-intensity field of white onion influenced biodiversity more than the low-intensity field, which was also observed in cropland by Geiger et al. (2010), who found that agricultural intensification had major negative impacts on the species richness of wild plants, carabids, and birds. In the present study, SALCA-BD estimated large decreases in the biodiversity score for crop flora, carabids, and birds in high-intensity fields (32%, 41%, and 54%, respectively). The higher biodiversity score of white onion for crop flora than for the other ISGs resulted from its low soil cover, which favours crop flora. When Jeanneret et al. (2014) applied SALCA-BD to winter wheat of different management intensities, the increase in intensity decreased bird and spider species richness, as in the present study. Because many spiders can live on plants or the ground (Simonneau et al., 2016), they are influenced by a wider range of management practices. Unsurprisingly, changing the entire production system influenced the aggregated biodiversity score at the field level more than changing only weed-control practices. This aligns with the holistic approach that Altieri and Rosset (1996) describe as necessary in the perspective of an agroecological transition.

4.4. Importance of SNHs in the landscape

Changing farming practices may improve the biodiversity score to a certain extent. At the farm level, however, SNHs had higher scores than cultivated fields, regardless of the farming practices; thus, SNHs improved the farm scores greatly. Their importance of SNHs in the landscape for biodiversity has been reported for a variety of ISGs (Baños-Picón et al., 2013; Billeter et al., 2007; Burel et al., 2004; Chaplin-Kramer et al., 2011; Chiron et al., 2010; Hendrickx et al., 2007; Ph. Jeanneret et al., 2021; Rischen et al., 2021; Tscharntke et al., 2005). Nemecek et al. (2011) used SALCA-BD to compare organic and conventional fields and concluded that lower-impact practices cannot entirely compensate for a lack of SNHs. Combining low-intensity farming with the presence of SNHs enhances the biodiversity of farming landscapes.

4.5. Limits of the expert system and prospects for development

SALCA-BD performs analyses at field and farm levels to calculate individual and aggregated ISG biodiversity scores. It considers detailed farming practices applied to crops and SNHs. Estimating impacts at a fine level can distinguish between fields or farms that have the same land use and similar management intensities.

Most existing methods focus on a single taxon, mainly vascular plants (e.g. Knudsen et al., 2017; Mueller et al., 2014), whereas SALCA-BD assesses 11 ISGs. In comparison, Chaudhary et al. (2015) and Chaudhary and Brooks (2018) estimated CFs for five ISGs. The ISGs reacted differently to practices and habitats, making assessment of multiple ISGs useful for assessing biodiversity as widely as possible (Lüscher et al., 2017). However, SALCA-BD does not consider soil biodiversity (e.g. microorganisms, nematodes, earthworms), which is also influenced by farming practices (Tsiafouli et al., 2015) and plays a key role in shaping aboveground biodiversity (Bardgett and van der Putten, 2014) and sustaining agro-ecosystem functioning (Brussaard et al., 2007). Including impacts of farming practices and habitats on soil biodiversity in SALCA-BD would widen the scope of its assessments and increase their value.

SALCA-BD also does not consider spatial issues such as the size or spatial arrangement of fields. Lüscher et al. (2017), who compared SALCA-BD biodiversity scores to on-farm species observations, found that data for mobile ISGs (i.e. spiders and wild bees) correlated at the field level but not the farm level, which suggests an influence of spatial issues that SALCA-BD does not consider. Farmland biodiversity is enhanced by small fields (Fahrig et al., 2015; Martin et al., 2020; Šálek et al., 2018) and fields with a higher perimeter:area ratio (Clough et al., 2020). SALCA-BD considers field size indirectly when assessing an entire farm, as farms with smaller fields tend to have a higher ratio of SNH area to cultivated area than farms with larger fields. This higher perimeter:area ratio gives more weight in the aggregation to SNHs on farms with smaller fields, which yields a higher biodiversity score. Field size is considered indirectly only when SNHs are included. These spatial aspects could be included in SALCA-BD by attributing additional points for small fields, following the example of bonus points attributed for soil cover.

Finally, the expert system assesses only impacts on biodiversity at the farm level that result from direct effects of farming practices, thus ignoring indirect impacts upstream and those downstream of the farm gate (Bockstaller et al., 2015). Conversely, methods based on global CFs (Chaudhary and Brooks, 2018) can estimate potential species loss on land used for upstream processes (e.g. production of seeds or animal feed), but they cannot estimate in detail impacts of specific changes in production practices applied to individual crops. Thus, combining SALCA-BD with a comprehensive method would be useful. Bystricky et al. (2020) combined SALCA-BD (Jeanneret et al., 2014) and the method of Chaudhary and Brooks (2018) to create a complementary analysis, as the two methods addressed different aspects of their research question. SALCA-BD allowed them to compare scenarios in detail, while the other method included upstream impacts in its predictions. The authors concluded that more research is needed to combine the two methods.

5. Conclusion

This study showed that SALCA-BD can model VPSs when vegetables with similar characteristics are grouped into a single habitat. Few studies in the literature have investigated impacts of VPSs and their associated practices on biodiversity. The farm case study highlighted the importance of SNHs and low-intensity practices for enhancing biodiversity. SALCA-BD considers field size indirectly when assessing an entire farm, including its SNHs. Consideration of spatial issues and soil biodiversity would increase the value of SALCA-BD. Due to its detailed consideration of habitats and practices, SALCA-BD is useful for assessing biodiversity at field and farm levels and for ecodesign. Impacts of the background system could be considered by combining SALCA-BD with comprehensive methods for assessing biodiversity.

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Transition

Le chapitre 3 a montré que les fermes maraichères peuvent être modélisées en utilisant SALCA-BD. Une classification a permis de regrouper les légumes ayant des caractéristiques similaires dans une même catégorie d'habitat. Par sa catégorie « intercropped vegetables », il est adapté aux différents types de fermes, y compris les plus diversifiées associant plusieurs cultures sur une même parcelle. L'application sur une ferme a souligné l'importance des habitats semi-naturels pour la biodiversité, en complément de pratiques adaptées. Grâce à la prise en compte détaillée des habitats et des pratiques, SALCA-BD permet l'évaluation de la biodiversité à l'échelle du champ et de la ferme.

Dans le chapitre 4, j'évalue les performances environnementales de trois fermes maraichères, choisie comme cas d'étude correspondant à l'un des types de fermes identifiés dans le chapitre 2. J'emploie une approche système de l'ACV, permettant de répondre au défi de la complexité posée par les fermes diversifiées et fortement agroécologiques. L'outil développé dans le chapitre 3 fournit un indicateur sur la biodiversité. Le chapitre 4, utilisant les connaissances et outils développés dans les chapitres précédents, fournit une analyse des performances environnementales sur des fermes contrastées. Il apporte également une réflexion méthodologique sur l'ACV des systèmes agroécologiques complexes.

Chapitre 4. Performance environnementale de trois fermes maraichères contrastées

Effect of farm type and functional unit on environmental impacts of organic vegetable farms

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Abstract

French organic vegetable farms are diverse, ranging from complex biodiversity-based systems with many vegetables to simple input-based systems with few vegetables, which suggests that their impacts on the environment may differ. We used life cycle assessment (LCA) to assess impacts of three contrasting farms: a microfarm (MF, high crop diversity and a low input level), a medium-sized farm specialised in sheltered production (SP, low crop diversity and a high input level), and a large farm specialised in open-field production (OP, intermediate input level and crop diversity). To manage the complexity of organic vegetable farms, we opted for a system LCA, based on farm inputs and output (i.e. « vegetables ») for a one-year period. Using functional units based on mass of output, area, and economic value, we analysed five impacts: climate change, cumulative energy demand, marine eutrophication, on-farm biodiversity, and the use of plastic. Farming-system LCA assessed environmental impacts of farms with different levels of agroecology, including complex systems with a large diversity of crops grown on small areas. The three functional units strongly influenced the ranking of the systems. Per ha, the systems differed greatly in climate change and energy demand: SP had the highest impacts, whereas OP had the lowest impacts. Per kg and per €, the systems differed much less in climate change and energy demand, and even ranked differently. OP used much less plastic but performed worse on biodiversity and yield. Despite its higher yield, SP performed no better than the other two farms for climate change, energy demand, and plastic use per kg and €. The impact on biodiversity contrasted with the other impacts, which highlighted the importance of semi-natural habitats. Quantification of plastic use echoed growing concerns about (micro-)plastic pollution in agricultural soils and landscapes, and the newly identified planetary boundary on novel entities. Estimating nitrate leaching was difficult, and the Intergovernmental Panel on Climate Change (IPCC)

Tier 1 model used to do so seemed unsatisfactory; thus, estimated marine eutrophication impacts had high uncertainty. Crop residues contributed greatly to marine eutrophication. In this perspective, models for estimating crop residues and nitrate leaching in a farming-system LCA approach need to be improved. In agroecological systems, semi-natural habitats are part of the farming system. The farming-system LCA approach requires clear rules for setting farm boundaries, which strongly influence impacts per ha and biodiversity impacts.

Key words: life cycle assessment, agroecology, horticulture, organic farming, biodiversity, farming-system LCA

1. Introduction

French organic vegetable farms are diverse, ranging from complex biodiversity-based systems, with many vegetables, to simple input-based systems, with few vegetables. Beyond this conceptual dichotomy, Pépin et al. (2021) described four types: microfarmers (high crop diversity and a low level of inputs), medium-sized market gardeners (high crop diversity and variable level of inputs), producers specialised in cultivation under shelter (low crop diversity and a high level of inputs), and large market gardeners specialised in open-field cultivation (low crop diversity and moderate input use). The heterogeneity of input use and farming practices, which can be interpreted as sign of bifurcation between “agroecological” and “conventionalised” organic farming (Pépin et al., 2021), may influence environmental impacts, but these have yet to be quantified. Organic farming claims to be environmentally sound, and conventionalisation of organic practices is seen as a threat to the identity of organic farming (Darnhofer et al., 2010). Quantifying environmental impacts of different types of organic farms will inform the debate about the conventionalisation of organic farming.

Life cycle assessment (LCA) has been used to assess environmental impacts of agricultural products and systems for several years. LCA studies of vegetable production have been conducted at the crop scale for open-field (e.g. Abeliotis et al., 2013) and sheltered production (e.g. Cellura et al., 2012) and at the farm scale (Adewale et al., 2019; Markussen et al., 2014), for both conventional and organic farming, including studies that compared them (Foteinis and Chatzisymeon, 2016) LCA is a method that quantifies a variety of potential environmental and health impacts and resource depletion issues that are associated with goods or services (i.e. multi-criteria assessment). The environmental impacts relevant to agricultural production include climate change, eutrophication, biodiversity decline, and energy demand, among others. The first three impacts correspond to planetary boundaries that have already been exceeded (Rockström et al., 2009; Steffen et al., 2015). Agriculture contributes greatly to climate change (IPCC, 2019a). The runoff and leaching of nitrogen (N) from agricultural soils are the main cause of marine eutrophication (Le Moal et al., 2019). Biodiversity is rarely considered in LCA studies (Knudsen et al., 2019), although it is a key agri-environmental indicator (Haas et al., 2000) and is high on the political agenda (United Nations Environment Programme, 2021a). Organic farming claims to enhance biodiversity (European Commission, 2007) and rely more on natural regulation, which makes biodiversity an important issue. Current methods for assessing impacts on biodiversity, reviewed by Curran et al. (2016), include global approaches (Chaudhary et al., 2015; Chaudhary and Brooks, 2018; Knudsen et al., 2017), more detailed approaches (Jeanneret et al., 2014), and attempts to combine both in a case study (Bystricky et al., 2020).

Plastic pollution is an emerging concern worldwide, with for example a ban on certain single-use objects in the European Union (European Commission, 2019). The use of plastic in agriculture and the accumulation of microplastics in agricultural soil has been highlighted (United Nations Environment Programme, 2021b). Vegetable crop production, including in organic farming, is a major user of plastic, particularly as mulch and tunnels for several purposes (e.g. earlier production, higher yield, weed control, cleaner vegetables) (Lamont, 2017, 2005), which is a threat to long-term soil quality (Steinmetz et al., 2016). Massive use of plastic, especially in organic farming, has caused controversy (Held, 2019). Plastic pollution contributes greatly to exceeding the planetary boundary for novel entities (i.e. "novel in a geological sense and that could have large-scale impacts that threaten the integrity of Earth system processes") (Persson et al., 2022). However, there is no ready-made indicator in current LCA methods to assess plastic or microplastic pollution.

Organic vegetable farms can be complex systems that combine a wide range of crops, intercrops, and non-crop biodiversity to help maintain the farming system's health and resistance to disturbance (Morel and Leger, 2016). Within a field, farmers may grow several vegetables at the same time and that have different growing durations, which makes the spatial and temporal organization of crops complex (Aubry et al., 2011), with no clearly defined crop rotation (Morel and Leger, 2016). A crop that often has high value, such as tomato, may be preceded and/or followed by several other crops on the same part of the field.

Generally, fertilisers are applied to feed the soil (Fortier, 2012) rather than directly to the crops. Organic fertiliser such as compost may not be applied every year but instead every 2-4 years, which complicates the ability to allocate organic fertilisers to a given crop. Moreover, due to complex soil dynamics, allocating carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions as well as nitrate (NO_3) leaching to a given crop is challenging (Goglio et al., 2018). Another challenge is that farmers often do not know the yield of each crop, as for many vegetables, small quantities can be harvested regularly over time. These challenges increase uncertainty in the allocation of inputs and estimates of outputs.

Given these challenges related to the complexity of organic vegetable farms, it seems relevant to assess their environmental impacts using a farming-system LCA rather than a product LCA, which focuses on individual crops. Farming-system LCA approaches the farm as a whole that produces different products, which helps assess and compare farms and understand mechanisms that influence environmental impacts (Goglio et al., 2018). In this perspective, all inputs and operations are estimated for the entire farm, and the output is the total production of vegetables.

The objectives of this study were to 1) assess environmental impacts of contrasting organic vegetable farms, 2) describe strengths and weaknesses of farming-system LCA, and 3) identify needs for research to better assess impacts of complex organic vegetable farms. To reach these objectives, we performed an LCA of three French organic vegetable farms, each being a specific case corresponding to a more general farm type, using farming-system LCA. Using functional units (FUs) based on mass of vegetables, area, and economic value, we analysed the climate change impact, cumulative energy demand, marine eutrophication impact, impact on biodiversity, and the use of plastic.

2. Materials and methods

2.1. Description of the farms

We chose three farms that participated in the survey of Pépin et al. (2021)used to characterize the diversity of French organic vegetable farms. We chose farms that were among the most typical of their types. Because these farms were specific cases with individual characteristics, however, they should not be considered as completely representative. The farms were 1) a microfarm (MF, high crop diversity and a low input level), 2) a medium-sized farm specialised in sheltered production (SP, low crop diversity and a high input level), and 3) a large farm specialised in open-field production (OP, intermediate input level and crop diversity) (**Table 4.1**).

Table 4.1. Characteristics of three French organic vegetable farms studied

Characteristic	**Farm type**		
	Microfarm	Sheltered production	Open-field production
Farm area	0.34 - 1.1 ha	3.2 ha	21.3 ha
Cultivated vegetable area	0.28 ha	2.0 ha	17.5 ha
Open-field vegetable area	0.16 ha	0 ha	17.5 ha
Sheltered vegetable area	0.12 ha	2.0 ha	0 ha
Labour (full-time equivalent)	1.3	5.0	4.3
Number of tractors	1	3	3
Number of vegetable crops	35	6	20
Main vegetable crops	Many	Tomato, cucumber, lettuce, strawberry	Potato, cabbage, carrot, squash, onion
Fertilisation	Mainly compost of green waste + manure, green manure	Commercial fertiliser + green manure	Cattle + poultry manure + green manure
Tillage	Shallow tillage or no-tillage	Deep non-inversion tillage	Deep non-inversion tillage
Weed control	Organic mulch or reusable plastic mulch	Single-use plastic mulch	Mechanical weeding + thermal weeding on carrot
Pest and disease control	Mainly natural biocontrol	Purchased biocontrol	None + insect-proof netting on turnip and radish
Seeds and seedlings	Some seeds and seedlings self-produced	Seeds and seedlings purchased	Some seedlings self-produced
Food supply chain	Direct selling, locally	Long supply chain, to France and Germany	Direct selling + short supply chain, locally
Turnover	33 000 €	475 000 €	380 000 €
Year of creation	2017	1987	1992
Organic since the beginning	Yes	No, since 2005	No, since 1997
Region of France	North-west	South-east	North-west
Biotechnical Index[1]	0.73	0.07	0.47
Socio-economic Index[2]	1	0	0.88

[1] The biotechnical index estimates the extent to which organic practices were agroecological (towards 1) or conventionalised (towards 0). Values are from Pépin et al. (2021).

[2] The socio-economic index estimates the extent to which the socio-economic context was territorially embedded (towards 1) or connected to the global market (towards 0). Values are from Pépin et al. (2021).

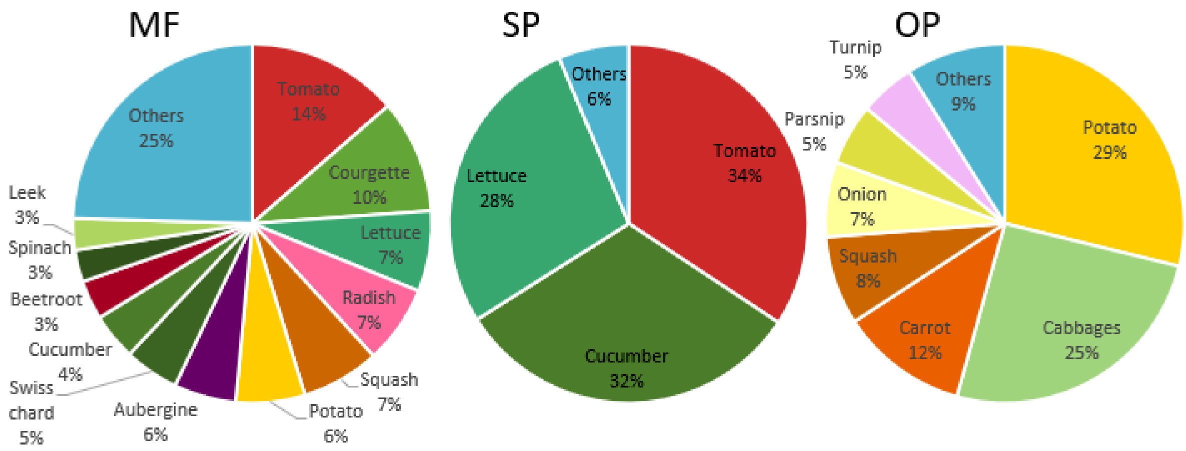

Fig. 4.1. Distribution of crops produced (fresh mass) by the three types of farms: microfarm (MF), sheltered production (SP), open-field production (OP)

MF was a recently established microfarm in the Brittany region that produced 35 types of vegetables (**Fig. 4.1**) in a 1200 m² tunnel and a 1600 m² open field (**Fig. 4.2**). The farmer was inspired by a French farming trend called "market gardening on living soil" (*maraîchage sur sol vivant*) that aims to protect and feed the soil - and its living organisms such as earthworms, bacteria and mycelia – by combining no-tillage and permanent cover of organic mulch and plants. Fertilisation consisted of compost of green waste, manure, and manure pellets to achieve long-term fertility and avoid short-term NO_3 deficiency due to microbial activity. Reusable insect-proof netting was used to decrease insect problems, and copper sulphate was used against blight on tomatoes (the only crop that received a treatment). The selling outlets were vegetable boxes, a local market, shops, and restaurants in the nearby village.

SP, in the Provence-Alpes-Côte-d'Azur region, produced mainly tomato and cucumber in summer and lettuce in winter (**Fig. 4.1**), in 33 tunnels, for a total cultivated area of 19 840 m² (**Fig. *4.3***). Sorghum cover crops were grown for 1-2 months each year in ca. 25% of the tunnels to add fresh biomass to the soil. Fertilisation consisted of industrial manure pellets and beet vinasse applied before each crop. Single-use plastic mulch was used against weeds. Purchased insects were released in the tunnels to control pests (*Macrolophus* sp., *Chrysoperla* sp.) and for pollination (bumblebees). The farmer sold the vegetables to wholesalers in France and Germany under the biodynamic label.

OP produced vegetables on 24 ha of open fields in Brittany (**Fig. 4.4**) following a four-year rotation: potato / rye followed by turnip / cabbages (cauliflower, green cabbage, savoy cabbage, Brussels sprouts, kale) / various vegetables (e.g. carrots, onions, squash) (**Fig. 4.1**). Fertilisation consisted of cow and poultry manure applied three out of every four years. Weeding was mechanical and, in carrot crops, thermal (natural gas). Reusable insect-proof netting was used to decrease insect problems on some vegetables, but overall pest and disease control was limited. The farmer sold the vegetables locally to organic stores and wholesalers, and at local markets.

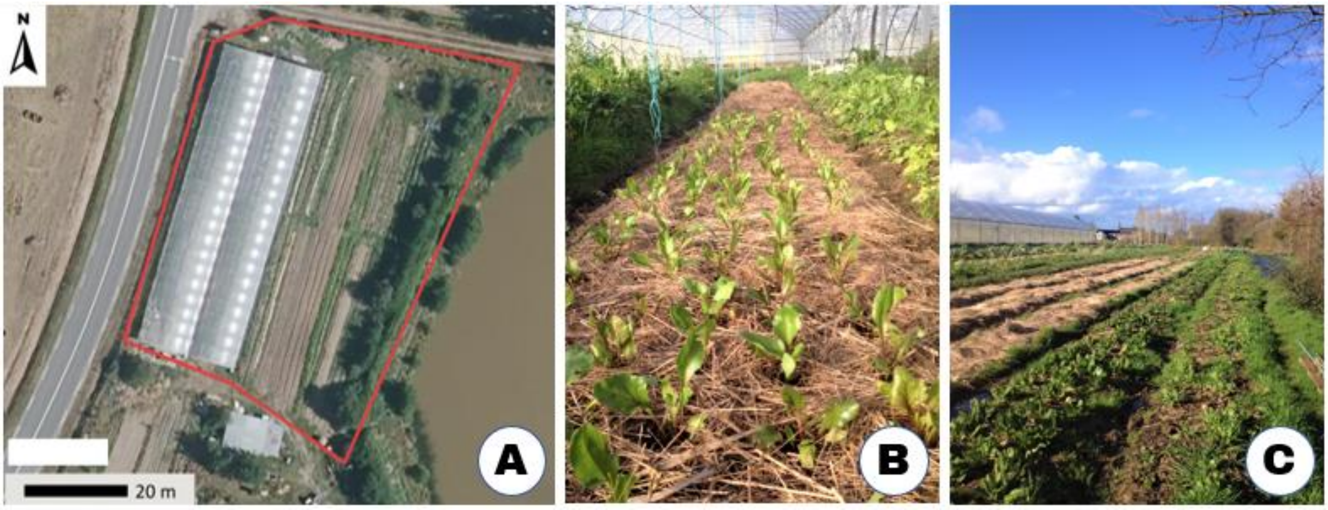

Fig. 4.2. (A) Satellite image (source: www.geoportail.gouv.fr) and (B, C) photographs (source: the authors) of the microfarm. The red line indicates the farm's boundary.

Fig. 4.3. (A) Satellite image (source: www.geoportail.gouv.fr) and (B, C, D) photographs (source: the authors) of the sheltered production farm. The red line indicates the farm's boundary.

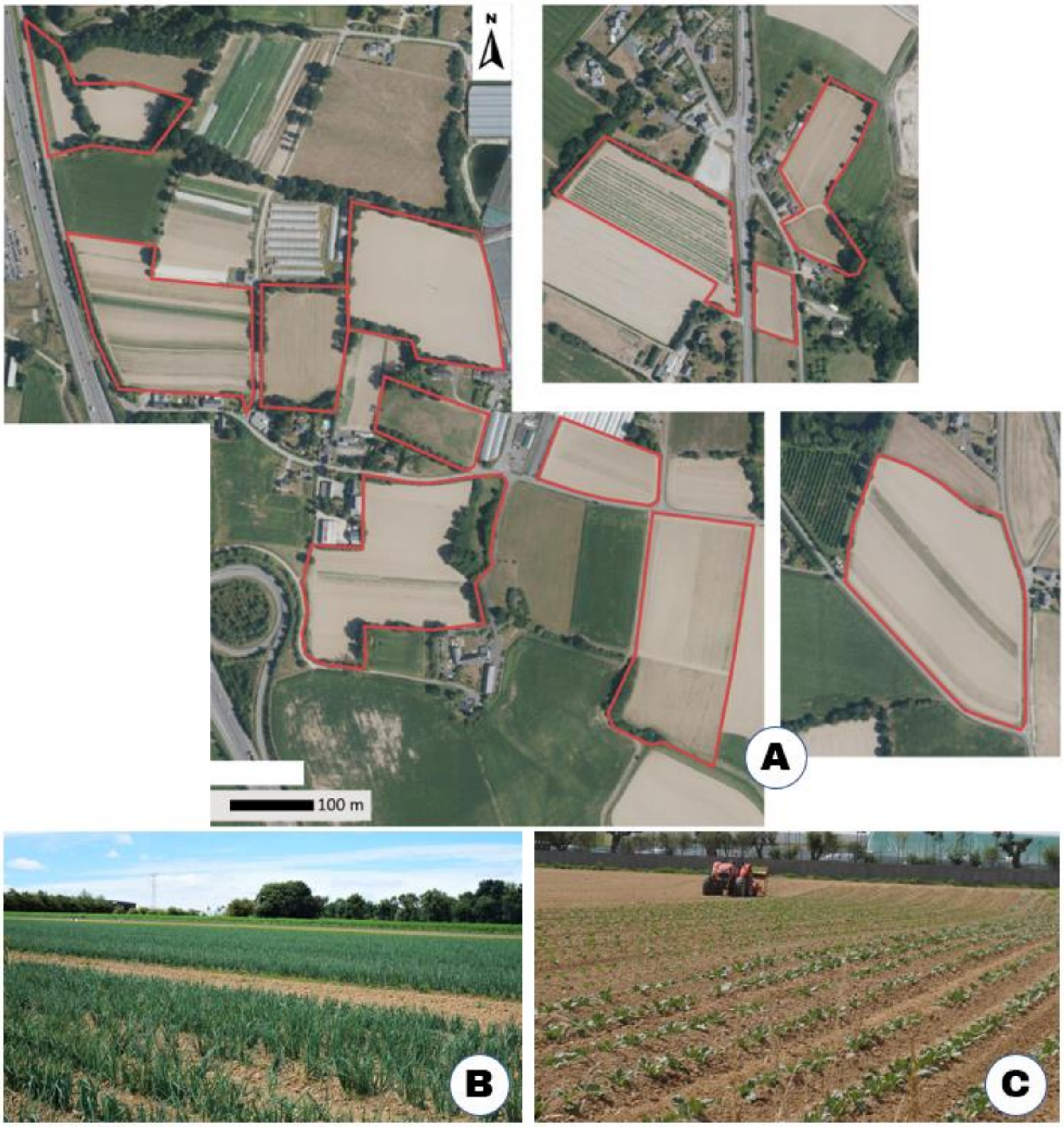

Fig. 4.4. (A) Satellite image (source: www.geoportail.gouv.fr) and (B, C) photographs (source: the authors) of the open-field production farm. The red lines indicate the farm's boundary.

2.2. Goal and scope definition

The aim of this study was to compare environmental impacts of three organic vegetable farms, each of which was a specific case that represented a more general farm type (Pépin et al., 2021). We analysed the farms as a whole in a farming-system LCA: we considered the total annual production of vegetables and the total inputs, without specifying which input was used for which crop.

The impact categories considered were climate change (CC) with a 100-yr temporal horizon, marine eutrophication (ME), cumulative energy demand (CED), and on-farm biodiversity; use of plastic was also assessed. The impact assessment method used for CC and ME was ReCiPe 2016 (Huijbregts et al., 2016). We calculated CED following Frischknecht et al. (2015). Biodiversity was assessed by adapting SALCA-BD (Jeanneret et al., 2014) to vegetable production. SALCA-BD assesses potential impacts on terrestrial biodiversity of 11 indicator-species groups of land-use types (including semi-natural habitats) and management practices. Field-scale impact scores were aggregated at the farm scale.

For biodiversity scores, the contribution of each land-use type equalled the land-use type's intrinsic score weighted by the proportion of the farm area it occupied. Thus, a large or small contribution could be due to a high or low intrinsic score, respectively, or to the occupation of a large or small proportion of the farm, respectively, or both. Because of the weighting, the farm score was not a simple sum of the values for each land-use type, as for LCA indicators. For this reason, we calculated scores of the entire farm separately from the scores of the cultivated land alone. A higher score indicated higher biodiversity.

Plastic use was calculated by summing the mass of plastic used per year on the farm (**Table 44.2**). The mass of materials that lasted several years was divided by their respective life span, which yielded a mean annual value. Plastic materials included tunnel covers and plastic components, (fert)irrigation pipes and drips, mulching sheets, insect-proof netting for pest protection, pots and trays for purchased and farm-grown seedlings, and plant support clips and strings.

Table 44.2. Quantities of plastic used per year (kg) by the three farm types (microfarm (MF), sheltered production (SP), and open-field production (OP))

Type of plastic	MF	SP	OP
Polypropylene	22.6	0.0	2.1
Polyethylene	7.1	1618.5	0.0
Polystyrene	11.8	38.9	0.0
Polyester resin	2.2	72.0	0.0
Phenolic resin	0.0	0.7	0.0
Polyvinylchloride	5.3	57.5	21.0
Ethylene vinyl acetate	52.3	1728.5	0.0
Polylactide	0.0	135.8	0.0
Nylon	0.0	0.0	11.9
Total	**101.3**	**3651.9**	**35.0**

2.2.1. Farming-system approach

As mentioned, given the complexity of organic vegetable farms, we opted for a system LCA based on farm inputs and output for a one-year period (**Fig. 4.5**).

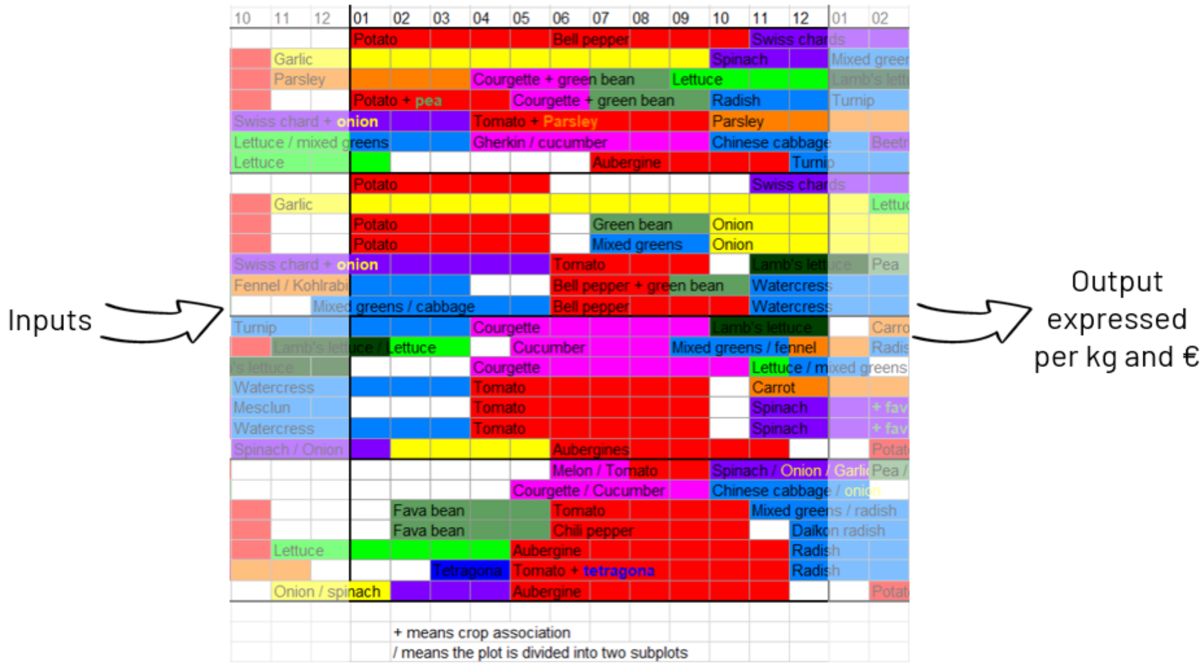

Fig. 4.5. System Life Cycle Assessment applied to a microfarm. The colours represent botanical families, each column is a month, and each line is a vegetable bed of 43 m² (1200 m²/28 beds).

2.2.2.Functional units

Agriculture has several functions, the first of which is to produce food. Product mass is often used as a FU to represent this function (Schau and Fet, 2008). Another function is to occupy land sustainably, for which an area-based FU was used. Last, agriculture has an economic function for farmers, and the economic value of products reflects their quality (van der Werf and Salou, 2015). In the present study, prices reflected value at the farm gate. An FU based on economic value is also a way to capture the heterogeneity of product mixtures among farms.

Except for impacts on biodiversity, which were expressed by a single score for the entire farm, impacts were expressed according to the following FUs:

- per ha of farmland occupied for one year, which included cultivated land and on-farm semi-natural habitats (e.g. hedges, pastures, ruderal areas, spaces between tunnels), as they may provide regulating ecosystem services, but excluded off-farm land associated with production of inputs
- per kg of vegetables produced during one year
- per € of vegetables produced during one year, based on sales to the first buyer, who may or may not have been the final consumer

2.2.3. System boundary

We assessed impacts from the cradle to farm gate. The foreground system included field preparation, fertilisation, sowing and planting, weeding, pest and disease control, irrigation, harvesting, and on-farm storage (**Fig. 4.6**). The background system included the production of fertilisers, main materials, and energy used for production and on-farm storage. The construction phase of tunnels was included but not the production phase of tractors or pumps. Processes beyond the farm gate, such as transportation, packaging, retail, use, and end of life, were not included.

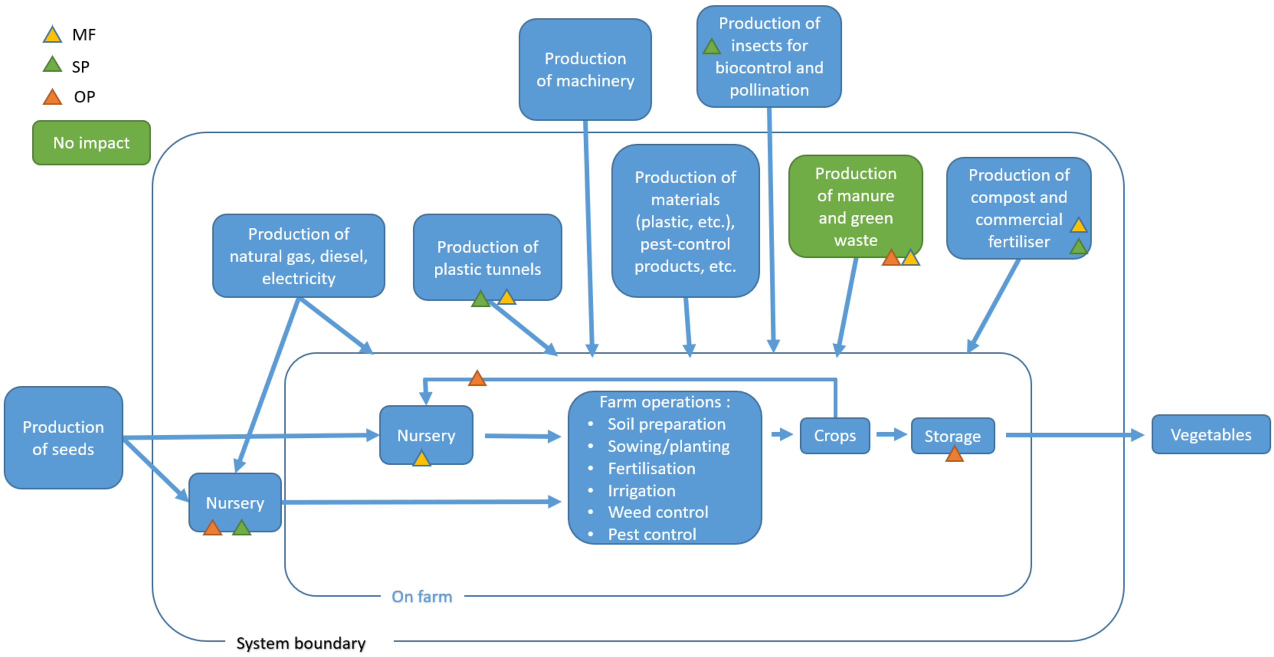

Fig. 4.6. Diagram of material flows of the three farm types (microfarm (MF), sheltered production (SP), and open-field production (OP)) and their system boundaries. Materials were common to all three types, except for those noted (triangles).

2.2.4. Estimation of emissions and biodiversity scores

For organic fertilisers, field emissions, including direct and indirect N_2O, ammonia (NH_3), and nitric oxide (NO) emissions, as well as NO_3 leaching, were calculated according to EMEP (2019) and IPCC (2019b). N and ammonium contents of fertilisers were obtained from their commercial documents when available or from Avadí and Paillat (2020) and Koch and Salou (2020). N supplied by crop residues and cover crops was calculated according to IPCC (2019b) using generic values. Emissions factors for NH_3 emissions were obtained from the French data base Agribalyse® (Koch and Salou, 2020), which follows EMEP methodology (Supplementary Material). Impacts of producing manure and raw green waste, which were considered as waste from upstream systems, were attributed to the producers of livestock and green waste, according to Agribalyse® methodology. Impacts of producing commercial fertiliser and composts were estimated using Avadí (2020). We adapted the green-waste composting process to divide environmental burdens between the producer of green waste (92.8%) and the production of compost (7.2%) using economic allocation based on the cost of composting and the price of compost. This type of allocation was suggested by Ekvall and Tillman (1997) and used by Christensen et al. (2018) for similar composts. A variety of organic plant-protection substances, including biodynamic preparations, sexual confusion substances, plant-stimulation products and natural pesticides (**Table 4.1**), were used in small quantities. Life cycle inventories (LCIs) for these inputs and for purchased insects for biocontrol and pollination were not available; we thus excluded them, except for copper sulphate, which existed in the ecoinvent® data base. Seedling production on- and off-farm was included, but seed production was not, due to the lack of data for it and its minor impact. When seedling LCIs did not exist in the Agribalyse® data base, we used the LCI of the seedling of a similar crop after modifying the amount of natural gas consumed in a heated greenhouse nursery. Natural gas consumption was estimated using the Hortinergy tool (www.hortinergy.com), with data on period of the year, duration, and seedling density based on expert opinion. We included plastic use on the farm but not off of the farm (e.g. plastic trays for purchased seedlings). We excluded boxes for harvest and storage and nets for selling potatoes. Biogenic carbon (i.e. in the biomass produced) was excluded, as the biomass produced was consumed (vegetables) or decomposed (crop residues) in the short term. Transport of inputs to the farms was not included except when it was included in ecoinvent® or Agribalyse® LCIs.

Using SALCA-BD adapted to vegetable production, farm-scale impact scores on biodiversity were calculated at two scopes: cultivated land alone, and both cultivated land and semi-natural habitats. For SP and OP, the crops were assessed individually and considered as different habitats. For MF, since many vegetables were intercropped in the tunnel and open field, we used the SALCA-BD category “intercropped vegetables”.

2.3. Life cycle inventory and data collection

The foreground system was based on the use of inputs and infrastructure as reported by the farmers. LCI data for the inputs and infrastructure in the background system came from ecoinvent® 3.5 (Wernet et al., 2016) in SimaPro® 9.0. Farming practice data were collected through interviews with the farmers. In the first part of the interview, we asked general questions to obtain an overview of the farm (e.g. farm map; crops grown; farmer’s approach to fertilisation; weed, pest and disease control; irrigation). In the second part, we asked about practices at the farm or crop scale, depending on the farm’s management. For example, most data for SP was at the crop scale (e.g. fertilisation, pest management), while the rest was at the farm scale (e.g. diesel, disposable drip pipes). Quantitative records of practices were used when available. Follow-up phone calls and e-mails allowed us to obtain missing or inaccurate data.

Production quantities, farm area, and turnover were key data as they were used for the FUs. Turnover, calculated from farmers' accounts, was considered reliable. Farm areas were calculated from the French Géoportail web mapping service (www.geoportail.gouv.fr). Because OP grew rye in the rotation, its area (4.2 ha for 1 year, i.e. 20% of its cultivated land) was subtracted from the farm area, and consequently, 20% of fertiliser input was subtracted. Other inputs (mainly diesel) used to produce rye were not included. SP and OP had recorded the quantities of vegetables sold at the farm and crop scales, respectively. MF practiced direct selling (i.e. boxes and markets), with nearly daily harvest of small quantities, which were not weighed. We estimated the total production by dividing the farm turnover by the mean price per kg of vegetables (estimated from the boxes). This estimate was double-checked by multiplying the mean yields of organic vegetables by the area occupied by each, which yielded a difference of only 4%. Mean yields were provided by the farmer of MF, who estimated expected yields based on a variety of technical references.

2.4. Sensitivity analysis of farm area

We performed a sensitivity analysis of the farm area of MF by including semi-natural areas to differing degrees. The MF farmer owned 1.10 ha of land, but one field was not cultivated at the time of the survey (**Fig. 4.7A**). Excluding this field resulted in an area of 0.71 ha (**Fig. *4.7*B**). With these boundaries, a large area was covered by pond banks that lay far from the farm's core. Excluding the furthest banks resulted in 0.46 ha (**Fig. 4.7C**). Considering only the closest semi-natural habitats resulted in an area of 0.34 ha (**Fig. 4.7D**), which was used as the reference area of MF when comparing it to the other farms. The sensitivity analysis was performed for CC and biodiversity.

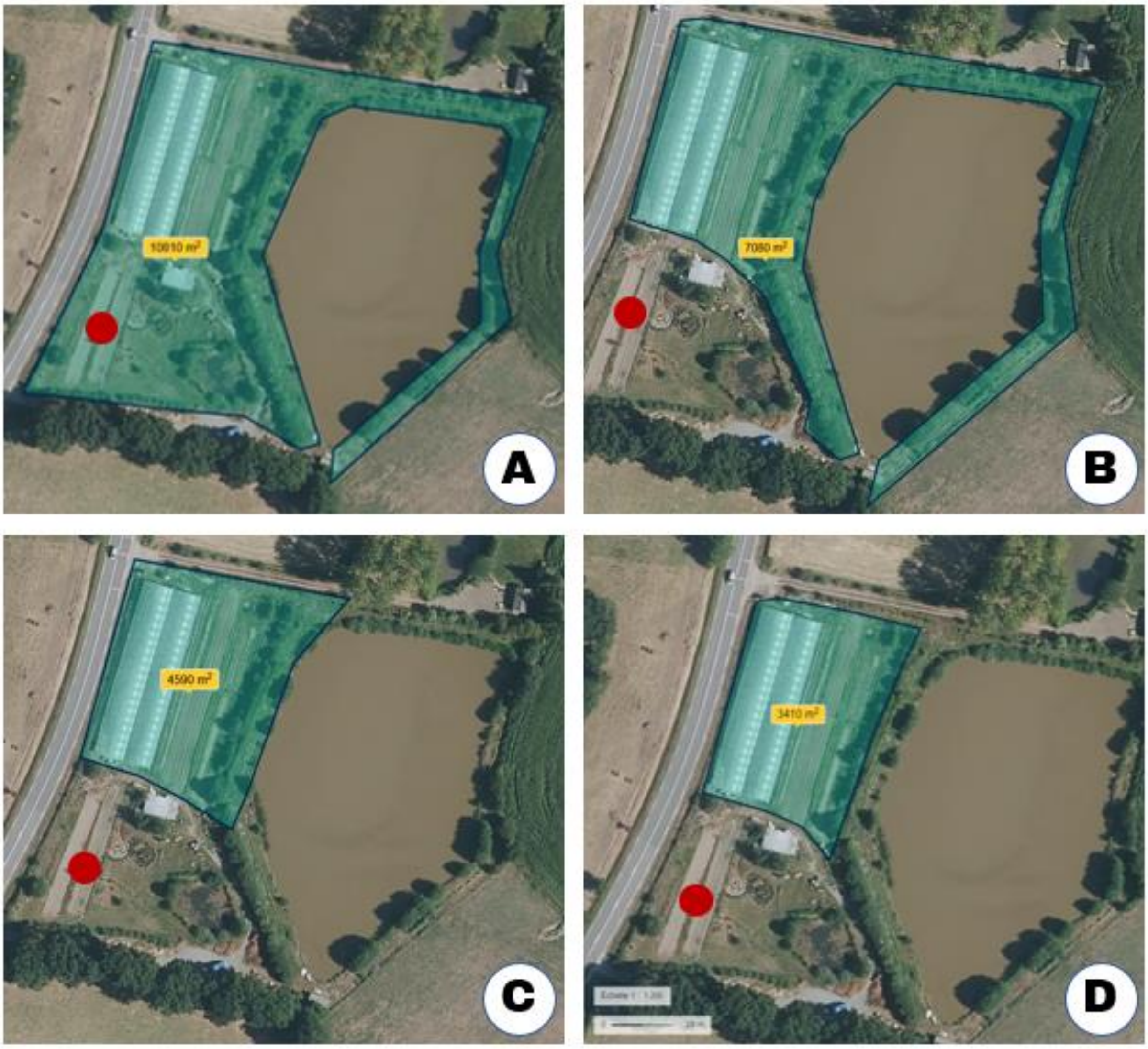

Fig. 4.7. Estimates of the area of the microfarm using different boundaries: (A) 1.10 ha, (B) 0.71 ha, (C) 0.46 ha, and (D) 0.34 ha. The field identified with the red spot was not cultivated at the time of the survey.

3. Results

3.1. Main input and output flows

The main input and output flows were expressed per ha of land occupied per year (**Table 4.3Table *4.3***). SP had the highest N fertiliser input (362 kg N/ha/yr), mainly from solid (90%) and liquid (10%) commercial fertilisers made with raw materials such as livestock manure, castor bean meal, bone meal, phosphate, or plant-based compost and waste. MF applied 141 kg N/ha/yr, which was provided mainly by slow-release N fertilisers: composted cow manure (40% of N input), shredded green waste (30%), and compost of green waste (25%). OP had the lowest N input, with 96 kg N/ha/yr from livestock manure. The direct energy used by SP (74 GJ/ha/yr) was composed mainly of electricity (72%), mainly for irrigation. The direct energy used by MF (48 GJ/ha/yr) was composed entirely of diesel, also mainly for irrigation. The direct energy used by OP (16 GJ/ha/yr) was composed of diesel for tractors (64%) and electricity for a storage refrigerator (33%). SP had the highest yield (109 t/ha/yr), followed by MF (43 t/ha/yr) and OP (11 t/ha/yr). MF had the highest mean vegetable price (2.83 €/kg), followed by SP (2.20 €/kg) and OP (1.90 €/kg).

Direct emissions of NO, NO_3, and N_2O were nearly proportional to fertiliser N input. NH_3 was also emitted after application of N fertiliser, but because fertiliser types varied, emissions were not proportional the amounts applied. CO_2 emissions were caused by lime used to whitewash tunnels.

Table 4.3. Main annual inputs and output flows of the three farms expressed per ha of total cultivated land

Type	Item	Unit	Microfarm	Sheltered production	Open-field production
Inputs	Fertiliser	kg N/ha/yr	141	362	96
	Electricity	GJ/ha/yr	0	53.4	5.1
	Diesel	GJ/ha/yr	48.4	20.3	10.0
	Natural gas	GJ/ha/yr	0	0	0.4
	Irrigation water	m³/ha/yr	4622	4111	0
	Plastic	kg/ha/yr	363	1821	1
	Seedlings	no./ha/yr	0 (self-production of seedlings and direct sowing) Potting soil: 5357 kg/ha/yr	Tomato: 3355 Cucumber: 3097 Lettuce: 119 323 Strawberry: 4788 Celery: 3327 Fennel: 6397	Cabbage: 3903 Onion: 2857 Leek: 1029 Swiss chard: 263 Squash:143 Potato: 286 kg/ha/yr + self-production of seedlings and direct sowing
	Chemicals	-	Copper sulphate: 0.47 kg/ha/yr Iron phosphate: 36 kg/ha/yr	Wettable sulphur: 0.6 kg/ha/yr Neem oil: 1.8 L/ha/yr Plant-based biostimulant: 0.8 L/ha/yr Sex pheromone: 180 doses/ha/yr Horn silica (501): 20 g/ha/yr Prepared horn manure (500P): 140 g/ha/yr	-
	Purchased insects	no./ha/yr	-	*Macrolophus* sp. (box of 1000 insects): 6 *Chrysoperla* sp. (box of 10 000 insects): 28 Bumblebee hives: 17	-
	Shading paint	kg/ha/yr	0	590	0
	Plastic tunnel	ha/ha/yr	0.43	1	0
Output	Vegetables	t/ha/yr	43	109	11
	Price	€/kg	2.83	2.20	1.90
Emissions	N_2O	kg/ha/yr	2.75	7.30	1.73
	NH_3	kg/ha/yr	7.22	16.90	9.39
	NO	kg/ha/yr	5.69	13.92	3.54
	NO_3	kg/ha/yr	214	531	131
	CO_2	kg/ha/yr	0	259	0

3.2. Assessment of farm impacts

Per ha, SP had the highest CC impact, followed by MF and OP (13.3, 7.5, and 1.3 t CO_2 eq./ha, respectively) (**Fig. 44.8**). The ranking of SP, MF, and OP was the same for CED (387, 157, and 29 GJ/ha, respectively) and ME (23.2, 12.2, and 7.2 kg N eq./ha, respectively).

For CC, the contribution of system components varied among farms. Field emissions contributed more for SP than for MF or OP (1.51, 0.68, and 0.52 t CO_2 eq./ha, respectively). Fertiliser production also contributed more for SP than for MF or OP (2.17, 0.75, and 0 t CO_2 eq./ha, respectively). Diesel contributed much more for MF than for SP or OP (3.70, 1.04, and 0.68 t CO_2 eq./ha, respectively). Conversely, plastic tunnels contributed more for SP than for MF or OP (4.49, 2.01, and 0 t CO_2 eq./ha, respectively). Plastic production (other than for tunnels) also contributed more for SP than for MF or OP (1.31, 0.23, and 0.01 t CO_2 eq./ha, respectively). Seedling production contributed much more for SP than for MF or OP (2.02, 0.15, and 0.06 t CO_2 eq./ha, respectively).

For MF, diesel was the main contributor (49%) to CC, followed by tunnels (27%), fertiliser (10%), and field emissions (9%). For SP, tunnels were the main contributor (34%), followed by seedling production (15%, mainly for greenhouse heating), fertiliser (16%), field emissions (11%), and plastic (10%). For OP, diesel and field emissions were the two main contributors (54% and 34%, respectively).

For CED, the contributions were generally similar to those to CC, except that field emissions did not contribute; instead, seedlings (because of the use of peat) contributed more, particularly for MF (2% of CC vs. 23% of CED), as did electricity, particularly for SP, where it was used for irrigation (4% of CC vs. 33% of CED). Field emissions dominated ME for MF, SP, and OP (98%, 96%, and 96%, respectively), followed by a modest contribution of fertiliser production (2% for SP) and seedlings (4% for OP).

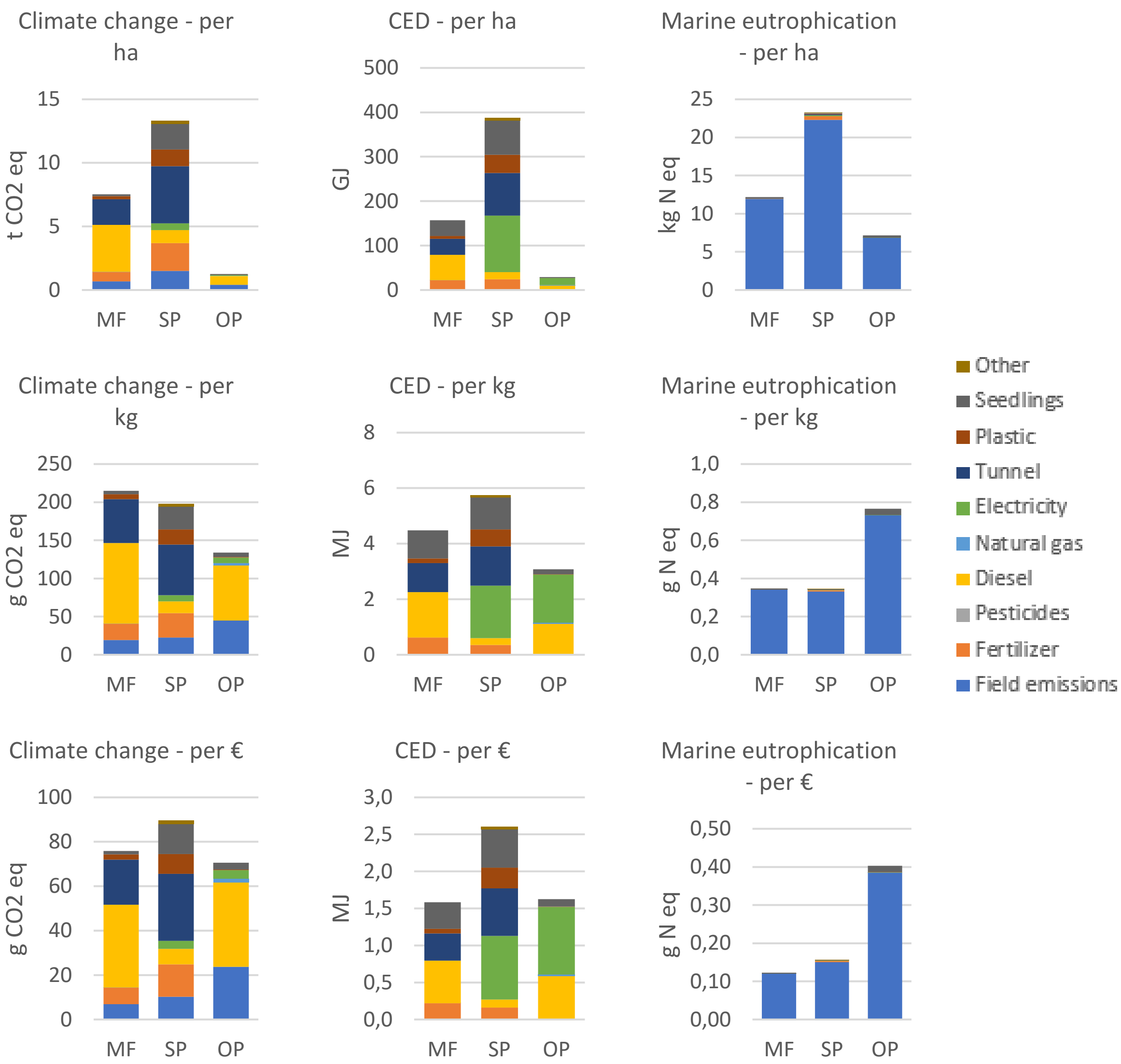

Fig. 44.8. Impacts per ha of farmland during one year, per kg of vegetables, and per € of vegetables; and contributions of inputs and field emissions for the microfarm (MF), sheltered production farm (SP), and open-field production farm (OP)

Per kg of vegetables, MF had the highest CC impact, followed by SP and OP (215, 198, and 134 g CO_2 eq./kg, respectively) (**Fig. 44.8**). The ranking of MF, SP, and OP was the same for CED (4.5, 5.7, and 3.1 MJ/kg, respectively). Conversely, OP had the highest ME impact, followed by OP and SP (0.77, 0.35, and 0.35 g N eq./kg, respectively).

Per € of vegetables, SP had the highest CC impact, followed by MF and OP (90, 76, and 71 g CO_2 eq./€, respectively) (**Fig. 44.8**). SP also had the highest CED, followed by MF and OP (2.6, 1.6, and 1.6 MJ/€, respectively). OP had the highest ME impact, followed by SP and MF (0.40, 0.16, and 0.12 g N eq./€, respectively).

3.3. Biodiversity

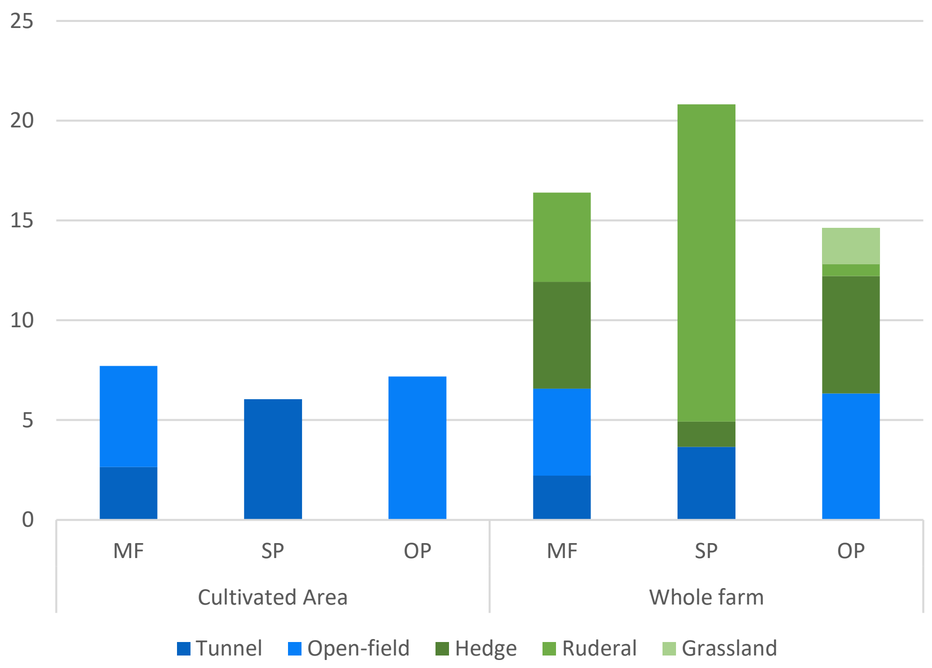

Fig. 4.9. On-farm biodiversity scores (higher = better for biodiversity) and contributions of land-use types for the three types of farms (microfarm (MF), sheltered production (SP), and open-field production (OP)) for the entire farm (cultivated land (blue bars) and semi-natural habitats (green bars)) and for the cultivated land alone

Differences in the biodiversity score among the farms were smaller when considering cultivated land alone (7.7, 6.0, and 7.2 for MF, SP, and OP, respectively) than when considering the entire farm, for which SP had the highest score (20.8), with a contribution of 82% from semi-natural habitats (especially ruderal areas (76% of the total)) and 18% from tunnels (**Fig. 4.9**). MF had a score of 16.4, with relatively equal contributions from cultivated land (40%) and semi-natural habitats (60%). OP had a score of 14.6, with cultivated land contributing 43% and semi-natural habitats contributing 57%, of which 40% of the total was due to hedges.

3.4. Plastic use

Depending on the FU, SP used 2-4 times as much plastic as MF (1129 and 299 kg/ha, 16.8 and 8.5 kg/t of vegetables, and 7.6 and 3.0 kg/k€ of vegetables, respectively), whereas OP used little plastic (2 kg/ha, 0.2 kg/t of vegetables, and 0.1 kg/k€ of vegetables) (**Fig. 4.10**). Plastic was used mainly in tunnels (60% of plastic use for MF and SP). For MF, insect-proof netting and pots and trays represented 17% and 12% of plastic use, respectively. For SP, plastic mulch in tunnels and disposable water pipes represented 28% and 9% of plastic use, respectively.

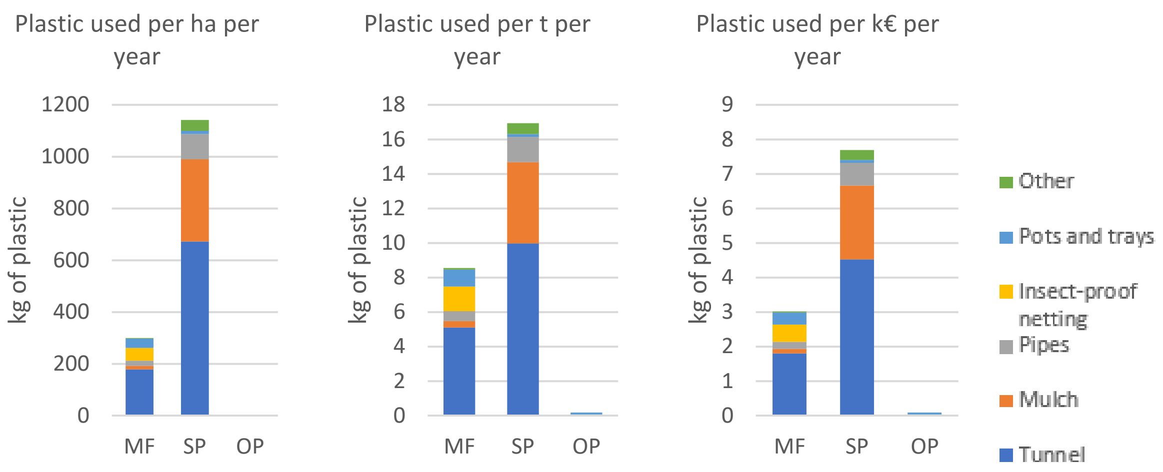

Fig. 4.10. On-farm plastic use per ha of farmland, per t of vegetables, and per k€, and contributions of plastic uses for the three types of farms: microfarm (MF), sheltered production (SP), and open-field production (OP).

3.5. Effects of farm area on impacts per ha

In the sensitivity analysis of farm area, the cultivated area of 0.28 ha represented 25%, 39%, 61%, and 82% of the farm area when farm area equalled 1.10, 0.71, 0.46 and 0.34 ha, respectively. These four areas resulted in CC impacts of 2.3, 3.6, 5.6, and 7.5 t CO_2 eq./ha, respectively (**Fig. 4.11A**), while biodiversity scores were 28.8, 24.3, 20.0, and 16.4, respectively (**Fig. 4.11B**).

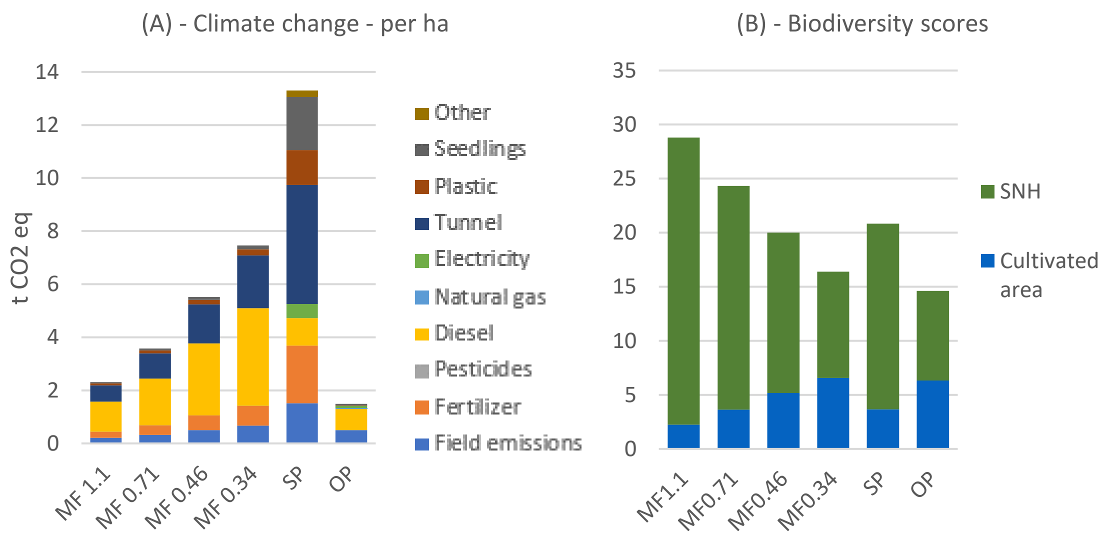

Fig. 4.11. (A) Climate change impact expressed per ha of farmland and (B) biodiversity scores for four scenarios for the microfarm (MF) (for areas of 0.34, 0.46, 0.71, and 1.10 ha), sheltered production farm (SP), and open-field production farm (OP). SNH: semi-natural habitats.

4. Discussion

4.1. Comparison of the farms

4.1.1. Climate change and cumulative energy demand

Environmental impacts of the three farms differed among impact categories and FUs. Per ha of land occupied, OP had the lowest CC impact and CED, due to its low input use. Conversely, SP had the highest CC impact and CED per ha because it produced 2-3 crops per year, which led to higher input use. MF had an intermediate CC impact and CED. Part of this farm had one crop per year (open field), and the other part had two crops per year (tunnel). The CC impact of SP per ha was 10.6 times as high as that of OP. Major contributors to CC impact and CED included the use of diesel (MF) and electric (SP) pumps for irrigation, the tunnel structure (MF and SP), the use of plastic water pipes and mulch (SP), and seedling production in heated greenhouses (SP); these inputs were not used by OP. Impacts of tunnels were due mainly to their galvanized steel structures, which was assumed to last 20 years, and plastic covers, which were assumed to last 4-8 years, depending on the farm. Using the same tunnel longer would reduce impacts.

Per kg of vegetables, MF and SP had a similar CC impact, while that of MF was 1.6 times as high as that of OP. This difference was much smaller than for the CC impact per ha because OP had a lower total yield than MF. The higher productivity of SP gave it a similar or slightly lower CC impact per kg despite using more inputs per ha; however, for CED, SP had higher impact than MF per kg. SP relied more on direct (diesel and electricity) and indirect (plastic and seedlings) energy than MF and OP. Per €, the highest CC impact (SP) was 1.3 times as high as the lowest CC impact (OP). MF practiced direct selling of several vegetables, including those with high value (e.g. tomatoes, mixed greens), for a mean price of 2.83 €/kg. SP sold in a long supply chain, which dilutes the value among more stakeholders. Nevertheless, SP's high-value vegetables (e.g. tomatoes, strawberries, lettuces) under a biodynamic label sold for a mean price of 2.20 €/kg. OP produced mainly less valuable vegetables (e.g. potatoes, cabbages, turnips, carrots) that were sold in a short supply chain for a mean price of 1.90 €/kg.

4.1.2.Marine eutrophication

For ME, the ranking of the farms depended on the FU, with OP having the lowest impact per ha but the highest impact per kg and €. NO_3 leaching, which is the main contributor to ME, was estimated using proportions of fertiliser and crop residue N (IPCC, 2019b) and ignoring N output. The farms' yields differed greatly, which suggests that their levels of crop N output did as well. The type of fertilisers also differed among the farms, because some mineralise faster (e.g. commercial fertiliser used by SP, poultry manure used by OP) than others (e.g. shredded green waste used by MF), which results in differing rates of N release in the soil. According to Qasim et al. (2021), incorporating straw into a greenhouse soil tended to reduce NO_3 leaching by stimulating denitrification. The Agence de l'eau Seine Normandie (2018) found low NO_3 leaching under vegetable crops grown with "market gardening on living soil" principles, as on MF. The high C:N ratio of the fertilisers used by MF enhances the activity of soil microbes and immobilises NO_3 (Kirchmann et al., 2002), and these fertilisers increase water retention (Zemánek, 2014), which decreases leaching. Furthermore, soil sequestration of N decreases NO_3 leaching (Knudsen et al., 2019) and depends on fertiliser properties. NO_3 leaching may also depend on whether fertiliser is applied in a greenhouse (i.e. a controlled water supply) or an open field (i.e. rainfall) (Koch and Salou, 2020). The IPCC Tier 1 emission factor we used to estimate NO_3 leaching is rudimentary and easy to apply in a farming-system LCA, but it seems too coarse given the variety of the farms' fertilisation strategies. Consequently, estimated ME impacts had high uncertainty, which calls for considering fertiliser properties and soil sequestration to improve estimates of NO_3 leaching.

4.1.3. Plastic use

SP used the most plastic, particularly to cover its 33 tunnels. MF also covered its tunnel in plastic, but used less, for two reasons: 1) only some of the cultivated land was under shelter, whereas all was under shelter on SP, and 2) the plastic lifetime was 8 years for MF and 4 for SP. The smaller tunnel area of MF allowed the farmer to repair plastic when damaged. In south-eastern France, where SP was located, plastic on small farms similar to MF had a lifetime of 6-7 years (Oriane Mertz, Agribio 84, pers. comm.); thus, the climate may influence this practice, along with the effect of the farming system. SP also used more plastic for mulching than MF and OP. On SP, all crops were mulched with single-use plastic, whereas on MF, straw mulch, manual weed control, and reusable plastic mulch were combined.

Plastic use is not an LCA indicator, and to our knowledge it has not been included before in an environmental assessment of vegetable production. In our study, it revealed major differences among systems. Plastic use in agriculture is a growing concern (United Nations Environment Programme, 2021b). Plastic mulch is a major source of microplastics (Bläsing and Amelung, 2018; Campanale et al., 2022) as it is thin and hard to remove from the soil (Qi et al., 2020). Microplastics may have detrimental effects on plant growth (Liu et al., 2021), soil properties (Zhang et al., 2020), and the fitness of soil bacteria and earthworms (Jiang et al., 2020), and can be found in fruit and vegetables at worrying concentrations (Oliveri Conti et al., 2020). An alternative to single-use plastic mulch that SP used the year after the survey is biodegradable plastic mulch, which is a common substitution approach (Hill and MacRae, 1995). Its benefits remain uncertain, as some studies conclude that it has no noxious effects on soil organisms (Sforzini et al., 2016), while others state that single-use and biodegradable plastic mulch have the same effects on earthworms (Ding et al., 2021; Kumar et al., 2020).

Plastic use included all types of items, from thin single-use items (e.g. mulch, drip tape) to long-lasting items (e.g. hard pipes). All types of plastic, regardless of their life span, can generate microplastics because the breakdown process starts on the surface. However, plastic used on the soil is more likely to be a source of soil microplastics (United Nations Environment Programme, 2021b). We included on-farm plastic but excluded up-stream plastic and products unintentionally contaminated with plastic (e.g. compost). Considering these sources of plastic would improve the indicator.

4.1.4. Biodiversity

Assessing biodiversity on the cultivated land alone or on the entire farm gave contrasting results, which highlighted the importance of a farm's semi-natural habitats for biodiversity (Chiron et al., 2010; P. Jeanneret et al., 2021; Rischen et al., 2021). On SP, the cultivated land yielded a low biodiversity score, which was offset by the high proportion of ruderal area (i.e. spaces between tunnels that are left to ruderal organisms). On OP, fields were generally surrounded by a ruderal strip or hedge. As its fields were large, its proportion of semi-natural habitat was lower, which yielded a lower biodiversity score at the whole-farm scale. On MF, the cultivated land yielded a biodiversity score similar to those of the other systems. Out of a maximum score of 45 in SALCA-BD for semi-natural habitats such as hedges, biodiversity-friendly managed grasslands and pastures can reach a score of 25 (Lüscher et al., 2017), which was the case for the SP grassland. Such scores are far higher than those of the vegetable fields studied here (3-8).

Consequently, for all farms, semi-natural habitats obviously contributed more to the biodiversity score than cultivated land. This result is in line with ecological studies that concluded that semi-natural habitats were important for spiders (e.g. Šálek et al., 2018), carabid beetles (e.g. Knapp and Řezáč, 2015), butterflies (e.g. Dover et al., 2000), birds (e.g. Billeter et al., 2007), and vascular plants (e.g. Billeter et al., 2007). The benefits of small farms for biodiversity are also acknowledged by Ricciardi et al. (2021), since the fields of smaller farms have a higher perimeter:area ratio than those of larger farms. Smaller farms are also more likely to create heterogeneous landscapes.

SALCA-BD analysed impacts of land-use type, farmer practices, and elements of spatial organisation of the farms. Other biodiversity assessment methods (Chaudhary and Brooks, 2018; Knudsen et al., 2017; Koellner and Scholz, 2008; Mueller et al., 2014) quantify impacts on biodiversity based on land-use classes and the distinction between organic and conventional farming. These methods are not adapted for assessing organic farms that have the same land use (arable land) but different farming practices.

4.1.5. Ranking and farm-specific effects

Considering the different impacts and FUs, a clear ranking of the farms did not emerge. OP had the lowest impacts, except for CED per € and for ME per kg and per €, and it was not best for biodiversity.

However, OP had a much lower yield than MF and SP (75% and 90% lower, respectively), which required more land to produce the same quantity of vegetables. Although the three farms are typical of the variety of such farming systems, farm-specific effects cannot be ignored. For example, MF used a diesel pump for irrigation, which contributed strongly to its CC impact. MF tried to limit input use, whereas some microfarms inspired by "bio-intensive" practices may use commercial fertilisers or plastic mulch intensively. On MF, the tunnel had large impacts, but some microfarms, particularly in southern France, do not use tunnels. On SP, ruderal areas between tunnels occupied a large proportion of the farm, but farms similar to SP use glasshouses or multispan greenhouses rather than tunnels, without inter-tunnel areas. Microfarms, often inspired by permaculture design methods, include semi-natural areas (e.g. hedges, ponds, woodland) (Morel et al., 2019) that would increase their biodiversity score. OP reduced its use of plastic close to zero, but some farms that grow vegetables on large open fields such as OP use plastic mulch or small plastic "caterpillar" tunnels.

According to the biotechnical index (Pépin et al., 2021), the level of agroecology of the farm was highest for MF (0.73), intermediate for OP (0.47), and lowest for SP (0.07). Per ha, SP had the highest CC and ME impacts, and the highest CED and plastic use, which is in line with its low biotechnical index, which corresponds to intensive use of inputs. However, MF (high biotechnical index) did not have lower impacts per ha than OP (intermediate biotechnical index). For MF, the tunnel and diesel, used mainly used for irrigating, contributed 75% of CC and 60% of CED, but tunnels and irrigation were not considered in the biotechnical index, which appears to be a methodological oversight. Because their total yields differed, the farms ranked differently when expressing impacts per kg and per € than per ha. The ranking per kg and per ha did not correlate with the biotechnical index, which ignores the yield.

Microfarming is often promoted as a solution to produce food with lower environmental impacts, but the LCA results in this case study suggest that this benefit is not obvious. However, microfarms may be a good compromise by having higher yields than large open-field farms and lower impacts per ha, and promoting biodiversity by having a high ratio of semi-natural habitats to cultivated land and diversified crops.

4.2. Advantages and disadvantages of the farming-system approach

The farming-system LCA approach was able to estimate several environmental impacts of complex farms by considering the system as a whole, without modelling every single crop. It also compared farms and identified hotspots (i.e. the main contributors to impacts). For example, in unheated greenhouse production, we found fertilisers (including compost), the greenhouse structure, and heated seedling production to be major contributors to CC, which confirms other results in the literature (Boulard et al., 2011; Cellura et al., 2012; Martinez-Blanco et al., 2011). The FUs identified differences in environmental impacts and eco-efficiency. Expressing impacts per kg and per unit of economic value are two ways to relate impacts to products. The mass-based FU considered production but introduced a bias when comparing farms that produced vegetables with different characteristics and value. In contrast, the value-based FU can compare any vegetables.

The farming-system approach followed the rationale of agroecology, in which inputs are farm-oriented rather than crop-oriented (e.g. fertilising the soil rather than the crop (Gliessman, 2021)). On MF, the goal of fertilisation was to have a fertile soil that was rich in organic matter and soil organisms. In a product LCA approach, MF's tunnel would be allocated to the vegetables grown in tunnels and not to those grown on open fields. However, it is difficult for a microfarm in this region to earn a sufficient turnover with only open fields, which means that the vegetables require a tunnel. On OP, rye production in the crop rotation had the main functions of producing rye and reducing pest and disease pressure. Because the latter function influences the (non-)use of inputs for vegetable production, it would make sense to include rye impacts in vegetable LCAs, with the challenge of allocating impacts between the two functions.

Some vegetables may have higher impacts than others due to specific needs (e.g. seedlings, fertiliser, water, pest control), lower yields, and/or longer cropping periods, but the farming-system approach cannot identify such "hotspot" vegetables. Identifying specific operations that have high impact requires detailed information about farmer practices. For example, knowing total diesel consumption does not provide information about how it was used for individual operations.

4.3. Comparison to similar studies

CC impacts of the farms studied are consistent with the few studies of similar systems (**Table 4.4**). CC impact of a small-scale organic farm in Washington, USA, (Adewale et al., 2016) was 1.7-2.7 t CO_2 eq./ha/yr and 45-623 g CO_2 eq./kg, depending on the vegetable. Irrigation contributed strongly to CED, as for MF and SP. The greenhouse contributed 7-10% to the CC impact of vegetables produced under shelter. When assessing a small and a large organic farm, Adewale et al. (2019) estimated a CC impact of 7.1 and 3.4 t CO_2 eq./ha/yr, respectively. For onion and winter squash, they estimated 188 and 276 g CO_2 eq./kg, respectively, for the small farm and 50 and 68 g CO_2 eq./kg, respectively, for the large farm. Christensen et al. (2018) studied community-supported vegetable farms in California, USA, and estimated CC impacts of 1.72-6.69 kg CO_2 eq./kg and 1.4-6.3 t CO_2 eq./ha/yr. These farms had very low yields (534-949 kg/ha/yr), which explains their very high CC impact per kg. Cellura et al. (2012) estimated a CC impact of 740 g CO_2 eq./kg for conventional tomatoes produced in an unheated tunnel in Italy. These impacts are higher than those for SP, partly because of a wider scope that included packaging and transport, and a shorter tunnel life span. He et al. (2016) estimated a CC impact for organic tomatoes in China of 208 g CO_2 eq./kg, and Martinez-Blanco et al. (2011) estimated 182 and 289 g CO_2 eq./kg for conventional tomatoes produced in tunnels and on open fields, respectively, both with compost and mineral fertilisers. Tomatoes produced in a heated greenhouse had CC impacts 10-50 times as high as those of vegetables produced in unheated tunnels, and heating and lighting contributed 97% of the impact (Williams et al., 2006). In open-field production in Oregon, USA, which is likely similar to OP, Venkat (2012) estimated a CC impact of 409 and 268 g CO_2 eq./kg for organic broccoli and lettuce, respectively. As a comparison to other organic crops, Nitschelm et al. (2021) estimated a mean CC impact for 106 cereals and legumes (e.g. spring and winter barley, spring and winter wheat, winter pea, fava bean) of 0.8 ±0.2 and 258 ±112 g CO_2 eq./kg, respectively.

Table 4.4. Literature results for climate change impact (100-year horizon) per ha during 1 year and per kg of vegetables

Type of farm	Vegetable	Country	t CO_2 eq./ha/yr	g CO_2 eq./kg	Greenhouse (GH)/open-field (OF)	Organic (Yes/No)	Source
Microfarm (MF)	Various	France	7.5	215	GH+ OF	Yes	Present study
Sheltered production (SP)	Various	France	13.3	198	GH	Yes	
Open-field production (OP)	Various	France	1.3	134	OF	Yes	
Small vegetable farm	Winter squash	USA	1.9	101	OF	Yes	Adewale et al. (2016)
	Potato		2.7	45	OF	Yes	
	Dry bush beans		1.7	623	OF	Yes	
	Chard		1.7	101	OF	Yes	
	Summer squash		2.1	62	OF	Yes	
	Peppers		2.6	65	OF	Yes	
	Onion		2.1	79	OF	Yes	
	Cauliflower		2.7	155	OF	Yes	
Small vegetable farm	Various	USA	7.1	-	OF	Yes	Adewale et al. (2019)
	Onion		-	188	OF	Yes	
	Winter squash		-	276	OF	Yes	
Large organic vegetable farm	Various	USA	3.4	-	OF	Yes	
	Onion		-	50	OF	Yes	
	Winter squash		-	68	OF	Yes	
Community-supported agriculture	Various	USA	2.9	3290	GH+ OF	Yes	Christensen et al. (2018)
	Various		1.3	1720	OF	Not certified	
	Various		6.4	6690	GH+ OF	Yes	
	Various		2.0	3720	GH+ OF	Not certified	
	Various		3.7	3980	GH+ OF	Not certified	
Mediterranean greenhouse	Tomato	Italy	-	740	GH	No	Cellura et al. (2012)
Mediterranean greenhouse	Tomato	Spain	-	182	GH	No	Martinez-Blanco et al. (2011)
Open field	Tomato	Spain	-	289	OF	No	
Heated greenhouse	Tomato	UK	-	9400	Heated GH	No	Williams et al. (2006)
Mediterranean greenhouse	Tomato	Morocco	-	220	GH	No	Payen et al. (2015)
Heated greenhouse	Tomato	France	-	1750	Heated GH	No	
Urban greenhouses	Tomato	China	-	208	GH	Yes	He et al. (2016)
Urban greenhouses	Tomato	China	-	261	GH	No	
National data base (practices considered typical)	Broccoli	USA	-	409	OF	Yes	Venkat (2012)
	Broccoli		-	353	OF	No	
	Lettuce		-	268	OF	Yes	
	Lettuce		-	192	OF	No	

4.4. The farm area and production area

In a product LCA, the area of the field or greenhouse is usually used for an area-based FU. In a farming-system LCA, the farm area is used, but farms often have uncultivated semi-natural areas. On microfarms, farmers may leave land uncultivated due to a lack of time or labour, or to enhance biodiversity and/or regulating ecosystem services (Morel et al., 2019). On farms with tunnels, areas between tunnels are rarely considered in yields or for an area-based FU. Microfarms and small farms that specialise in sheltered production have small areas; thus, uncultivated land may represent a much higher proportion of the area than that on a larger farm. The sensitivity analysis of farm area showed large differences in CC per ha and yielded a different ranking of the farms for biodiversity, depending on the area considered for MF. It is therefore important to establish clear rules for defining farm area, in particular when comparing farms of different types and sizes. Consequently, results with area-based FUs must be interpreted cautiously. It is reasonable to consider semi-natural areas as part of the farming system, as they provide regulating ecosystem services.

4.5. Methodological concerns when assessing organic vegetable farms

Estimates of NO_3 leaching influence the ME impact greatly. On agroecological farms that use organic fertiliser with high stability and slow mineralisation, the IPCC Tier 1 equation for NO_3 leaching (IPCC, 2019b) we used seems inappropriate, although it was easy to use. This calls for improving modelling of NO_3 leaching in a farming-system approach for systems that use organic fertilisers.

N added to the soil by crop residues was estimated using a generic coefficient for all vegetables, although the N content of residues differs among vegetables. N_2O emissions from crop residues and cover crops represented 5-12% of farm N_2O emissions and 1-2% of CC impacts. Crop residues and cover crops caused 18-28% of NO_3 leaching and 17-27% of ME impacts. These results suggest that improving estimates of crop residues is a priority for estimating ME impacts but not CC impacts, which agrees with Akkal-Corfini et al. (2021), who observed a large contribution of crop residues to NO_3 leaching from artichoke and cauliflower.

Biocontrol, particularly using macro-organisms against pests or for pollination, is commonly used in organic vegetable production. Producing them requires infrastructure, feed, heat, and rapid transportation, but to our knowledge, their impacts are not known or no data are available. Studies that mention the use of insects for pest control or pollination excluded their impacts (Cellura et al., 2012). Estimating impacts of these insects would improve estimates of impacts of organic vegetable production, as the biocontrol market is growing rapidly.

5. Conclusion

Farming-system LCA assesses environmental impacts of farms that have different levels of agroecology, including complex systems with a wide variety of crops grown on small areas. The three FUs strongly influenced the ranking of the systems. Depending on the FU and the impact, each farm ranked first, second, or third. Per ha, differences in the CC impact and CED among the systems were large. SP had the highest impacts, whereas OP had the lowest impacts, which correlated with the intensity of input use. Per kg and per €, differences in the CC impact and CED among the systems were much smaller. OP had a lower CC impact and CED per kg, but not per €. OP used much less plastic, but had a lower biodiversity score and total yield. Despite its high total yield, SP did not perform well for CC impact, CED, or plastic use per kg or per €.

Our results show that the biotechnical index developed by Pépin et al. (2021) did not correlate with LCA-based estimates of environmental impacts. Including the use of greenhouses and irrigation infrastructure in the index would likely improve estimates of the CC impact and CED. Microfarms may be a good compromise, however, by having higher yields than large open-field farms and lower impacts per ha, and promoting biodiversity with a high ratio of semi-natural habitats to cultivated land and diversified crops. Although we selected farms that were typical of three farming systems, their potential farm-specific effects cannot be ignored. Farming-system LCA was able to assess farms using a relatively moderate amount data, and it can compare contrasting farming systems and identify hotspots within them.

The impact on on-farm biodiversity, which highlighted the importance of semi-natural habitats, contrasted with the other impacts. The quantification of plastic use echoes growing concerns about (micro-)plastic pollution in agricultural soils and landscapes, and the newly identified planetary boundary for novel entities. Estimating NO_3 leaching accurately was difficult, and IPCC Tier 1 modelling seemed inappropriate; consequently, estimates of the ME impact had high uncertainty. Because crop residues contributed greatly to this impact, models that estimate NO_3 leaching in a farming-system LCA need to be improved. In agroecological systems, semi-natural habitats are important for natural regulation, as they are part of the farming system. The farming-system LCA approach requires clear rules for setting farm boundaries, which strongly influence impacts per ha and biodiversity impacts.

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Chapitre 5. Synthèse générale, discussion et perspectives

1. Contribution de la thèse, limites et perspectives

Dans cette partie, j'expose et discute les contributions de la thèse aux méthodes et connaissances dans les domaines de l'évaluation environnementale et de l'agroécologie, les réponses aux questions de recherche posées dans l'introduction de la thèse ainsi que les perspectives pour la recherche.

1.1. Appréhender la diversité des fermes par une typologie et un cadre d'analyse

La diversité des systèmes agricoles, et plus spécifiquement celle des systèmes maraichers en agriculture biologique, a été décrite dans la littérature dans plusieurs contextes géographiques et avec différents critères. L'existence conjointe de petites fermes diversifiées adoptant des pratiques agroécologiques et peu consommatrices d'intrants et de plus grosses fermes, spécialisées sur certains légumes et s'appuyant largement sur des intrants était établie. Cette vision dichotomique, pouvant présumer d'un gradient d'intensité entre ces deux pôles, ne permet cependant pas d'appréhender toute la diversité des fermes, de leurs structures et de leurs pratiques agricoles et commerciales.

Les données collectées auprès de 165 fermes ont fourni de nombreuses informations quantitatives et qualitatives permettant de caractériser la diversité des fermes par une approche statistique multivariée. Un clustering a permis de déterminer des types de fermes et d'en décrire les caractéristiques principales et leur variabilité.

Le cadre d'analyse de Thérond et al. (2017), qui caractérise les formes d'agriculture, a fourni une base conceptuelle pour positionner les fermes maraichères dans leur relation aux pratiques agroécologiques et circuits de commercialisation, sans toutefois apporter de méthode pour le faire. À partir de données qualitatives simples, nous avons créé des index composites quantitatifs qu'il a été possible de relier aux axes du cadre d'analyse. Cela a permis de discuter la possible existence d'une bifurcation (Darnhofer et al., 2010) entre des systèmes biologiques agroécologiques et des systèmes biologiques « conventionnalisés », c'est-à-dire avec des méthodes s'inspirant de l'agriculture conventionnelle conduisant à une démarche d'efficience ou de substitution plutôt qu'à une reconception en rupture (Hill et MacRae, 1995).

La bifurcation est un processus temporel, s'analysant sur le temps long. Les données ne permettent pas d'analyser si la diversité observée est le résultat ou non d'un processus de bifurcation, ni si les fermes situées au milieu du gradient vont bifurquer vers l'un ou l'autre des pôles. Les microfermes, qui, d'après l'index biotechnique, ont des pratiques plus agroécologiques que les autres, sont souvent jeunes (comme c'est le cas dans notre échantillon) et leur création est souvent motivée par des convictions écologiques fortes (Morel et Leger, 2016). Ces fermes sont souvent peu mécanisées, génèrent un revenu relativement faible pour une charge de travail importante et parfois physiquement dure (Dumont et Baret, 2017; Morel et al., 2017). Il serait intéressant de voir sur le long terme si ces pratiques sont maintenues ou si les agriculteurs font des compromis en allant vers une certaine forme de conventionnalisation.

Grâce à ces index composites, j'ai mis en évidence le lien entre l'installation directement en production biologique et le développement de pratiques agroécologiques, alors que les maraichers ayant converti leur production à l'agriculture biologique, parfois depuis longtemps, semblent hériter d'une structure et d'un savoir-faire conventionnel freinant la reconception du système dans une perspective agroécologique. J'ai discuté le rôle des circuits de commercialisation et de la taille des fermes en montrant que les pratiques agroécologiques étaient liées à des fermes de petite taille vendant en circuit court, même si des exceptions laissent penser que d'autres modèles existent.

Le chapitre 4 révèle des limites à ces index, en mettant en évidence la forte contribution des tunnels (infrastructure) et de l'irrigation (énergie) dans les impacts sur le changement climatique et la demande en énergie. Au sens de l'ACV, les infrastructures sont des intrants, puisqu'on peut les définir comme un flux de matériel entrant dans le process (ISO, 2006b), ce que nous n'avions pas considéré dans la définition des index composites. Les tunnels et l'irrigation pourront être intégrés dans la création des index composites pour mieux corréler ces derniers aux impacts environnementaux et améliorer la pertinence d'une telle approche simplifiée.

La typologie et l'analyse de la diversité des fermes se sont appuyées sur une base de données de 21 variables – huit quantitatives et 13 qualitatives – décrivant 165 fermes.

En 2019, année de la collecte de données auprès des 165 fermes, la France comptait 9780 fermes produisant des légumes en AB depuis plus d'un an, d'après l'observatoire national de l'agence bio (Agence Bio, 2022). L'échantillon ayant servi au clustering représentent donc 1,7% des producteurs de légumes en AB. La formule de Yamane (Yamane, 1967) permet de déterminer la taille minimale d'un échantillon à partir de la taille de la population totale :

$$n = \frac{N}{1 + Ne^2}$$

Avec n = taille minimale de l'échantillon ; N = taille de la population ; e = marge d'erreur

Avec une marge d'erreur de 10% appliquée à la population de 9780 fermes, la taille minimale de l'échantillon est de 99 fermes. Le mode de diffusion de l'enquête n'étant pas un tirage aléatoire, il n'est pas possible de s'appuyer sur cette formule pour en déduire avec certitude la représentativité de l'échantillon. Néanmoins le résultat donne une indication sur le fait que l'échantillon permet de capter la diversité des fermes maraichères en AB.

De plus, la répartition géographique (**Fig. 2.1**) de l'échantillon correspond à la répartition des fermes sur le territoire (**Fig. 5.1**), avec des nombres de fermes élevés dans le Nord-Ouest et de Sud-Est, régions initialement visées par l'enquête de la thèse, ainsi que le Sud-Ouest où de nombreuses réponses de questionnaires ont été obtenus.

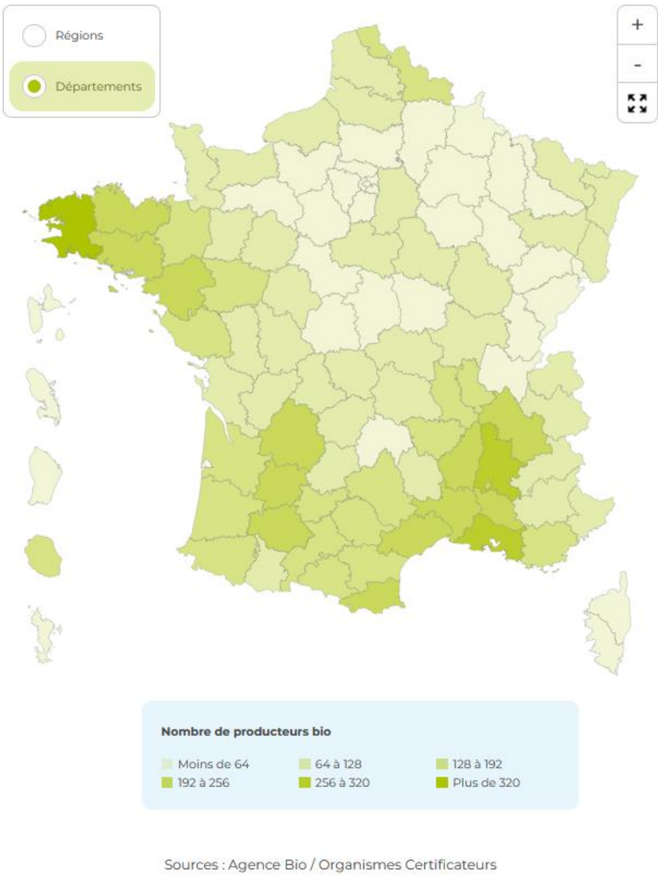

Fig. 5.1. Répartition géographique des producteurs de légumes en AB en France en 2019 (Source : Agence Bio (2022))

Collecter des données décrivant les aspects physiques, techniques et commerciaux d'un grand nombre de fermes prend du temps. La stratégie adoptée d'un formulaire en ligne, rapide à remplir (10 à 15 minutes), avec des questions simples, essentiellement qualitatives, ne nécessitant pas de se référer à des documents (comptes, fichiers d'enregistrement des pratiques), a permis d'obtenir un grand nombre de réponses en un temps limité. Les questions fermées, permettant d'obtenir les variables descriptives des fermes, étaient obligatoires afin d'obtenir un jeu de données complet. Les questions ouvertes étaient facultatives, permettant aux agriculteurs qui le souhaitaient d'apporter des précisions. Le choix a donc été fait de privilégier l'obtention d'un grand nombre de réponses synthétiques plutôt que moins de réponses très détaillées. Le mode de diffusion du questionnaire, en ligne et transmis aux agriculteurs par des animateurs de réseaux variés, a permis d'obtenir beaucoup de réponses. Il a toutefois introduit un biais, certains réseaux étant plus dynamiques que d'autres, et tous les agriculteurs n'étant pas autant impliqués dans les réseaux. Les répondants participaient sur une base volontaire, il est probable que certains agriculteurs peu intéressés par la démarche n'aient pas répondu. Cela n'invalide pas les conclusions sur la diversité mais modère la représentativité.

1.2. Utiliser un système expert pour évaluer la biodiversité dans une ACV

Prendre en compte l'impact sur la biodiversité de l'utilisation des terres pour des activités humaines est une préoccupation majeure pour l'ACV. Dès 2000, Haas et al. (2000) identifient la biodiversité comme une question clé pour l'ACV agricole et suggèrent la création d'une catégorie d'impact dédiée. La « Life Cycle Initiative », coordonnée au niveau mondial par l'UNEP/SETAC (United Nations Environnement Programme / Society of Environmental Toxicology and Chemistry) dans le but d'obtenir des consensus méthodologiques, consacre une « task force » à ce sujet (Milà i Canals et al., 2016).

Le chapitre 3 présente l'adaptation du système expert SALCA-BD aux cultures de légumes. SALCA-BD, était initialement conçu pour estimer l'impact sur la biodiversité de parcelles ou fermes en grandes cultures et prairies. L'outil considère l'aptitude des milieux qui composent la ferme (cultures, haies, prairies, etc.) à héberger des groupes espèces indicatrices, et l'impact présumé des pratiques agricoles sur ces groupes d'espèces, pour estimer un impact global au niveau de la parcelle, de la rotation ou de la ferme. Face à la multiplicité des types de légumes, constituant théoriquement autant d'habitats différents dans SALCA-BD et à l'absence de littérature permettant d'attribuer à chaque légume (et donc habitat) un coefficient représentant son potentiel pour la biodiversité, un regroupement des légumes par analyse multivariée et clustering a permis de définir un nombre réduit de groupes de légumes présentant des critères communs choisis pour leur influence sur la biodiversité (hauteur, couverture du sol, durée de la culture, présence de fleurs). Cela permet également d'utiliser l'outil pour des légumes qui ne sont pas dans la liste ayant servi à son paramétrage, comme c'était le cas avec le topinambour (Jerusalem artichoke) de la ferme OP.

L'intérêt d'utiliser cet outil plutôt que d'autres méthodes récentes (Chaudhary et Brooks, 2018; Knudsen et al., 2017) réside dans la possibilité de comparer des fermes avec une même occupation des terres, en l'occurrence du maraîchage biologique. Il permet également d'intégrer des habitats semi-naturels (e.g. haies, espaces rudéraux, mares), dont le rôle prépondérant dans l'impact d'une ferme sur la biodiversité est montré dans les chapitres 3 et 4 et soutenu par la littérature. Les haies sont prises en compte par Knudsen et al. (2017) mais pas les surfaces rudérales. Les méthodes proposées par Chaudhary et Brooks (2018) et Chaudhary et al. (2015) qui sont actuellement recommandés provisoirement par l'UNEP/SETAC life cycle initiative uniquement pour l'analyse des

« hotspots[6] » et pas pour des évaluations comparatives, incluent les zones naturelles dans leur modèle, mais pas spécifiquement les habitats semi-naturels des paysages agricoles.

SALCA-BD s'est donc révélé utile pour comparer des fermes par sa capacité à considérer les différences de cultures, d'habitats semi-naturels et de pratiques agricoles avec un niveau de détail supérieur aux autres méthodes. C'est d'autant plus important pour l'agriculture biologique, et particulièrement pour des fermes très agroécologiques ou s'inspirant de courants comme la permaculture où les habitats semi-naturels font partie intégrante du système (Morel et al., 2019).

SALCA-BD se concentre sur la biodiversité sur le site de la ferme, il ne prend pas en compte les processus en amont et aval qui utilisent des terres (surfaces indirectes) et peuvent causer des dommages à la biodiversité. L'outil n'est donc pas complètement dans une logique de cycle de vie. Dans le cas des fermes maraichères, ces surfaces indirectes sont faibles et concernent principalement les productions de semences (champs) et plants (pépinières). Cette limite est évidemment plus gênante pour des fermes d'élevage qui peuvent, ou non, utiliser de grandes surfaces indirectes pour la production de l'aliment du bétail. Combiner un outil détaillé comme SALCA-BD avec des méthodes plus globales est une perspective prometteuse pour la prise en compte des impacts sur la biodiversité en ACV.

SALCA-BD repose sur la littérature scientifique disponible et sur des avis d'expert. Cet outil développé par Jeanneret et al. (2014) a été validé par Lüscher et al. (2017) par des relevés de terrains dans huit pays d'Europe pour la flore ségétale et prairiale, les araignées et les abeilles sauvages. La littérature concernant la biodiversité en parcelles maraichères a donné peu de résultat, avec pour conséquence un rôle important des experts dans l'élaboration des paramètres de l'outil. Une validation par des observations naturalistes apporterait une meilleure légitimité.

Le système expert ne prend pas en compte la taille des parcelles dans son évaluation, ni l'hétérogénéité compositionnelle du paysage. Ainsi, un champ d'un ha ou de dix ha avec les mêmes cultures et les mêmes pratiques aura le même score. L'effet de la taille sur la biodiversité est bien documenté, les parcelles plus petites étant généralement plus favorables que les grandes, de même que l'effet positif de la présence d'habitats semi-naturels dans le paysage (e.g. Fahrig et al., 2015; Martin et al., 2020; Šálek et al., 2018; Sirami et al., 2019). Les paysages agricoles avec de petites parcelles ont généralement un ratio habitats semi-naturel / champs cultivés plus élevé, avec pour conséquence d'obtenir un score plus élevé avec SALCA-BD. La taille des parcelles est donc

[6] Le terme "hotspot" fait ici référence aux étapes du cycle de vie ou aux intrants qui contribuent le plus aux impacts environnementaux, et non aux "points chauds de la biodiversité" utilisés pour décrire des régions du monde très riches en biodiversité.

indirectement prise en compte lors d'une évaluation à l'échelle de la ferme incluant les habitats semi-naturels. Une prise en compte directe de la taille des parcelles dans l'outil est une piste à explorer.

1.3. L'ACV système, une réponse au défi de la complexité

Les fermes complexes, cultivant une grande diversité de légumes en les associant sur de petites surfaces, posent des défis à l'ACV. La microferme (MF) étudiée dans le chapitre 4 représente bien cette situation. Sur 1200 m² de tunnel et 1600 m² de plein champ, divisés en bandes de 41 m², sont cultivés 35 légumes chaque année. La fertilisation de fond est apportée par du compost et des déchets verts broyés, apportés tous les quatre ans. L'irrigation, assurée par une pompe diesel, arrose tous les légumes, à des doses variant selon les besoins et la météo, sans recours à un enregistrement des volumes. Les questions posées par cette approche agronomique sont : Comment évaluer les impacts, et donc allouer les intrants, pour une culture en particulier ? Dans mon objectif de comparer des types de fermes, représentés chacun par un cas d'étude, quel sens y a-t-il à faire l'évaluation de chaque culture alors même que les intrants clés sont raisonnés à l'échelle du système ? Pour réaliser l'ACV d'un système de cultures, correspondant à un ensemble de cultures cultivées successivement ou ensemble dans un même champ avec une approche systémique, Goglio et al. (2018) recommandent d'aborder la ferme comme un tout produisant différents produits et où tous les intrants, opérations et émissions sont estimés pour l'ensemble de la ferme, et sont rapportés à la production annuelle totale. Par ailleurs la norme ISO (2006b), qui régit les ACV, indique que l'allocation des intrants, c'est-à-dire l'attribution d'un intrant aux différents produits l'utilisant, doit être évitée si possible, ce que permet l'approche système.

Par ailleurs, cette approche système correspond bien à la façon suivant laquelle il est possible de collecter les données dans les fermes. Dans un premier temps, j'ai cherché à obtenir les informations nécessaires à l'ACV culture par culture. Pour la ferme SP avec six cultures, la plupart des données (e.g. fertilisants, rendements, opérations de travail du sol) étaient disponibles par culture, car raisonnée ainsi par l'agriculteur. Pour la ferme OP, avec 20 cultures, une partie des données (e.g. rendements, opérations de travail du sol) était disponibles par culture alors que d'autres données clés (fertilisants) étaient raisonnés à l'échelle de la ferme. Sachant sur quels légumes étaient apportés les engrais, il était possible de faire une allocation entre les légumes de la succession en tenant compte de la dynamique de minéralisation propre à chaque engrais. Pour la ferme MF, avec 35 légumes, la plupart des données étaient disponibles uniquement à l'échelle de la ferme. La rotation était raisonnée de façon à éviter que deux cultures d'une même famille botanique se suivent, mais au-delà de ce principe, il n'y avait pas de rotation claire. Des processus d'optimisation de l'espace avaient lieu, avec par exemple des tomates implantées dans une planche de tétragone qui serait récoltée avant que les pieds de tomates ne prennent toute la place. Pour obtenir des données par culture, une allocation serait nécessaire pour la majorité des intrants, alors que les relations physiques entre les intrants et les cultures qui les utilisent, qui doit servir de base de référence pour une allocation (ISO, 2006b), sont peu évidentes à établir.

Table 5.1. Format des données collectée à l'échelle de la ferme (F) ou de la culture (C) pour une microferme (MF), une ferme spécialisée en culture sous tunnel (SP) et une ferme de plein champ (OP).

Intrant	MF			SP			OP		
	F	C	Commentaire	F	C	Commentaire	F	C	Commentaire
Fertilisant solide	I	A		I	I		I	A	
Fertilisant liquide	-	-		I	A		-	-	
Plants	-	-		S	I		S	I	
Terreau pour plants	I	A		-	-		-	-	
Plaques et pots pour plants	I	A		-	-		-	-	
Diesel	I	A	Principalement pour l'irrigation	I	E	Estimation de la consommation des tracteurs par type d'opération	I	E	Estimation de la consommation des tracteurs par type d'opération
Electricité	-	-		I	A		I	A	
Gaz	-	-		-	-		I	I	Une seule culture concernée
Eau	I	A		I	A		-	-	
Soufre et cuivre	I	I	Une seule culture concernée	S	I		-	-	
Insectes pour biocontrôle et pollinisation	-	-		S	I		-	-	
Préparation biodynamique	-	-		I	I		-	-	
Paillage plastique	I	A		I	I		-	-	
Filet de protection	I	A		-	-		S	I	
Fils, clips	I	I		I	I		-	-	
Tuyaux et gaines d'irrigation	I	A		I	A		-	-	
Blanchisseur pour ombrage tunnel	-	-		I	A		-	-	
Tunnel	I	A		I	I		-	-	
Surface	I	I	Fichier d'assolement	I	I	Fichier d'assolement	I	I	Dire d'agriculteur
Production	E	E	Estimation à partir du chiffre d'affaires ou du rendement attendu par l'agriculteur	S	I		S	I	
Chiffre d'affaires	I	E	Estimation avec un prix estimé par légume	I	E	Estimation avec un prix estimé par légume	I	E	Estimation avec un prix estimé par légume
Total I	13	3		13	10		6	5	
Total E	1	2		0	2		0	2	
Total A	0	9		0	5		0	2	
Total S	0	0		3	0		3	0	

I : Information directe (avec parfois certaines hypothèses à faire, par exemple sur la densité d'un intrant)
E : Estimation à faire, à partir d'informations à l'échelle de la culture
A : Allocation à faire, à partir de l'information à l'échelle de la ferme
S : Somme des informations par culture
- : ferme non concernée

Par ailleurs, la norme ISO précise qu'une comparaison de systèmes doit utiliser des considérations méthodologiques équivalentes pour tous les systèmes évalués. La **Table 5.1** décrit pour chaque ferme comment les données sont disponibles pour l'approche à l'échelle de la ferme (F) et de la culture (C).

Pour SP et OP il y a une majorité de « I » aux niveaux ferme et culture, soulignant qu'à ces deux niveaux beaucoup d'informations sont disponibles directement. Pour MF, en revanche, il y a une majorité de « I » au niveau ferme et une majorité de « A » au niveau culture, illustrant bien l'intérêt d'une approche ferme pour ce type de ferme.

L'approche système a permis de comparer les fermes entre elles et de repérer les opérations ou intrants qui contribuent le plus aux impacts environnementaux (*hotspots)* au sein de chaque ferme. La phase d'interprétation est importante et doit être reliée aux informations acquises grâce aux échanges avec l'agriculteur. Par exemple, la contribution du diesel aux impacts de MF est principalement liée à l'irrigation, alors que pour SP et OP, elle est surtout liée aux tracteurs. De même, l'électricité de SP est utilisée pour l'irrigation alors que pour OP, elle l'est pour le frigo de stockage. Cette phase d'interprétation souligne la nécessité d'éclairer l'ACV, outil permettant d'appréhender quantitativement une situation complexe, par une compréhension qualitative du terrain.

Certains légumes peuvent avoir un impact plus important que d'autres, en raison de besoins spécifiques, d'un rendement plus faible et/ou de périodes de culture plus longues. L'approche système ne permet pas d'identifier ces légumes *hotspots*. Pour cela, Goglio et al. (2018) proposent des approches d'ACV produits tout en en relevant les nombreuses limites.

Cependant, cette approche produit n'est pas fidèle au fonctionnement et à la stratégie d'une ferme agroécologique. Le fonctionnement des fermes répond à une logique de gestion systémique, les pratiques et résultats pour un légume donné dépendent du reste de la ferme. Par exemple dans une ferme diversifiée, certains légumes sont plus importants commercialement (e.g. tomate, salade) que d'autres (e.g. navet), qui ne reçoivent pas la même attention. Donc comparer le navet d'une ferme diversifiée au navet d'un spécialiste de ce légume n'a pas grand sens. L'approche système correspond mieux à la logique de l'agroécologie, où beaucoup d'intrants sont raisonnés à l'échelle de la ferme et non à la culture, par exemple en fertilisant le sol plutôt que la culture (Gliessman, 2021), et où les cultures sont complémentaires les unes des autres. Par exemple, dans une approche ACV par produit, le tunnel de MF serait attribué aux légumes cultivés sous le tunnel et non à ceux cultivés en extérieur. Mais dans cette région, il serait difficile, voire impossible, de vivre d'une micro-ferme sans tunnel, ce qui signifie que les légumes de plein champ dépendent de la présence d'un tunnel. Ne pas leur attribuer une part d'impact du tunnel semble donc non conforme à la logique de la ferme.

Le cas de la ferme OP, qui inclut du seigle dans la rotation des légumes, soulève la question des fermes maraichères mixtes, ayant d'autres cultures ou de l'élevage en plus des légumes. Dans le cas d'OP, et dans le cadre de la comparaison entre systèmes maraichers, la production de seigle et les surfaces, intrants et opérations associés n'ont pas été inclus dans l'analyse. Cette dissociation a été facile, car les opérations étaient faites par une entreprise de travaux agricoles, donc n'utilisant pas les intrants de la ferme. Seuls les fertilisants ont dû être alloués entre les légumes et le seigle, sur une base surfacique. Si cette dissociation semble utile pour comparer les fermes maraichères, elle est discutable du point de vue agronomique. En effet, outre la fonction de production de seigle, la culture de cette céréale dans la rotation des légumes a pour fonction de casser les cycles des ravageurs et des maladies, affectant ainsi la (non-)utilisation d'intrants pour la production de légumes.

Des cas plus complexes de fermes mixtes sont nombreux. Dans l'échantillon enquêté dans le chapitre 2, 47% des fermes déclarent une activité de diversification. Pour les fermes de type 1 et 2 (petites et moyennes fermes diversifiées vendant en circuit court), nombreuses sont celles qui ont un atelier fruits (verger ou petits fruits) ou des volailles. Les fermes de type 4 (producteurs de plein-champ) ont souvent des cultures de céréales, et parfois des prairies et un élevage bovin, en plus des légumes. La présence d'animaux sur les parcelles recevant ensuite des légumes modifie la gestion de la fertilité. Cette diversité d'ateliers entretenant des liens fonctionnels forts est un nouveau défi que posent les systèmes complexes à l'ACV.

L'ACV système à l'échelle de la ferme pose la question des limites de la ferme. Les habitats semi-naturels font partie intégrante d'un système agroécologique, pour des fonctions de régulation et pour la préservation de la biodiversité des milieux agricoles. Dans le chapitre 4, nous avons montré que la définition des limites physiques du système influe beaucoup sur les impacts par hectare, sur le score de biodiversité et sur le rendement (ou l'occupation des terres). Pour les petites fermes, cette définition est d'autant plus importante que la proportion d'habitats semi-naturels peut être élevée, et donc avoir une grande influence. Cela pose également la question de la nature de ces milieux, notamment pour la notion de rendement et d'occupation des terres, car les habitats semi-naturels sont souvent des terres marginales ou difficilement cultivables.

1.4. Évaluation environnementale des fermes : modèles, allocation, impacts

1.4.1. Fertilisation organique et influence des méthodes

Les fertilisants sont pour la plupart issus de co-produits ou de déchets d'autres processus. Les fumiers, les lisiers, les poudres de plumes ou d'os, le sang séché sont issus d'élevages. Les déchets verts sont issus des espaces verts et des jardins des particuliers. Dans les travaux présentés dans cette thèse, suivant la méthodologie Agribalyse (Koch et Salou, 2020), la production de ces fertilisants, considérés comme des déchets, ne génère pas d'impacts. Tous les impacts sont attribués à la production du produit ou des co-produits, y compris les émissions générées par le stockage des fumiers et lisiers à la ferme. Les impacts liés à la mise à disposition (le transport à partir de la ferme d'élevage) et à la transformation en fertilisant applicable en agriculture sont quant à eux attribués au fertilisant, donc à la production végétale qui le reçoit. Cette transformation peut être un broyage, un compostage et/ou une transformation industrielle en pellets.

L'opération de compostage génère d'importantes émissions de gaz à effet de serre (N_2O et CH_4 principalement). Plusieurs études montrent que, sur des légumes sous serre non chauffée et en plein champ, le compost est le principal contributeur pour toutes les catégories d'impact considérées lorsque les émissions générées pendant le compostage sont entièrement allouées aux légumes (Bartzas et al., 2015; Martinez-Blanco et al., 2011). Alors que les émissions liées au stockage et à la maturation d'un fumier à la ferme sont portées par l'élevage, les émissions liées au compostage d'un déchet vert sont portées par les légumes. Cette différence mérite d'être questionnée et regardée plus précisément.

Les plateformes de compostage de déchets verts ont deux fonctions, elles traitent des déchets et produisent du compost. La fonction de traitement est généralement le moteur économique de la plateforme, ce qui est reflété dans le prix payé par le producteur de déchet plus élevé que le prix auquel est vendu le compost. Pour cette raison, nous avons effectué une allocation économique répartissant les impacts du compostage entre le producteur du déchet et l'utilisateur du compost, en respectant les rapports de masse entre les déchets entrants et le compost sortant. Ce type d'allocation est décrit dans Ekvall et Tillman (1997) et European Commission - Joint Research Centre (2010) et utilisé par Christensen et al. (2018) pour des composts similaires en production de légumes.

La multifonctionnalité du compostage peut également être approchée en pratiquant une extension du système (*system expansion*) avec substitution, c'est-à-dire en élargissant le système pour prendre en compte ces deux fonctions, puis en substituant la fonction secondaire par la soustraction d'un processus équivalent. Ainsi, certaines études considèrent que le compostage évite la production de fertilisant ou de support de culture, et soustraient la production d'une quantité équivalente d'engrais minéraux ou de tourbe (e.g. Boldrin et al., 2009; Brockmann et al., 2018). Pour Brockmann et al. (2018) et Hanserud et al. (2018), ce principe de substitution s'applique aussi pour les produits résiduaires organiques (PRO) d'origine animale (fumier, lisier). Ces études concluent à la grande influence de la méthode de substitution sur le résultat.

D’autres études considèrent que le compostage évite de traiter autrement les déchets compostés et soustraient l’impact de la mise en décharge de déchets organiques (e.g. Adewale et al., 2018; Martinez-Blanco et al., 2011). Dans le cas de tomate fertilisée avec du compost (Martinez-Blanco et al., 2011), considérer les impacts évités d’une mise de décharge des déchets aboutit à des émissions négatives (i.e. un stockage de carbone), de -267 et -134 g CO_2 eq./kg respectivement sous serre ou en plein champ, contre 289 et 183 g CO_2 eq./kg sans substitution. Dans cette approche, on ne considère pas d’impact évité pour les PRO d’origine animale.

Le choix de prendre en compte la multifonctionnalité du compostage de déchets et le choix de la méthode pour le faire (allocation ou extension du système + substitution, et choix de la substitution) influencent fortement les résultats. Ce sujet mérite d’être investigué tout particulièrement dans les systèmes dont la fertilisation repose sur le compost et les PRO d’origine animale. Il est intéressant de noter que certains courants, comme l’agriculture naturelle (Fukuoka et al., 1975) rejettent l’usage du compostage, lui préférant l’application de matière végétale non compostée. Les impacts liés au compostage industriel est sujet à débat (Fuchs, 2020).

Enfin certains auteurs plaident pour attribuer un impact à la production de PRO d’origine animale (Michiels et al., 2021), avec plusieurs méthodes possibles. Par une allocation massique ou économique, une partie des impacts de l’élevages sont attribué au PRO au prorata de sa masse ou de sa valeur. Les auteurs discutent plusieurs modes de calcul pour chaque type d’allocation conduisant à des résultats différents. Ils proposent aussi une extension de système, en remplaçant l’impact du PRO par celui d’un fertilisant à base de plante ou minéral, considérant une situation « comme si » l’agriculteur avait fertilisé avec un engrais minéral. Cette méthode, très différente de l’extension de système exposée ci-dessus, et selon moi contestable car remplaçant l’usage d’un engrais par un autre qui n’est pas réellement utilisé, conduit à des impacts sur le climat et l’eutrophisation marine beaucoup plus élevés.

Dans une vision d’ACV conséquentielle, une future extension de l’agriculture biologique augmentera la demande en fertilisants organiques, alors qu’une diminution des cheptels envisagée dans de nombreux scénarios prospectifs aurait pour conséquence d’en diminuer l’offre. Leur attribuer un impact de production permettrait de refléter cette tension.

En synthèse, vu la diversité des approches et des méthodes d’attribution d’un impact de leur production et des méthodes de prise en compte de la multifonctionnalité de leur traitement, les perspectives pour une approche harmonisée des fertilisants issus de déchets et sous-produits sont nombreuses et méritent d’être investiguées.

1.4.2. Estimation de émissions de nitrate et impact sur l'eutrophisation marine

Il existe de nombreux modèles pour calculer les pertes de NO_3 par lessivage, en fonction des types de cultures, des sols, des climats, allant de modèle simple comme les facteurs d'émission, à des modèles très complexes (Avadí et al., 2022). La plupart des modèles sont à appliquer à l'échelle d'une culture, et nécessitent des données sur celle-ci. Par exemple le modèle SQCB (Faist Emmenegger et al., 2009) utilisé dans la base de données Agribalyse (Koch et Salou, 2020) pour les légumes nécessite comme variable d'entrée la quantité d'azote appliquée incluant les résidus de culture, la quantité d'azote absorbée par la plante, la teneur en argile du sol et la quantité d'azote dans la matière organique du sol, les précipitations et l'arrosage, la profondeur des racines et le rendement.

Dans l'approche d'ACV système à l'échelle de la ferme mobilisée dans la thèse, nous avons privilégié une approche permettant d'appréhender la ferme dans son ensemble, sans entrer dans le détail des cultures. Le facteur d'émissions de l'IPCC (2019b) a donc été utilisé. Il s'appuie uniquement sur la quantité d'azote appliquée incluant les résidus de culture.

Le chapitre 4 discute l'importance de mieux estimer les pertes de NO_3 par lessivage, pour une meilleure évaluation de l'impact sur l'eutrophisation marine. En agriculture biologique, et particulièrement dans certaines formes de maraichage comme le maraichage sur sol vivant, les agriculteurs utilisent des fertilisants à minéralisation lente dans le but d'enrichir le sol en carbone et azote organique. Des engrais à minéralisation plus rapide sont également utilisés. La présence de tunnels, où le risque de lessivage est beaucoup plus faible (grâce à la protection contre les pluies), ajoute une situation différente. Le projet Agribalyse fruits et légumes (Grasselly et al., 2017) a estimé qu'il n'y a généralement pas de perte d'eau par drainage ou par lessivage sous un tunnel, et donc pas de lessivage de NO_3. SQCB a été utilisé pour les pertes de NO_3 dans la zone entre deux tunnels.

Parmi les perspectives pour améliorer l'estimation du lessivage de NO_3 pour les fermes étudiées dans cette thèse, les suivantes semblent les plus prometteuses, par le fait qu'elles restent à l'échelle de la ferme :

- Réaliser un bilan d'azote à l'échelle de la ferme en tenant compte de la séquestration d'azote dans le sol (Knudsen et al., 2019), et en calculant les exports par les légumes avec une teneur en azote moyenne, qui peut éventuellement être affinée par légume.
- Considérer des émissions nulles sous les tunnels, et garder le facteur d'émission d'IPCC pour le reste de la ferme
- Appliquer le modèle SQCB à l'échelle de la ferme, en considérant des valeurs moyennes ou en regroupant les légumes ayant des caractéristiques similaires.

Il serait intéressant d'explorer la sensibilité des résultats obtenu par ces différentes méthodes.

Les résidus de cultures et les cultures intermédiaires enfouies sont des sources d'azote qui contribuent au lessivage de NO_3 et aux émissions de N_2O au même titre que les engrais. Le volume des résidus et des cultures intermédiaires, et leur contenu en azote ont été estimés avec IPCC (2019b) à l'aide d'un coefficient générique pour tous les légumes, même si les résidus peuvent être très variables selon les légumes : de négligeable pour, par exemple, des radis bottes à bien plus important pour des légumes comme les choux ou les artichauts. Les émissions de N_2O issues des résidus et des cultures intermédiaires ont très peu contribué à l'impact changement climatique (1 à 2 % selon les fermes), améliorer leur estimation n'est pas une priorité. A l'inverse, le lessivage de NO_3 dû aux résidus et cultures intermédiaires a contribué significativement à l'impact eutrophisation marine, de 17 à 27 % selon les fermes. Pour mieux estimer les pertes de NO_3 par lessivage, l'estimation des volumes des résidus et des cultures intermédiaires, et leur contenu en azote, est un enjeu important. Une piste serait de regrouper les légumes ayant des résidus similaires et d'estimer leur volume. Les surfaces par légume sont généralement connues, la plupart des fermes disposant d'un fichier d'assolement, pouvant servir de base de calcul.

1.4.3. Consommation de plastique

Le choix de quantifier la consommation de plastique répond à une problématique environnementale émergente, mise en évidence, entre autres, par le concept des limites planétaires (Persson et al., 2022). Cela répond aussi aux préoccupations de nombreux maraichers bio, qui se tournent de plus en plus vers des alternatives biodégradables ou biosourcées. À ma connaissance, c'est la première fois qu'une évaluation environnementale d'un système agricole aborde ce thème. L'indicateur choisi, la masse de plastiques, est facile à mesurer du fait que les quantités de plastiques sont répertoriées dans les inventaires de cycles de vie (ICV) des fermes ou dans les ICV de matériel utilisé dans les fermes, comme les tunnels. Les résultats ont permis une distinction nette entre les fermes.

Notre indicateur intègre tous les types de plastiques et tous les types d'objets, qu'ils soient à usage unique (e.g. paillis, gaine de goutte à goutte) ou à longue durée de vie (e.g. tuyaux durs). Cela s'appuie sur le fait que tout plastique peut générer des microplastiques (United Nations Environment Programme, 2021b). Cependant, l'indicateur ne présume pas du devenir des plastiques sur la ferme, ni des voies de traitement en fin de vie, donc ce n'est pas un indicateur d'impact. Par ailleurs, il n'intègre pas le plastique consommé lors des processus en amont du système, ni les emballages (e.g. sac d'engrais ou de terreau), ni les produits contaminés involontairement par du plastique (par exemple, le compost). Ryberg et al. (2019) estiment que 9.1 % des microplastiques relargués dans l'environnement proviennent de l'application des boues issues du traitement des eaux. En France, l'application de ces boues (brutes ou compostées) est interdite en agriculture biologique et sur les cultures de légumes, mais elle est fréquente sur les autres cultures conventionnelles. Le devenir des plastiques agricoles, et la quantification de leurs flux, sont identifiés comme des perspectives de recherche importantes (Ryberg et al., 2019). Identifier les principales voies de contamination selon les sources et les types de plastique ouvrirait la voie à un indicateur d'impact utilisable en ACV (pas uniquement agricole), avec par exemple des facteurs d'émissions liés à la part de chaque type de plastique qui est estimée finir dans l'environnement. On peut imaginer des facteurs d'émission territorialisés selon les capacités et voies de traitement des pays.

Persson et al. (2022) utilisent les volumes de plastique produits comme l'une des variables de limite planétaire, c'est-à-dire un indicateur équivalent à celui que nous avons développé, tout en reconnaissant ses limites liées au fait qu'il ne représente pas les impacts finaux de pollution au plastique. Ils utilisent en complément un indicateur des quantités de plastique libérées dans l'environnement, plus proche de l'impact, mais dont les méthodes pour le calculer font à ce jour défaut. Cela renforce l'idée de l'intérêt d'un indicateur ACV reflétant la contamination de l'environnement (eaux douce et marine, sols) par les plastiques.

Quelques récentes études proposent des méthodes pour créer une nouvelle catégorie d'impact pour la pollution marine par les déchets plastiques, avec des facteurs d'émission différents selon les types de plastique (Lavoie et al., 2021; Saling et al., 2020; Woods et al., 2021).

1.5. Comparaison environnementale de trois fermes contrastées

L'ACV système à l'échelle de la ferme a permis d'évaluer chaque ferme avec une méthode homogène, ce qui permet la comparaison. Les trois unités fonctionnelles (UF) choisies permettent de considérer différentes fonctions de la ferme (produire en quantité, produire de la valeur, occuper la terre). Selon les UF et les catégories d'impact, aucune des fermes ne ressort clairement meilleure qu'une autre pour l'environnement. La ferme de plein-champ (OP) a les plus faibles impacts sur le changement climatique, en consommation d'énergie et en consommation de plastique, quelle que soit l'UF considérée, mais elle est moins bonne pour la biodiversité et pour le rendement, donc l'occupation des terres. Elle a le plus d'impact sur l'eutrophisation marine par kg et par €, mais ce résultat est peu fiable du fait d'une évaluation trop grossière de émissions de NO_3. La ferme spécialisée sous serre (SP) a les plus forts impacts par ha et par € pour le changement climatique, la consommation d'énergie et la consommation de plastique. Du fait de rendements plus élevés, elle a légèrement moins d'impact sur le climat par kg que la microferme (MF). Malgré ses rendements, la consommation énergétique par kg de SP est la plus élevée des trois fermes, liée à l'irrigation, la fabrication des tunnels, les plants produits en pépinière chauffée et la production de plastiques. Il en est de même pour la consommation de plastique par kg, plus élevée que pour les autres fermes. SP est la meilleure pour la biodiversité, grâce aux habitats semi-naturels constitués par les espaces enherbés entre les tunnels, et le rendement le plus élevé, donc l'occupation des terres la plus faible. MF ne se classe première que pour la consommation énergétique par € (à égalité avec OP), pour la biodiversité sur les parcelles cultivées, et pour la biodiversité à l'échelle de la ferme lorsque l'on inclut tous les habitats semi-naturels dans les limites de la ferme. A l'inverse, elle ne se classe dernière que pour le changement climatique par kg, légèrement derrière SP. Plus productive et plus intéressante pour la biodiversité qu'OP, et moins gourmande en énergie et en plastique que SP, elle pourrait être considérée comme un compromis intéressant.

L'index biotechnique basé sur les intrants, utilisé dans le chapitre 2 pour caractériser le degré d'agroécologie des fermes n'a pas inclus les infrastructures que sont les serres et tunnels. Les résultats montrant un impact majeur des tunnels dans les deux fermes cultivant sous abri, les inclure est nécessaire. Au sens de l'ACV, ils constituent bien des intrants du système (ISO, 2006a). Les insectes achetés pour le biocontrôle et la pollinisation sont un intrant identifié dans le chapitre 2, exclu de l'ACV par manque de données. Identifier l'impact de ces intrants est nécessaire pour une évaluation plus complète.

Bien que ces exploitations soient typiques de différents systèmes agricoles, les spécificités propres à chaque ferme ne peuvent être ignorées. Une généralisation des résultats demanderait une étude sur plus de cas d'études. Dans le chapitre 4, nous identifions quelques spécificités de chaque ferme au regard des informations fournies par la typologie. L'ACV système à l'échelle de la ferme étant relativement simple dans sa mise en œuvre, il serait intéressant de l'appliquer sur un nombre de fermes plus élevé, y compris des fermes diversifiées de taille moyenne (identifiée comme type 2 dans le chapitre 2), afin de monter en généricité.

Comparer des fermes ne revient pas nécessairement à les opposer pour voir « qui gagne », comme on me l'a souvent demandé lorsque j'expliquais mon sujet de thèse. Les fermes étudiées se distinguent par une production différente et complémentaire. OP et SP ne produisent pas les mêmes légumes : SP est spécialisé dans les légumes fruits d'été (tomate, courgette) et la salade, alors qu'OP cultive essentiellement des pommes de terre, des choux, des courges, des oignons et des légumes racine (carottes, panais, navet, etc.). MF couvre l'ensemble des légumes produits par OP et SP, dans des volumes moindres et destinés au marché de proximité. La complémentarité de ces créneaux de production est illustrée par le fait qu'OP soit membre d'un groupement d'intérêt économique, avec deux autres maraichers dont l'un cultive en grande partie sous tunnel, dans le but de diversifier l'offre commerciale.

L'analyse des fermes permet d'identifier leurs forces et faiblesses vis-à-vis de l'environnement. Cela peut servir de base à des démarches d'écoconception à l'échelle de la ferme, voire à l'élaboration de scénarios territoriaux (e.g. alimenter en légumes un territoire à partir de petites fermes locales). Il convient toutefois de garder à l'esprit que ce type d'analyse ne peut être qu'un point de départ à de telles démarches. En effet, la question « quel est l'impact environnemental d'une ferme ? » est différente de « faut-il promouvoir ce type de ferme ? », qui nécessite une approche conséquentielle[7] de l'ACV. Par exemple, favoriser OP plutôt que SP sur un territoire, à consommation constante, pourrait avoir pour conséquence d'importer les légumes d'été de l'étranger, générant des impacts liés au transport ou à des systèmes de production différents, comme le chauffage des serres en Europe du Nord ou la tension sur la ressource en eau en Europe du Sud et Afrique du Nord (Payen et al., 2015). Il serait intéressant pour un territoire et une demande alimentaire donnés, d'étudier quelles combinaisons de fermes, de production locale et d'importations, conduiraient au meilleur bilan environnemental.

L'évaluation environnementale réalisée dans la thèse a été « du berceau à la porte de sortie de la ferme ». Les fermes étudiées, et plus généralement les types de ferme identifiés dans le chapitre 2, commercialisent leur produit différemment (e.g. vente à la ferme, sur des marchés, en grande distribution). L'impact des voies de commercialisation jusqu'à la consommation finale des légumes est une perspective pour aller plus loin dans la comparaison des systèmes, d'autant que son impact n'est pas clairement établi dans la littérature. Markussen et al. (2014) évalue la phase de distribution d'une ferme en vente directe à 36 g CO_2 eq./kg de légumes diversifiés, correspondant à environ 8% de l'impact climat incluant la phase de production. Pour les mêmes légumes en circuit long (supermarché, 250 km de transport), l'impact de la distribution est de 109 g CO_2 eq./kg de légumes diversifiés soit environ 33% de l'impact climat incluant la phase de production. Variable selon les hypothèses, Pérez-Neira et Grollmus-Venegas (2018) ont estimé la distribution à 11-35 g CO_2 eq./kg pour des légumes biologiques en vente directe, soit 9-25% de l'impact climat incluant la phase de production, contre 96-128 g CO_2 eq./kg (dont 88 g d'emballage) pour des légumes conventionnels vendus en supermarchés locaux (42-47% de l'impact climat incluant la phase de production). Enfin, Majewski et al. (2020) a évalué différents circuits de distribution de produits alimentaires en Europe et trouve un impact sur le changement climatique de 70 g CO_2 eq./kg pour les ventes par internet, 330 g CO_2 eq./kg pour les ventes en marché et 970 g CO_2 eq./kg pour la vente à la ferme. Sur les circuits longs, l'impact est 240-

[7] La notion d'ACV conséquentielle est abordée dans le chapitre 1.

400 g CO_2 eq./kg selon le type de magasin. Ces impacts pour la phase de distribution sont supérieurs à l'impact de production des légumes des trois fermes étudiées. L'ampleur et la variabilité des résultats, parfois contradictoires, suggèrent que c'est un sujet à considérer pour enrichir la comparaison des systèmes, d'autant plus que les circuits courts semblent avoir une marge d'optimisation importante (Mundler et Rumpus, 2012).

Pour compléter l'évaluation des différents systèmes maraichers bio au-delà des impacts environnementaux, il serait intéressant de regarder la durabilité sociale et économique des fermes. La viabilité possible des microfermes a été montrée (Morel, 2016), en mettant en avant les aspirations sociales et de qualité de vie des porteurs de projets. Néanmoins les niveaux de revenu sont faibles, il serait intéressant de les comparer avec ceux des autres types de fermes.

Pour finir cette partie de la discussion, il est intéressant de comparer les impacts des légumes biologiques étudiés à des légumes produits en agriculture conventionnelle. Pour les impacts sur le changement climatique, le chapitre 4 (**Table 4.4**) n'établit pas clairement un mode de production de légumes moins impactant entre biologique et conventionnel, hormis les productions sous serre chauffées qui ont un impact plus élevé. Une comparaison entre légumes bio et conventionnel nécessiterait d'ajouter des catégories d'impacts sur la toxicité et l'éco-toxicité. Dans son scénario prospectif pour un régime sain et environnementalement durable, l'étude EAT-Lancet (Willett et al., 2019) accorde aux légumes une part importante, plus grande que la part actuelle. Les recommandations françaises pour une alimentation saine encouragent également une augmentation de la consommation de légumes (Ministère des solidarités et de la santé, 2019). Dans un contexte de croissance du marché de l'AB, où la consommation de légumes est appelée à augmenter, la question des performances environnementales du maraichage bio prend un intérêt plus marqué.

2. Conclusion générale

En s'intéressant aux performances environnementales des fermes maraichères bio, ma thèse a permis de traiter la question de la diversité des exploitations agricoles et de proposer une méthode pour la caractériser sous l'angle de leur relation à l'agroécologie. A partir de données issues d'une enquête auprès de 165 agriculteurs et agricultrices, j'ai montré que le secteur du maraichage bio en France n'est pas monolithique et ne peut être considéré comme un ensemble homogène en termes de pratiques et de structures. Sans pouvoir affirmer qu'un processus de bifurcation du maraichage biologique est à l'œuvre, du fait d'un manque de données sur la dynamique temporelle, j'ai montré que les pratiques et structures différencient d'un côté des fermes diversifiées, fortement agroécologiques, économes en intrants, plutôt de petite taille et vendant en circuit courts, et de l'autre des fermes spécialisées, reposant sur les intrants pour la majorité des pratiques clés de la ferme, produisant généralement sous abri. Pour autant, cette dichotomie est une simplification conceptuelle, de nombreuses fermes se trouvant entre ces deux pôles. Méthodologiquement, une enquête courte et qualitative a montré son intérêt pour caractériser les fermes et les positionner sur un cadre conceptuel sur leur relation aux pratiques agroécologiques.

Ma thèse a contribué à améliorer l'évaluation par l'ACV de fermes agroécologiques complexes, en tenant compte de leur dimension systémique. En utilisant un système expert que j'ai adapté aux cultures maraichères, j'ai montré l'importance des espaces semi-naturels, en complément de pratiques adaptées, pour la préservation de la biodiversité. La question des limites de la ferme s'est posée fortement par son influence sur les résultats de l'évaluation, notamment sur la biodiversité. Considérer des limites étendues permet de capter plus largement les fonctions non-productives, dans une approche multifonctionnelle de l'agroécologie. Poursuivre le développement d'un indicateur ACV pour la biodiversité, par exemple en combinant des méthodes globales et détaillée, est nécessaire.

L'approche système de l'ACV, qui aborde la ferme comme un tout produisant différents produits et où tous les intrants, opérations, et émissions sont estimés pour l'ensemble de la ferme et rapportés à la production annuelle totale, correspond à la logique de l'agroécologie, où beaucoup d'intrants sont raisonnés à l'échelle de la ferme et non à la culture, et où les cultures sont complémentaires les unes des autres. Préférée à une ACV par culture, l'approche système prend en compte les interactions qui ont lieu au sein du système, et permet de comparer des systèmes entre eux. D'un point de vue pratique, elle est adaptée au format des données souvent disponibles dans les fermes diversifiées et évite de recourir à des allocations, à éviter, si possible, selon la norme (ISO, 2006b).

La thèse a mis en évidence des perspectives de développement méthodologique pour l'ACV. L'estimation des flux de NO_3 par un facteur d'émission sur les apports totaux d'azote n'est pas adaptée à la diversité des fertilisants, une approche par bilan prenant en compte la dynamique du stock d'azote dans le sol et les spécificités des cultures sous abris est à étudier. Le maraichage agroécologique utilise des fertilisants organiques, issus de déchets animaux ou végétaux, bruts ou transformés. La production de ces fertilisants peut avoir un impact considérable, fortement variable selon la méthode de comptabilisation ce qui plaide pour la nécessité d'harmoniser les méthodes. L'indicateur de consommation de plastique a permis une analyse complémentaire des fermes, en répondant à un enjeu croissant. Face à la pollution des sols et des eaux aux microplastiques aujourd'hui largement reconnue, développer un indicateur ACV sur la pollution plastique est d'un intérêt majeur.

L'approche système de l'ACV a permis d'évaluer les impacts environnementaux de trois fermes contrastées, faisant apparaître de grandes différences entre les systèmes. Selon les fermes, les postes qui contribuent aux impacts sont les tunnels, l'énergie pour l'irrigation, les émissions au champ, le diesel des tracteurs, la production des plants en serre chauffée et le plastique. Avec l'utilisation de plusieurs catégories d'impact et unités fonctionnelles, aucune ferme ne ressort clairement meilleure qu'une autre pour l'environnement. Par ha, la ferme de plein champ, plus extensive, a le moins d'impact et la ferme spécialisée sous tunnel a le plus d'impact, quelle que soit la catégorie d'impact. En revanche, les différences par kg et par euro entre les trois fermes sont plus faibles.

L'intérêt de cette évaluation porte principalement sur l'analyse des forces et faiblesses des fermes vis-à-vis de l'environnement. La question de « qui gagne » n'est pas ici centrale, les fermes ayant des productions différentes et complémentaires. Alors que la thèse porte sur trois cas d'étude, une généralisation des résultats demanderait une évaluation sur de plus nombreux cas d'étude, ce que permet l'approche système de l'ACV à l'échelle de la ferme qui s'est révélée relativement efficace dans sa mise en œuvre.

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Annexes

Matériel supplémentaire du chapitre 2

Matériel supplémentaire 1. Formulaire de l'enquête pour caractériser la diversité des fermes

Étude sur les performances environnementales des fermes maraichères et légumières bio

*Obligatoire

Caractéristiques de la ferme

1. Année d'installation : *

2. Année de conversion bio : *

3. Dans quel département se trouve votre ferme ? (n°) *

4. Quelles certifications ou cahier des charges avez-vous, y compris marques privées ou régionales ?

   Plusieurs réponses possibles.

   - [ ] Certification AB (Ecocert, ...)
   - [ ] Biocohérence
   - [ ] Nature et Progrès
   - [ ] Biodynamie (Demeter...)
   - [ ] Global Gap
   - [ ] ISO 14001

   Autre : [ ] ____________

5. Quelle est la Surface Agricole Utile (SAU) de votre ferme ? (en hectare) *

6. Quelle est la surface cultivée en légumes ? (passe-pieds inclus) *

7. Quelle surface de légumes cultivez-vous en plein champ ? (en hectare) *

8. Quelle surface cultivez-vous sous abri froid ? (en hectare ou m²) *

9. Quelle surface cultivez-vous en serres chauffées ? (en hectare ou m²) *

10. Quelles autres productions avez-vous, si vous en avez ? (autre que légumes) *

11. Toutes vos surfaces sont-elles en bio ? *

Une seule réponse possible.

- Oui *Passer à la question 13*
- Non *Passer à la question 12*

Surfaces en bio

12. Quelle surface en légumes bio ? *

Le travail

13. Combien êtes-vous de travailleurs familiaux ou associés (non salariés) ? *

(en équivalent temps plein)

14. Combien employez-vous de salariés permanents ? *

(en équivalent temps plein)

15. Combien employez-vous de salariés saisonniers au maximum du pic de travail ? *

(un saisonnier compte pour 1, peu importe la durée de son travail)

16. Combien de tracteurs possédez-vous ? *

Modes de production et pratiques culturales

17. Combien de légumes différents produisez-vous ? (s'il y en a beaucoup, un ordre de grandeur suffit) *

On compte ici les types de légumes au sens "grand public". Par exemple, chou-fleur et chou vert sont 2 légumes différents; idem pour haricot vert et haricots secs. On ne distingue pas les variétés : par exemple oignon jaune et oignon rouge comptent pour 1. Les salades (laitue, batavia, etc.) comptent pour 1.

18. Quels sont les principaux légumes ? *

si vous êtes très diversifié, indiquez "diversifié"

19. Parmi les engrais suivants, lesquels utilisez-vous de façon principale ? secondaire ? jamais ? *

Une seule réponse possible par ligne.

	Principale	Secondaire	Jamais
Engrais de ferme (origine animale) auto-produit ou produit localement (fumier, lisier...)			
Engrais organique du commerce			
Compost auto-produit			
Compost du commerce			
Engrais verts			

20. Si vous voulez apporter des précisions (marque de l'engrais, type de fumier, tonnages...), ou si la liste d'engrais ne vous correspond pas, c'est ici !

21. Quel type de travail du sol effectuez-vous ? *

Une seule réponse possible par ligne.

	Toutes les surfaces ou presque (entre 75% et 100%)	Une partie des surfaces (entre 25% et 75%)	Une faible partie des surfaces (moins de 25%)	Jamais
Labour (travail du sol avec retournement)	◯	◯	◯	◯
Décompactage (travail profond, sans retournement)	◯	◯	◯	◯
Travail du sol superficiel (outils à griffes)	◯	◯	◯	◯
Pas de travail du sol	◯	◯	◯	◯

22. Le travail du sol est essentiellement :

Une seule réponse possible par ligne.

	Tracteur	Motoculteur	Traction animale	Manuel	Non concerné
Plein champ	◯	◯	◯	◯	◯
Sous abri	◯	◯	◯	◯	◯

23. Si vous voulez apporter des précisions sur le travail du sol, ou si les propositions ne vous correspondent pas, c'est ici !

24. Parmi les stratégies de lutte contre les adventices suivantes, lesquelles utilisez-vous de façon principale ? secondaire ? jamais ? *

Une seule réponse possible par ligne.

	Principale	Secondaire	Jamais
Paillage plastique (bâche noire)	◯	◯	◯
Paillage bâche tissée	◯	◯	◯
Bâche biodégradable	◯	◯	◯
Occultation (bâche) entre 2 mises en culture	◯	◯	◯
Paillage végétal (mulch)	◯	◯	◯
Désherbage manuel (binage, sarclage...)	◯	◯	◯
Désherbage mécanique (herse étrille, bineuse tractée...)	◯	◯	◯
Faux semis, travail du sol	◯	◯	◯
Vapeur ou brulage	◯	◯	◯
Solarisation (élévation de la température en recouvrant le sol d'un film plastique transparent)	◯	◯	◯

25. Si vous voulez apporter des précisions sur le désherbage, ou si les propositions ne vous correspondent pas, c'est ici !

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26. Parmi les stratégies suivantes de lutte contre les ravageurs et maladies, lesquelles utilisez-vous de façon principale ? secondaire ? jamais ? *
Une seule réponse possible par ligne.

	Principale	Secondaire	Jamais
Cuivre			
Soufre			
Produits de bio-contrôle (Bt, phéromones, micro-organismes...)			
Lâchers de prédateurs des ravageurs			
S'appuyer sur la biodiversité environnante			
Association de cultures			
Plantes de service (répulsion, plantes pièges...)			
PNPP (purins, décoctions végétales...)			

27. Si vous voulez apporter des précisions sur les méthodes de lutte, ou si les propositions ne vous correspondent pas, c'est ici !

28. Certains producteurs laissent volontairement ou entretiennent des espaces dans le but de favoriser la biodiversité (haies, jachères, prairies extensives, mares, plantes à fleur, etc.). Dans votre ferme, cette démarche est : * *Une seule réponse possible.*

- centrale, c'est au coeur du système de production
- importante, vous y consacrez du temps et de l'espace
- peu importante, vous y pensez sans y consacrer beaucoup de temps ni d'espace
- mineure

29. Si vous voulez apporter des précisions sur les espaces pour la biodiversité, c'est ici !

30. Gestion des semences et plants

Une seule réponse possible.

- Vous produisez vos propres semences et plants (au moins en partie)
- Vous produisez vos propres plants (au moins en partie) à partir de semences achetées
- Vous achetez vos semences et plants produits localement
- Vous achetez vos semences et plants à une grande entreprise

31. Si vous voulez apporter des précisions sur les semences et plants, c'est ici !

32. Quelles pratiques ou modes de culture correspondent à votre ferme ? *

Une seule réponse possible par ligne.

	Correspond bien	Correspond plutôt bien	Ne correspond pas
Une seule culture par parcelle ou par tunnel			
Plusieurs cultures sur une même parcelle ou dans un même tunnel			
Associations de cultures (recherche d'interactions)			
Agricultures "alternatives" (Permaculture et autres courants)			
Agroforesterie ou Verger maraîcher			
Maraichage sur Sol Vivant (MSV)			

33. Si vous voulez apporter des précisions sur vos modes de cultures, c'est ici !

Commercialisation

34. Utilisez-vous ces voies de commercialisation de façon : principale ? secondaire ? jamais utilisées ? *

Une seule réponse possible par ligne.

	Principale	Secondaire	Jamais
Vente directe (marché, paniers...)			
Autre circuits courts (1 intermédiaire)			
Grossiste ou expéditeur			
Autres circuits longs (au moins 2 intermédiaires)			
Coopérative			

35. Vos produits sont commercialisés : *

Plusieurs réponses possibles.

- [ ] Dans le département
- [ ] Dans la
- [ ] région En
- [ ] France à

l'étranger

36. Si vous voulez apporter des précisions, ou si les propositions ne vous correspondent pas, c'est ici !

37. Quel est le chiffre d'affaires de votre ferme ? *

Une seule réponse possible.

- <30 000€ entre 30 000 et
- 60 000 € entre 60 000 et
- 100 000 € entre 100 000 et
- 300 000 € entre 300 000 et
- 500 000 € entre 500 000 et
- 1 000 000 €
- > 1 000 000 €

Contact

38. Nom de la ferme

39. Votre nom / prénom

40. Êtes-vous intéressés par les résultats de l'étude ? (si oui, pensez à indiquer votre e-mail ci-dessous) *

Une seule réponse possible.

- Oui
- Non

41. Votre e-mail

42. Votre n° de téléphone

43. M'autorisez-vous à vous recontacter pour la suite de l'étude ? (sans aucun engagement) *

Une seule réponse possible.

- Oui
- Non

Vous pouvez m'aider encore plus en transmettant le questionnaire à d'autres producteurs bio, le bouche à oreilles est toujours le plus efficace.

Merci infiniment pour vos réponses !

N'oubliez pas de cliquer sur "envoyer" ci-dessous !

Matériel supplémentaire du chapitre 3

Table S1. List of the experts interviewed with their institution and field of expertise.

Surname	Name	Institution	Field of expertise
Baudry	Jacques	INRAE - Institut national de recherche pour l'agriculture, l'alimentation et l'environnement, France	Landscape ecology, biodiversity
Bianchi	Felix	WUR - Wageningen University and Research, The Netherlands	All the ISGs, specific focus on natural enemy interactions, pollinators
Birkhofer	Klaus	Brandenburg University of Technology Cottbus, Germany	Spiders
Bonthoux	Sébastian	INSA - Institut National des Sciences Appliquées Centre Val de Loire, France	Birds
Chauvel	Bruno	INRAE - Institut national de recherche pour l'agriculture, l'alimentation et l'environnement, France	Crop flora, grassland flora
Entling	Martin	Universität Koblenz-Landau, Germany	Spiders
Faloya	Vincent	INRAE - Institut national de recherche pour l'agriculture, l'alimentation et l’environnement ; IGEPP - Institute for Genetics, Environment and Plant Protection, France	Spiders, carabids, butterflies, bees and bumble bees, grasshoppers, biocontrol, VPSs
Jeavons	Emma	University of Rennes 1, France	Spiders, carabids, butterflies, bees and bumble bees, grasshoppers, biocontrol
Le Lann	Cécile	University of Rennes 1, France	Spiders, carabids, butterflies, bees and bumble bees, grasshoppers, biocontrol
Le Ralec	Anne	Institut Agro Rennes-Angers, France	Spiders, carabids, butterflies, bees and bumble bees, grasshoppers, biocontrol, VPSs
Nicolai	Annegret	University of Rennes 1, France	Snails and slugs
Pétillon	Julien	University of Rennes 1, France	Spiders
Plantegenest	Manuel	Institut Agro Rennes-Angers, France	Carabids
Roume	Anthony	ISARA - Lyon, France	Crop flora, grassland flora, epigeous fauna, carabids, biocontrol
Rusch	Adrien	INRAE - Institut national de recherche pour l'agriculture, l'alimentation et l'environnement	Spiders

Table S2. Characteristics of the vegetables used for the multiple component analysis.

Vegetable	Height	Coverage	Duration	Flowers
Shallots	Medium	Low_coverage	Short	No
Fresh onion	Medium	Low_coverage	Short	No
Onion	Medium	Low_coverage	Short	No
Leek	Medium	Low_coverage	Long	No
Garlic	Medium	Low_coverage	Long	No
Head cabbage (e.g.: Brussels sprouts, Savoy cabbage)	Medium	High_coverage	Short	No
Leafy cabbage (e.g.: kale)	Medium	High_coverage	Short	No
Cauliflower, broccoli	Medium	High_coverage	Short	No
Cabbage miscellaneous	Medium	High_coverage	Short	No
Annual aromatic herbs	Low	High_coverage	Short	No
Squash	Low	High_coverage	Short	Yes
Melons	Low	High_coverage	Short	Yes
Watermelon	Low	High_coverage	Short	Yes
Courgette	Medium	High_coverage	Long	Yes
Lamb's lettuce	Low	Medium_coverage	Short	No
Spinach	Low	Medium_coverage	Short	No
Radish (bunch)	Medium	Medium_coverage	Short	No
Beetroot	Medium	Medium_coverage	Short	No
Swiss chard	Medium	Medium_coverage	Short	No
Carrot	Medium	Medium_coverage	Long	No
Celery	Medium	Medium_coverage	Long	No
Celeriac	Medium	Medium_coverage	Long	No
Salad	Low	Medium_coverage	Short	No
Mixed leaves	Low	Medium_coverage	Short	No
Endive	Low	Medium_coverage	Short	No
Fennel	Medium	Medium_coverage	Short	No
Turnip	Low	Medium_coverage	Short	No
Parsnip	Medium	Medium_coverage	Short	No
Winter radish	Medium	Medium_coverage	Short	No
Cucumber	Medium	Medium_coverage	Short	Yes
Bean	Medium	Medium_coverage	Short	Yes
Early potato	Low	Medium_coverage	Short	Yes
Edible flowers	Medium	Medium_coverage	Short	Yes
Eggplant	High	High_coverage	Long	Yes
Fava bean	High	Medium_coverage	Long	Yes
Pea	High	Medium_coverage	Long	Yes
Bell pepper	High	Medium_coverage	Long	Yes
Potato	Medium	Medium_coverage	Long	Yes
Tomato	High	Medium_coverage	Long	Yes
Sweet potato	Medium	Medium_coverage	Long	Yes

Matériel supplémentaire du chapitre 4

Table S3 – Emissions sources, equations or emission factors (EF) used and reference.

Pollutant/source	Equation/emission factor		Reference
NH_3 (kg NH_3)	= quantity of fertiliser (t DM [a]) x N-NH4 (kg N-NH_4 / t DM) x EF [b] x 17/14		
	Poultry manure	N-NH4 = 3.2 kg N-NH_4 / t DM EF = 0.45	Avadí and Paillat, 2020 EMEP, 2019 Tier 2
	Cow manure	N-NH4 = 0.9 kg N-NH_4 / t DM EF = 0.68	Avadí and Paillat, 2020 EMEP, 2019 Tier 2
	Compost of green waste	N-NH4 = 0.05 kg N-NH_4 / t DM EF = 0.81	Compost producer Koch and Salou, 2020
	Composted cow manure	N-NH4 = 0.6 kg N-NH_4 / t DM EF = 0.68	Avadí and Paillat, 2020 EMEP, 2019 Tier 2
	Shredded green waste	N-NH4 = 0.135 kg N-NH_4 / t DM EF = 0.81	Koch and Salou, 2020 Koch and Salou, 2020
	Bochevo	N-NH4 = 1.5 kg N-NH_4 / t DM EF = 0.81	Koch and Salou, 2020 Koch and Salou, 2020
	Humi-activ	N-NH4 = 1 kg N-NH_4 / t DM EF = 0.81	Koch and Salou, 2020 Koch and Salou, 2020
	Castor oil meal	N-NH4 = 2.6 kg N-NH_4 / t DM EF = 0.81	Koch and Salou, 2020 Koch and Salou, 2020
	AB'Flor	N-NH4 = 2.5 kg N-NH_4 / t DM EF = 0.81	Koch and Salou, 2020 Koch and Salou, 2020
	Beet vinasse	N-NH4 = 0.96 kg N-NH_4 / t DM EF = 0.81	Koch and Salou, 2020 Koch and Salou, 2020
NO (kg NO)	= EF x [∑(quantity of fertiliser (t DM) x N (kg N / t DM)) - NH3 emissions (kg NH_3) x 14/17]		
	All fertilisers	EF = 0.04 kg NO / kg of fertiliser and manure N applied	EMEP, 2019b Tier 1
Direct N_2O (kg N_2O)	= EF x ∑(quantity of fertiliser (t DM) x N (kg N / t DM) + N in crop residues and catch crops residues) x 44/28		
		EF = 0.006 kg N_2O–N / kg N	IPCC, 2019 Tier 1
Indirect N_2O (kg N_2O)	N_2O from atmospheric deposition of N volatilised from managed soils = 44/28 x EF x (14/17 x NH_3 + 14/30 x NO)		
		EF = 0.014 kg N2O–N / (kg NH3–N + NOX–N volatilised)	IPCC, 2019 Tier 1
	N_2O from N leaching/runoff from managed soils = 44/28 x EF x 14/62 x NO_3		
		EF = 0.011 kg N2O–N / kg N leaching/runoff	IPCC, 2019 Tier 1
NO_3 (kg NO_3)	= (quantity of fertiliser N (kg N) + quantity of N in crop residues (kg N)) x $Frac_{LEACH}$ (kg N / kg N additions)		
		$Frac_{LEACH}$ = 0.24 kg N / kg N additions	IPCC, 2019 Tier 1
CO_2 (kg CO_2)	= quantity of lime (kg) x EF x 44/12		
		EF = 0.12 kg CO_2 / kg	IPCC, 2006 Tier 1

[a] t DM: ton of dry matter

[b] NH_3: EFs are given as a proportion of total ammoniacal nitrogen.

Article de données issu du chapitre 2

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Article Title

Data on structure and farming practices of French organic vegetable farms, with focus on the use of inputs and the socio-economic context

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Abstract

Organic vegetable farming systems in France have diverse farm structures, farming practices and socio-economic contexts. From April-July 2019, Pépin et.al. [1] surveyed 165 farms using an online form. The questions about farming practices or socio-economic context did not require quantitative responses to make them simple and easy to answer. From a list of practices, farmers were asked which one(s) they used most often. Using decision rules, the answers were transformed into variables that are suitable for multivariate analysis. The data set also contains analysed data, including composite indexes derived from survey answers, as well as the number of the cluster to which each farm belonged, created after multivariate analysis and clustering performed on the data set.

Keywords

Organic farming; vegetable farms; farming diversity; farming practice; agroecology; multivariate analysis

Specifications Table

Subject	Agricultural Sciences
Specific subject area	Organic vegetable production systems, Agroecology
Type of data	Table
How data were acquired	Online survey
Data format	Raw and analysed data
Parameters for data collection	The survey included only farms that produced organic vegetables for the fresh market as their main production. We focussed our survey on two contrasting regions of France: the north-west (Brittany, Normandy, Pays de la Loire) and south-east (Provence-Alpes-Côte-d'Azur, Languedoc-Roussillon). Because of word-of-mouth communication, however, some farmers in other regions answered the survey.
Description of data collection	Data were collected using an online survey, made with Google Forms, sent to farmers from April-July 2019. The online survey was disseminated to the farmers through several networks – specialised in organic farming or not – including local agricultural development organisations and commercial organisations, to capture as many farm types as possible. Follow-up e-mails and phone calls were made regularly based on the responses collected, to ensure that sampling was as complete as possible.
Data source location	Country: France
Data accessibility	Raw and analysed data are deposited in a public repository Repository name: INRAE dataverse (https://data.inrae.fr/) Data identification number: 10.15454/YAXXYH Direct URL to data: https://doi.org/10.15454/YAXXYH
Related research article	A. Pépin, K. Morel, H.M.G. van der Werf, Conventionalised vs. agroecological practices on organic vegetable farms: investigating the influence of farm structure in a bifurcation perspective, Agricultural Systems. In press.

Value of the Data

- The data set contains information on farming practices, with focus on the use of inputs and socio-economic issues in organic vegetable production, as well as farm and farmer characteristics.
- The data set can be used by other researchers who work on organic practices in vegetable farming from an agro-ecological perspective.
- These data can be used for future research on the relation between farm structure, farming practices in organic vegetable production and socio-economic elements.
- This data set includes data from 165 farms which represent a diverse sample.

1. Data Description

The data reported in this data paper derive from a survey of farm structure, farming practices and socio-economic context conducted in France based on 165 organic vegetable farms. The data set is composed of 1 text document, 3 PDF documents and 6 Excel files that contain raw or analysed data (Table 1). It includes the survey form, the answers as raw data and analysed data. Pépin et al. [1] provide details about the method used to analyse data. Answers that were open-ended or contained personal data (e.g. name, e-mail, phone number) were excluded from the answer files.

Table 1. Contents of the data set.

File name	Description
A0_README_description_of_files.txt	Description of the files provided in the archive
A1_Codebook_Variable_information.csv	Table that presents the variables and their short names, full names, type (quantitative or categorical), units, possible values and details
A2_Codebook_Categorical_Variable_values.csv	Table that provides details about and explains the possible values taken by categorical values
B1_Survey_form_Fr.pdf	Original survey form created with Google Forms (in French)
B2_Survey_form_Eng.pdf	Survey form created with Google Forms, translated to English
C1_Survey_answers_Fr.csv	Original survey answers (in French)
C2_Survey_answers_Eng.csv	Survey answers, translated to English
D_Decision_rules.pdf	Document explaining how the survey answers were transformed into variables in the data set
E_Dataset.csv	Data set created based on the survey answers
F_Composite_indexes.csv	Data set with the values of the composite indexes calculated according to Pépin et al. [1]

The results of the multivariate analysis conducted on the data set are presented in table 2 and figures 1-3. It includes coordinates of the variables on the six principal components retained for the clustering, the correlation circle for the quantitative variables and the representation of the categories of the categorical variables on the first two principal components, and the associations between quantitative and categorical variables.

2. Experimental Design, Materials and Methods

Data were collected using an online survey sent to farmers from April-July 2019. The survey was carried out in two French regions with contrasting types of vegetable production: the north-west (Brittany, Normandy, Pays de la Loire) and south-east (Provence-Alpes-Côte-d'Azur, Languedoc-Roussillon).

The survey targeted farms that produced organic vegetables for the fresh market as their main production. The online survey, designed using Google Forms, was disseminated to farmers through several networks, including local agricultural development organisations and commercial organisations. Farmers completed 174 surveys, 165 of which were sufficiently complete to be included in the data set. In particular, we excluded six farms created in 2019 (i.e. less than one year of experience) and three farms that were not professional farms. Most farmers who answered the survey were located in the two targeted regions, but because of word-of-mouth communication, some farmers in other regions answered it.

The survey's questions focussed on farm structure, farming practices and socio-economic issues. The questions were divided into six categories:

- Farm history and geography
  - Farm age
  - Years since the farm was labelled "organic"
  - Location (administrative department)
- Land
  - Utilised agricultural area including non-cultivated areas
  - Area cultivated in vegetables, whether outdoors or sheltered (high plastic tunnels or multi-span greenhouses)
- Human and mechanical labour resources
  - Number of people working permanently or temporarily (labour)
  - Number of tractors
- Production
  - Number of different vegetables grown: farmers were asked to count the types of vegetables distinguished by consumers and marketing, regardless of their botanical species [2]. For example, cauliflower and kale are two different vegetables, as are green beans and dried beans. No distinction was made between varieties. Lettuce (e.g. Batavia, oakleaf) counted as one vegetable type. Potatoes and strawberries were considered vegetables.
  - Other types of production besides vegetables
- Farming practices
  - Type of tillage and tools used
  - Main practices to manage soil fertility
  - Main practices to control weeds
  - Main practices to control pests and diseases
  - Actions to protect or promote local biodiversity
  - Origin of seeds and seedlings
- Economy and selling strategy
  - Marketing supply chains
  - Destination of the vegetables sold (from local to export markets)
  - Annual revenue

As detailed online surveys that take too much time to fill out may deter the people targeted, the questions about farming practices or socio-economic context did not require quantitative responses, in order to make them easier to answer. In most cases, farmers were asked multiple-choice questions about which practices they used most often.

The answers were transformed into variables according to decision rules, as explained in *Decision_rules.pdf*. Missing answers were imputed using regularised iterative algorithms [1]. The variables and imputed values are available in *Dataset.csv*. The variables are suitable for statistical analyses such as multivariate analyses.

A subset of variables was transformed into normalised primary indicators. An additive combination of these indicators was calculated, which yielded composite indexes [1]. The values of these indicators and indexes for each farm are shown in *Composite_indexes.csv*.

Based on the data set, a farm typology was developed using Factor Analysis of Mixed Data and agglomerative hierarchical clustering (AHC) [1]. The resulting farm clusters are shown in *Composite_indexes.csv* and described by Pépin et al. [1]. Table 2 provides coordinates of the variables on the six principal components retained for the AHC.

Figures 1 and 2 respectively represent the correlation circle for the quantitative variables and the categories of the categorical variables on the first two principal components. Figure 3 represents the associations between quantitative and categorical variables.

Table 2. Coordinates of the variables on the six principal components

Variable	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5	Dim.6
Years	0,4744189560	0,0002729537	0,0000089979	0,0055371181	0,0171702803	0,0484797620
Total_Area	0,4816120530	0,1951894910	0,0212584800	0,0000214685	0,0064296329	0,0016749360
Area_Field	0,4832810650	0,2516595948	0,0019664960	0,0025306635	0,0084659622	0,0266581040
Area_Sheltered	0,3640788340	0,2482546602	0,0856935000	0,0606381536	0,0008848295	0,0012093140
Manpower_FTE	0,6603791330	0,0120947450	0,0000826780	0,0615448804	0,0071853753	0,0155653500
Tractors	0,7219243690	0,0714604090	0,0204398900	0,0178606686	0,0026845719	0,0094871850
Ratio_Shelter_Field	0,0297155540	0,4469441867	0,1289005000	0,0187018880	0,0119505998	0,0008926270
Nb_Veg	0,2262670220	0,0241374533	0,2128739000	0,0108485159	0,0117312376	0,0205301750
Diversification	0,0090462030	0,0299649219	0,0009783325	0,0170704049	0,0030599415	0,2846180570
Fertilization	0,0191671450	0,3431179387	0,0283827600	0,0193806616	0,1888816132	0,0261087680
Tillage	0,2696908290	0,1371368889	0,4099002000	0,0512841738	0,1201344743	0,1305419100
Weeding	0,1364180930	0,0874620224	0,3041534000	0,3033157781	0,0692559995	0,0702891130
Pests_Diseases	0,2313476070	0,0991839132	0,0870709400	0,2884497764	0,1037189664	0,0771766340
Seeds_Seedlings	0,2111297320	0,1064088337	0,0780870600	0,0868591718	0,2238424723	0,1048908640
Food_Supply_Chain	0,4973274600	0,0604273794	0,2077630000	0,1879828808	0,3752937908	0,1597672070

Sales	0,7813459380	0,2424041787	0,3375564000	0,4108268194	0,2803084414	0,3520761180
Conv_Organic	0,2384361720	0,0490676290	0,0403923500	0,0017559832	0,0184547693	0,0409591350

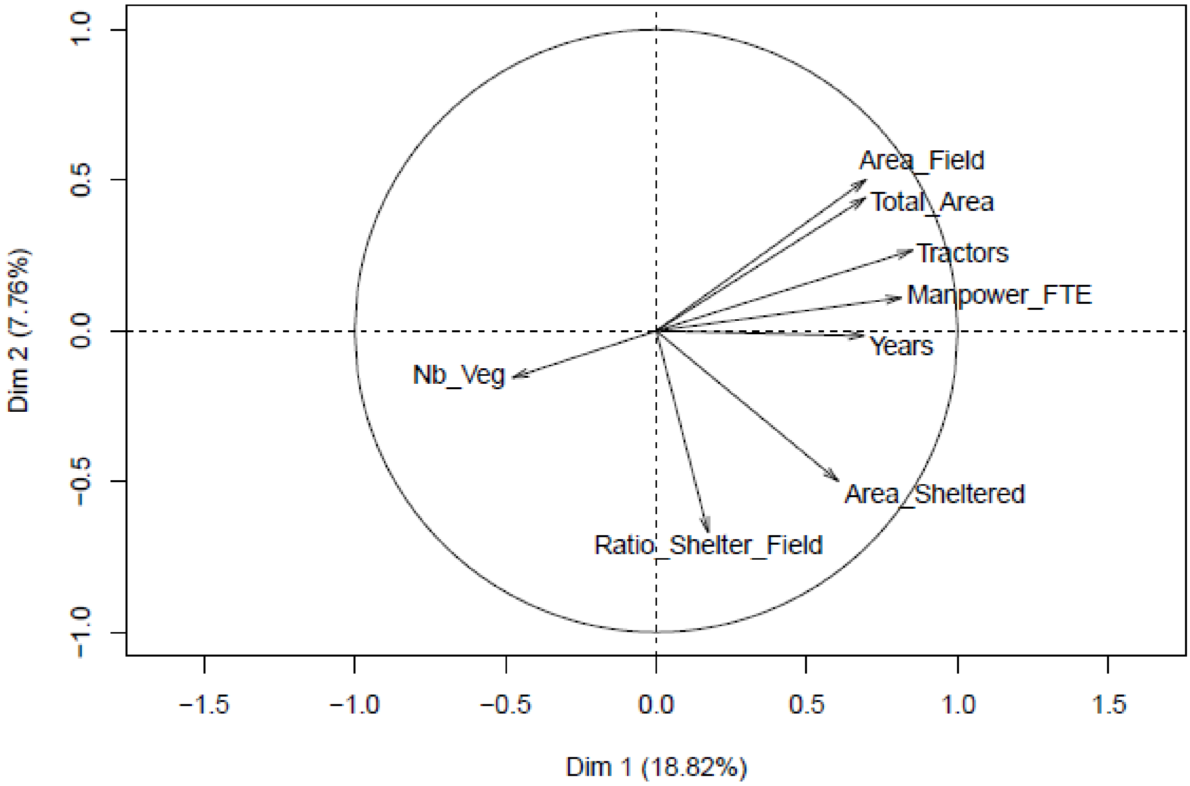

Figure 1. Correlation circle for the quantitative variables on the first two principal components

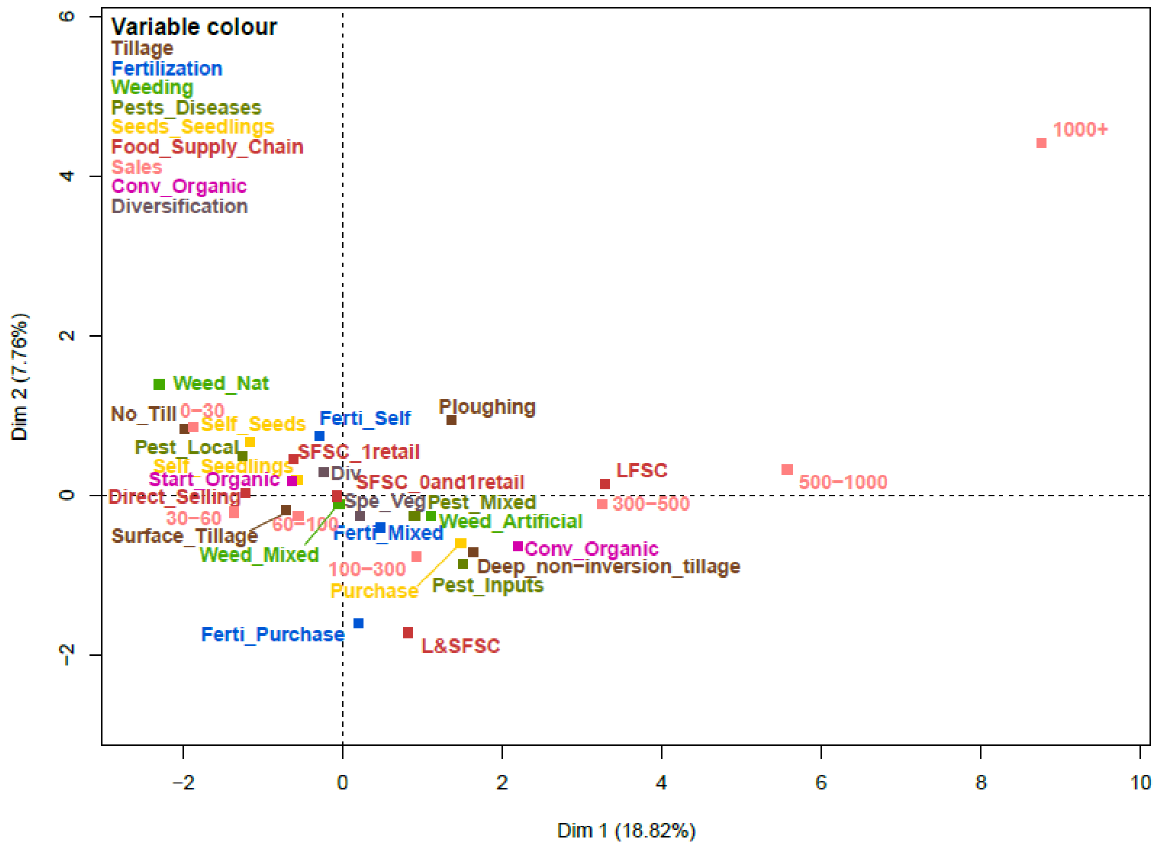

Figure 2. Representation of the categories of the categorical variables on the first two principal components

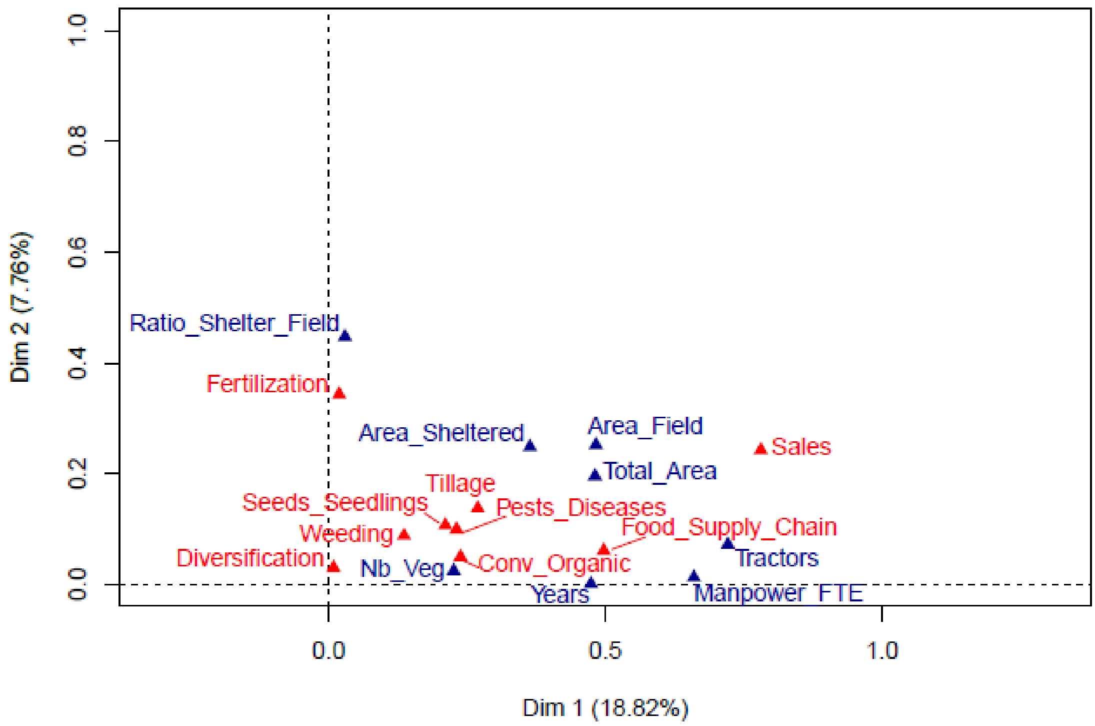

Figure 3. Associations between quantitative (blue) and categorical (red) variables on the first two principal components

Ethics Statement

All data were analysed anonymously. The farmers participated in the survey voluntarily and have agreed in writing to publication of the anonymised survey data for research purposes.

CRediT author statement

Antonin Pépin: Conceptualization, Methodology, Software, Writing- Original draft preparation. **Kevin Morel**: Conceptualization, Writing- Reviewing and Editing. **Hayo van der Werf:** Conceptualization, Writing- Reviewing and Editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

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DOCTORAT / ECOLOGIE
BRETAGNE \ GEOSCIENCES
LOIRE / AGRONOMIE ALIMENTATION

Titre : Performance environnementale de fermes maraîchères en agriculture biologique

Mots clés : analyse du cycle de vie, agroécologie, maraichage, agriculture biologique, biodiversité, diversité agricole

Résumé : Les fermes maraîchères biologiques françaises sont diverses, allant de systèmes complexes agroécologiques reposant sur la biodiversité et produisant de nombreux légumes différents, à des systèmes simples reposant sur les intrants et produisant peu de légumes différents, ce qui suggère des impacts sur l'environnement différents. L'objectif de la thèse est d'évaluer les performances environnementales de fermes maraîchères biologiques contrastées, au moyen de l'analyse de cycle de vie (ACV). La thèse s'organise autour de : (1) la caractérisation de la diversité des fermes maraîchères biologiques, en mobilisant une typologie réalisée à partir d'enquêtes, et un cadre d'analyse de la diversité des formes d'agriculture ; (2) l'adaptation d'une méthode d'évaluation de la biodiversité au contexte du maraichage ; (3) l'évaluation de trois fermes contrastées par une approche « système » de l'ACV, abordant la ferme comme un tout et où tous les intrants, opérations, et émissions sont rapportés à la production annuelle totale. L'analyse des impacts, exprimés par kg de légume, ha de ferme et Euro de valeur, sur le changement climatique, sur l'eutrophisation marine, sur la biodiversité, la demande cumulative en énergie et l'usage de plastique, fait apparaître de grandes différences entre les systèmes dans leurs principaux postes d'impact, mais ne permet pas d'obtenir un classement clair entre les trois fermes. L'approche « système » de l'ACV correspond au fonctionnement agroécologique et apporte une réponse au défi posé par la complexité de certaines fermes maraichères. L'indicateur d'utilisation de plastique apporte un éclairage nouveau sur une préoccupation croissante.

Title: Environmental performance of organic vegetable farms

Keywords: life cycle assessment, agroecology, horticulture, organic farming, biodiversity, farming diversity

Abstract: French organic vegetable farms are diverse, ranging from complex agroecological systems based on biodiversity and producing many different vegetables, to simple systems based on inputs and producing few different vegetables, suggesting different environmental impacts. The objective of the thesis is to assess the environmental performance of contrasting organic vegetable farms, using life cycle assessment (LCA). The thesis is organised as follows: (1) the characterisation of the diversity of organic vegetable farms, using a typology based on surveys and a framework for analysing farming system diversity; (2) the adaptation of a biodiversity assessment method to vegetable farming; (3) the assessment of three contrasting farms using a LCA "system" approach, considering the farm as a whole and in which all inputs, operations and emissions are related to the total annual production. The analysis of the impacts, expressed per kg of vegetable, ha of farmland and economic value expressed in Euro, on climate change, marine eutrophication, biodiversity, cumulative energy demand and plastic use, revealed large differences between the systems for their main impact contributors, but did not allow a clear ranking of the three farms. The LCA "system" approach corresponds to the agroecological functioning and addresses the challenge posed by the complexity of some vegetable farms. The plastic use indicator shed new light on a growing concern.