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This document is a post-print of the following paper:

Pépin, A., Morel, K., & van der Werf, H. M. (2021). Conventionalised vs. agroecological practices on organic vegetable farms: Investigating the influence of farm structure in a bifurcation perspective. *Agricultural Systems*, *190*, 103129.

Please cite this reference if you mention this work.

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 (EC, 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 (Le Monde, 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 (French Senate, 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 Van 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 (Francis et al., 2003; Fernandez et al., 2013; Guzmán et al., 2013; 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 (Sierra *et al.*, 2017; Kamau *et al.*, 2018; Blanco-Penedo *et al.*, 2019). 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 Therond *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. Navarrete, 2009; Sierra *et al.*, 2017; Lopez-Ridaura et al., 2018; Adewale et al., 2019). 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 (Therond *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. 1).

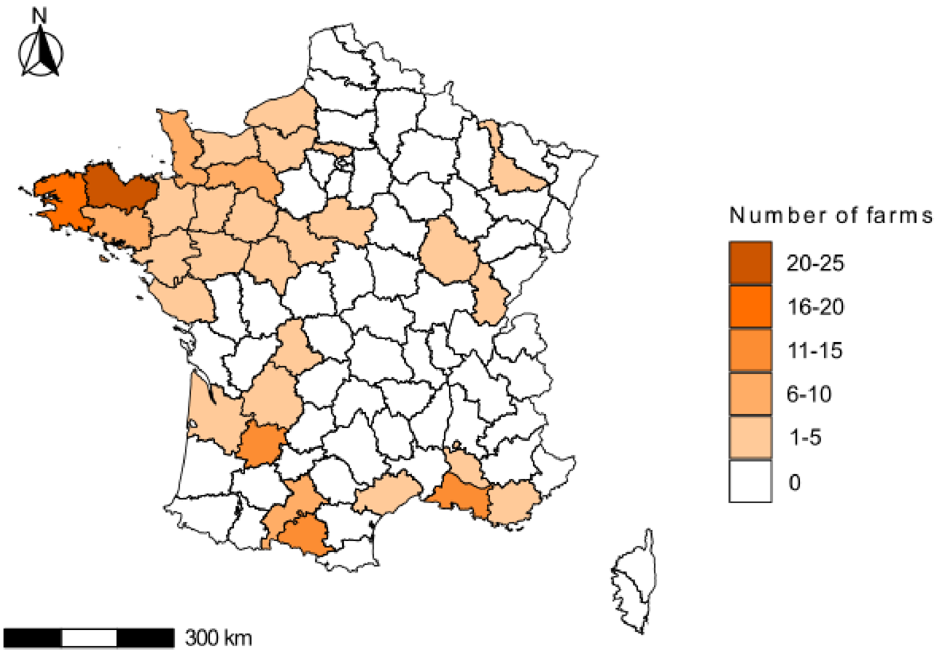

Fig. 1. Number of the 165 farms surveyed in each of the administrative departments of mainland France

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 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 (Tables 1 and 2).

Table 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. 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). 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).

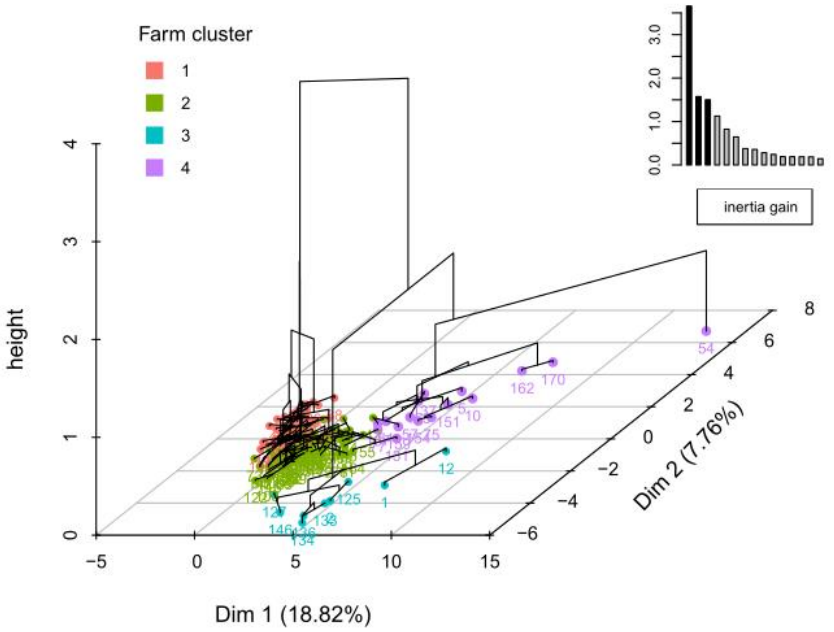

Fig. 2. Hierarchical clustering of the four farm clusters on the factor map

2.4. Composite indexes

The conceptual framework of Therond *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 Therond *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)):

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

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 Therond *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 (Therond *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 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”) (Therond *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, Therond *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 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). All quantitative variables were significantly related to the cluster variable (Table 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 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 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 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)**
Tillage (<0.001)				
No-tillage	**44%**	2%	11%	0%
Surface tillage	46%	**55%**	11%	19%
Deep non-inversion tillage	7%	28%	**78%**	31%
Ploughing	2%	15%	0%	**50%**
Fertilisation (<0.001)				
Self- or locally produced	63%	54%	0%	69%
Mixed	22%	27%	33%	31%
Purchased on the market	15%	19%	**67%**	0%
Weed control (<0.001)				
Based on natural techniques	**37%**	1%	0%	0%
Mixed	56%	**74%**	56%	63%
Based on artificialising the environment	7%	25%	44%	38%
Pest and disease control (<0.001)				
Based on local resources	**93%**	34%	0%	19%
Mixed	7%	**49%**	67%	63%
Based on external inputs	0%	16%	33%	19%
Willingness to dedicate space to biodiversity on the farm (<0.001)				
Major	**39%**	26%	11%	6%
Important	61%	52%	33%	63%
Unimportant	0%	22%	**56%**	31%
Seed and seedling management (<0.001)				
Seeds partly self-produced	**51%**	5%	11%	19%
Seedlings at least partly self-produced	49%	**59%**	0%	38%
Seeds and seedlings purchased	0%	36%	**89%**	44%
Food supply chain (<0.001)				
Direct selling (0 intermediary)	**73%**	54%	0%	0%
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)	2%	11%	**89%**	**75%**
Furthest selling destination (<0.001)				

Department	71%	**66%**	0%	13%
Regional	15%	17%	0%	6%
National	15%	15%	33%	**50%**
Foreign	0%	2%	**67%**	**31%**
Annual revenue (k€) (<0.001)				
0-30	**73%**	11%	0%	0%
30-60	17%	18%	0%	0%
60-100	10%	**36%**	0%	0%
100-300	0%	**31%**	44%	19%
300-500	0%	3%	22%	**38%**
500-1000	0%	0%	**33%**	**31%**
1000 +	0%	0%	0%	**13%**
Region (<0.001)				
South-east	**24%**	4%	**89%**	0%
North-west	32%	**69%**	11%	75%
South-west	29%	18%	0%	19%
Other	15%	9%	0%	6%
Conversion to organic farming (<0.001)				
Farm created as organic	**93%**	**84%**	0%	44%
Farm converted to organic farming	7%	16%	**100%**	**56%**
Diversification (0.26)				
Specialised in vegetable production	39%	59%	78%	44%
Diversified in other types of production	**61%**	41%	22%	56%
Alternative farming (<0.001)				
Alternative farming	**90%**	26%	33%	13%
Non-alternative farming	10%	**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. 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. 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 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. 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. 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. 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 (χ^2= 78.241, df=3, $p<0.001$), which was not surprising, as its components were variables that had influenced the clustering (Fig. 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. 5). Cluster 4 had the highest score for fertilisation but lowest score for tillage. Farm clusters also differed in the socio-economic index (χ^2= 52.324, df=3, $p<0.001$) (Fig. 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 τ = 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. 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.

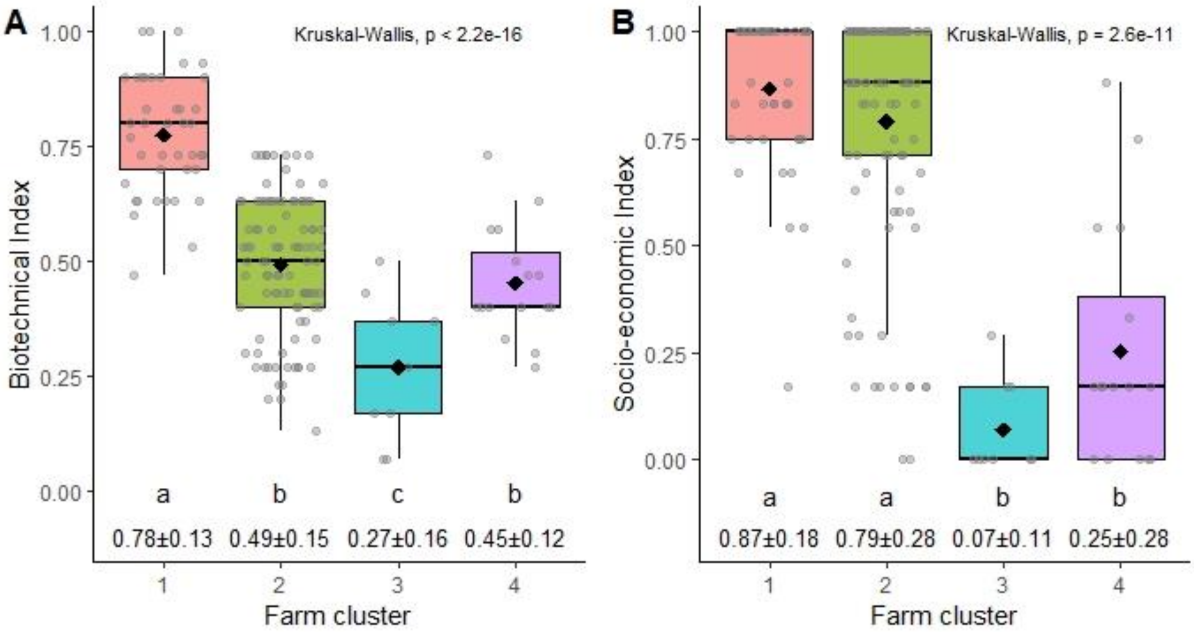

Fig. 4. Boxplots of the (A) biotechnical index and (B) socio-economic index for the 165 farms by farm cluster. A horizontal jitter function is used in the graph to visualise farm points more clearly. Medians differed significantly among farm clusters for the biotechnical index (Kruskal-Wallis χ2= 78.241, df=3, p<0.001) and the socio-economic index (Kruskal-Wallis χ2= 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.

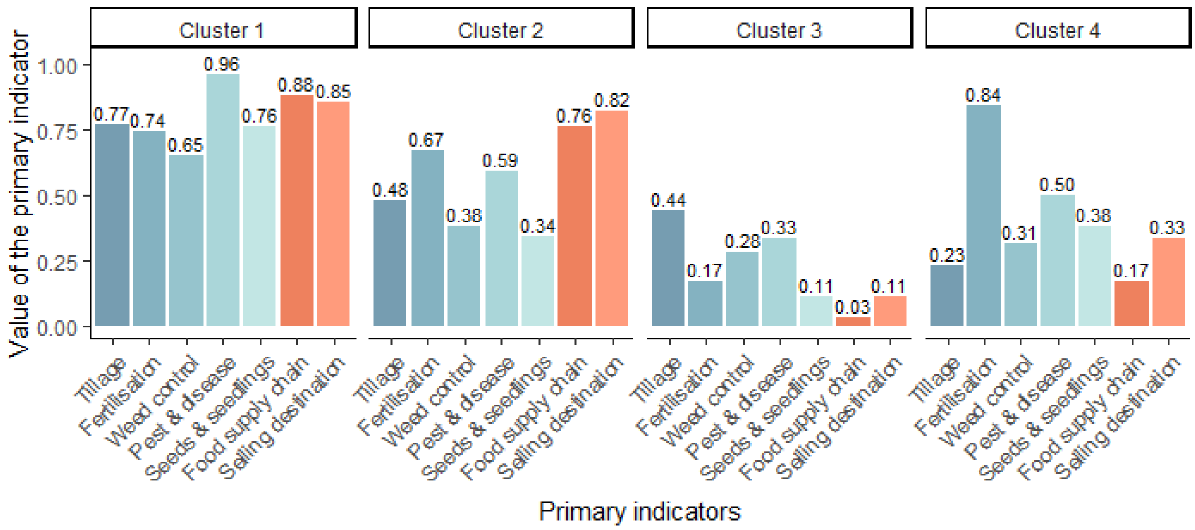

Fig. 5. Median scores of the primary indicators used to build the composite indexes of biotechnical functioning (blue) and socio-economic context (red) according to cluster. See Table 1 for full names and descriptions of primary indicators.

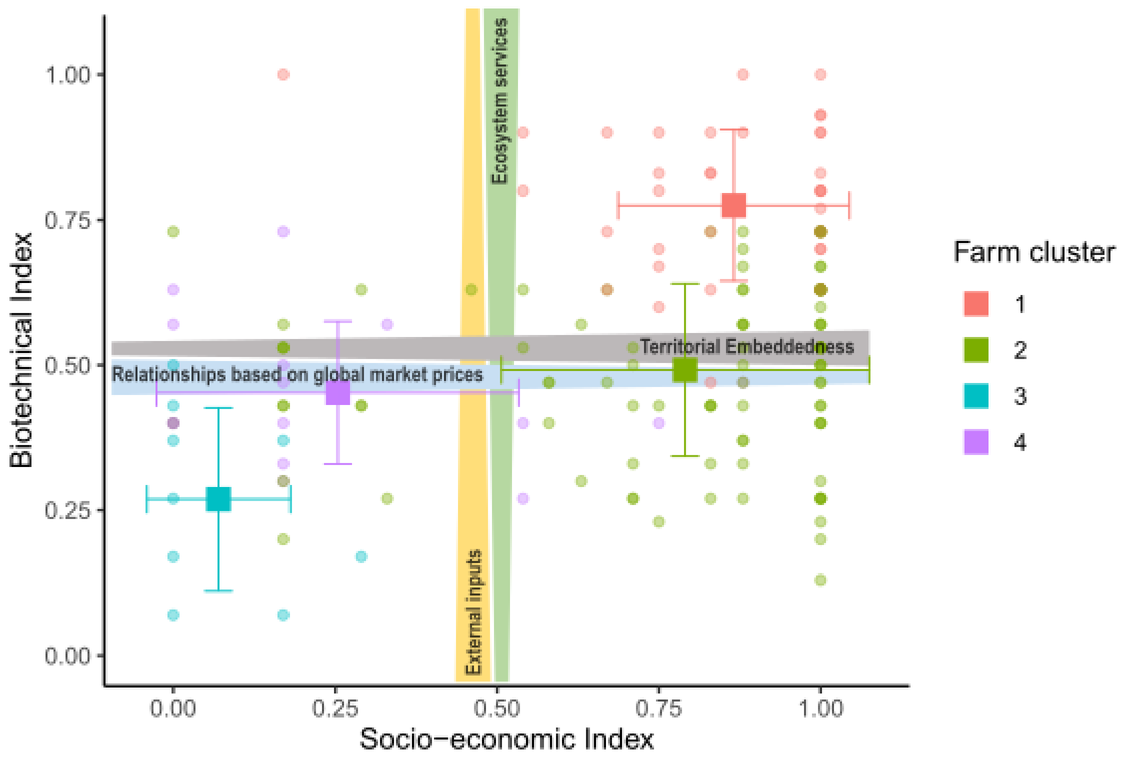

Fig. 6. Representation of the 165 farms sorted by farm cluster on a framework defined by the socio-economic index and the biotechnical index. Darker circles indicate overlapping farms with the same values. Squares represent the mean of each index, whereas error bars represent the standard deviation of the two indexes for each farm cluster. (Therond *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. 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).

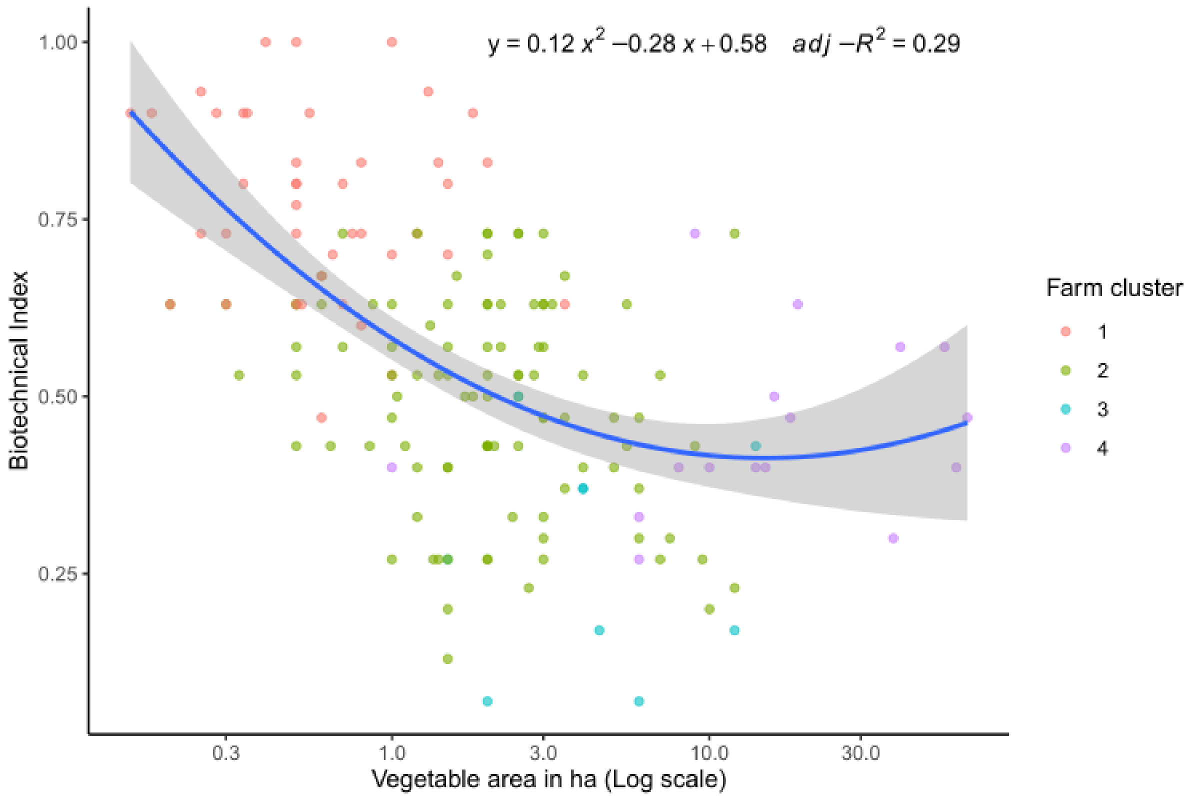

Fig. 7. Second-order polynomial regression (blue line) of the biotechnical index as a function of log (vegetable area). The grey zone represents the 95% confidence interval of the regression. Darker circles indicate overlapping farms with the same values.

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). 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 (Tables 1 and 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 (Dumont and Baret, 2017; Drouet *et al*., 2020) or economic characteristics (Clus, 2009; Navarrete, 2009; Jammes, 2012; Giraudet, 2019), 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). 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 Van 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 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 (Padel, 2008; Darnhofer, 2010). 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 (Francis et al., 2003; Fernandez et al., 2013; Guzmán et al., 2013; 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 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. 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 Léger, 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 (EU JRC, 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 Therond 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

The authors are grateful to the farmers who answered the survey and to the people who helped disseminate it. They also thank Mathieu Conseil (ITAB) and Vincent Faloya (INRAE), the vegetable experts who helped them develop the first hypothesis about the typology, and Goulven Maréchal (FRAB) for the opportunity to present these results to farmers to obtain their feedback. The research was supported by the Centre Technique Interprofessionnel des Fruits et Légumes (CTIFL) and the Association Nationale Recherche Technologie (ANRT).

References

Adewale, C., Higgins, S., Granatstein, D., Stockle, C.O., Carlson, B.R., Zaher, U.E., Carpenter-Boggs, L., 2016. Identifying hotspots in the carbon footprint of a small scale organic vegetable farm. Agricultural Systems 149, 112-121.

Adewale, C., Reganold, J.P., Higgins, S., Evans, D., Carpenter-Boggs, L., 2019. Agricultural carbon footprint is farm specific: Case study of two organic farms. Journal of Cleaner Production 229, 795-805.

Agence Bio, 2019. Organic farming and market in the European Union. 136 p.

Agence Bio, 2020. La consommation bio en hausse en 2019 stimule la production et la structuration des filières françaises - Les chiffres 2019 du secteur bio.

Alvarez, S., Paas, W., Descheemaeker, K., Tittonell, P.A., Groot, J.C.J., 2014. Typology construction, a way of dealing with farm diversity: General guidelines for Humidtropics. 37 p.

Alvarez, S., Timler, C.J., Michalscheck, M., Paas, W., Descheemaeker, K., Tittonell, P., Andersson, J.A., Groot, J.C.J., 2018. Capturing farm diversity with hypothesis-based typologies: An innovative methodological framework for farming system typology development. PLoS One 13, 24.

Audigier, V., Husson, F., Josse, J., 2016. A principal component method to impute missing values for mixed data. Advances in Data Analysis and Classification 10, 5-26.

Bavec, M., Robačer, M., Stajnko, D., Vukmanić, T., Bavec, F., 2017. Sustainability of vegetable production systems evaluated by ecological footprint. Good Agricultural Practices for greenhouse vegetable production in the South East European countries, pp. 227-243.

Beltran-Esteve, M., Reig-Martinez, E., 2014. Comparing conventional and organic citrus grower efficiency in Spain. Agricultural Systems 129, 115-123.

Best, H., 2008. Organic agriculture and the conventionalization hypothesis: A case study from West Germany. Agriculture and Human Values 25, 95-106.

Blanco-Penedo, I., Sjostrom, K., Jones, P., Krieger, M., Duval, J., van Soest, F., Sundrum, A., Emanuelson, U., 2019. Structural characteristics of organic dairy farms in four European countries and their association with the implementation of animal health plans. Agricultural Systems 173, 244-253.

Bolis, A., 2017. Vers une agriculture bio « à deux vitesses ». Le Monde. Published on 18/01/2017. https://www.lemonde.fr/planete/article/2017/01/18/vers-une-agriculture-bio-a-deux-vitesses_5064854_3244.html (accessed on 7 Dec. 2020).

Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: harnessing ecosystem services for food security. Trends in Ecology and Evolution 28, 230-238.

Buck, D., Getz, C., Guthman, J., 1997. From Farm to Table: The Organic Vegetable Commodity Chain of Northern California. Sociologia Ruralis 37, 3-20.

Carter, M.R., 1984. Identification of the inverse relationship between farm size and productivity - an empirical-analysis of peasant agricultural production. Oxford Economic Papers-New Series 36, 131-145.

Clus, Y., 2009. Typologie technico-économique des exploitations de maraîchage biologique diversifiées de l'aire de l'ADABio. Mémoire de fin d'études, Montpellier SupAgro, p. 84.

Darnhofer, I., Lindenthal, T., Bartel-Kratochvil, R., Zollitsch, W., 2010. Conventionalisation of organic farming practices: from structural criteria towards an assessment based on organic principles. A review. Agronomy for Sustainable Development 30, 67-81.

de Ponti, T., Rijk, B., van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. Agricultural Systems 108, 1-9.

Drouet, H., Réseau-AMAP-Ile-de-France, Le-Champ-des-possibles, 2020. Étude socio-économique du maraîchage biologique en AMAP en Ile-de-France. http://www.amapidf.org/images/imagesFCK/file/1reseau/paysans/amap_etude_socio_econ_final_web.pdf (accessed on 7 Dec. 2020), 36 p.

Dumont, A.M., Baret, P.V., 2017. Why working conditions are a key issue of sustainability in agriculture? A comparison between agroecological, organic and conventional vegetable systems. Journal of Rural Studies 56, 53-64.

Dumont, A.M., Vanloqueren, G., Stassart, P.M., Baret, P.V., 2016. Clarifying the socioeconomic dimensions of agroecology: between principles and practices. Agroecology and Sustainable Food Systems 40, 24-47.

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.A., Justes, E., Journet, E.P., Aubertot, J.N., Savary, S., Bergez, J.E., Sarthou, J., 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agronomy for Sustainable Development 35, 1259-1281.

European Commission, 2007. Council Regulation (EC) No. 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No. 2092/91. Official Journal of the European Union.

European Commission - Joint Research Centre, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment. Detailed Guidance. Publications Office of the European Union.

Fernandez, M., Goodall, K., Olson, M., Mendez, V.E., 2013. Agroecology and alternative agri-food movements in the United States: toward a sustainable agri-food system. Agroecology and Sustainable Food Systems 37, 115-126.

Foteinis, S., Chatzisymeon, E., 2016. Life cycle assessment of organic versus conventional agriculture. A case study of lettuce cultivation in Greece. Journal of Cleaner Production 112, 2462-2471.

FRAB, 2019. Fiche Thématique de l'Observatoire de la production bio : Les nouveaux bio au 1er semestre 2018. Fédération Régionale Des Agrobiologistes de Bretagne, https://www.agrobio-bretagne.org/wp-content/uploads/2019/02/Fiche_obs_nouveauxbio_1ersem_2018.pdf (accessed on 7 Dec. 2020), 4 p.

Francis, C., Lieblein, G., Gliessman, S., Breland, T.A., Creamer, N., Harwood, R., Salomonsson, L., Helenius, J., Rickerl, D., Salvador, R., Wiedenhoeft, M., Simmons, S., Allen, P., Altieri, M., Flora, C., Poincelot, R., 2003. Agroecology: the ecology of food systems. Journal of Sustainable Agriculture 22, 99-118.

Froehlich, A.G., Melo, A., Sampaio, B., 2018. Comparing the profitability of organic and conventional production in family farming: empirical evidence from Brazil. Ecological Economics 150, 307-314.

Giraudet, C., 2019. Les fermes maraîchères biologiques de la région Provence-Alpes-Côte d'Azur : trajectoires, systèmes technico-économiques, performances et adaptation au changement climatique. Mémoire de fin d'études, Montpellier SupAgro, p. 136.

Gliessman, S., 2013. Agroecology and going beyond organic. Agroecology and Sustainable Food Systems 37, 147-148.

Guzman, G.I., Lopez, D., Roman, L., Alonso, A.M., 2016. Participatory action research for an agroecological transition in Spain building local organic food networks. In: Mendez, V.E., Bacon, C.M., Cohen, R., Gliessman, S.R. (Eds.), Agroecology: a Transdisciplinary, Participatory and Action-oriented Approach, pp. 139-159.

Herzog, F., Steiner, B., Bailey, D., Baudry, J., Billeter, R., Bukacek, R., De Blust, G., De Cock, R., Dirksen, J., Dormann, C.F., De Filippi, R., Frossard, E., Liira, J., Schmidt, T., Stockli, R., Thenail, C., van Wingerden, W., Bugter, R., 2006. Assessing the intensity of temperate European agriculture at the landscape scale. European Journal of Agronomy 24, 165-181.

Howard, A.S., 1940. An Agricultural Testament. Oxford University Press, London.

Husson, F., Josse, J., Pagès, J., 2010. Principal component methods - hierarchical clustering - partitional clustering: why would we need to choose for visualizing data? Technical Report, http://factominer.free.fr/more/HCPC_husson_josse.pdf (accessed on 7 Dec. 2020), Agrocampus Ouest, 17 p.

Jammes, D., 2012. Acquisition de références techniques, économiques et commerciales Filière 1 : Le maraîchage biologique. Bio de Provence, 42 p.

Josse, J., Husson, F., 2016. missMDA: A package for handling missing values in multivariate data analysis. Journal of Statistical Software 70, 31.

Kamau, J.W., Stellmacher, T., Biber-Freudenberger, L., Borgemeister, C., 2018. Organic and conventional agriculture in Kenya: A typology of smallholder farms in Kajiado and Murang'a counties. Journal of Rural Studies 57, 171-185.

Key, N.D., Roberts, M.J., 2007. Commodity Payments, Farm Business Survival, and Farm Size Growth. United States Department of Agriculture, Economic Research Service.

Lamine, C., Dawson, J., 2018. The agroecology of food systems: Reconnecting agriculture, food, and the environment. Agroecology and Sustainable Food Systems 42, 629-636.

Läpple, D., Van Rensburg, T., 2011. Adoption of organic farming: are there differences between early and late adoption? Ecological Economics 70, 1406-1414.

Le, S., Josse, J., Husson, F., 2008. FactoMineR: an R package for multivariate analysis. Journal of Statistical Software 25, 1-18.

Lefevre, A., Perrin, B., Lesur-Dumoulin, C., Salembier, C., Navarrete, M., 2020. Challenges of complying with both food value chain specifications and agroecology principles in vegetable crop protection. Agricultural Systems 185, 102953.

Legendre, P., Legendre, L.F., 2012. Numerical Ecology. Elsevier.

Lockeretz, W., 2007. Organic Farming: An International History. Organic Farming: an International History, 282 p.

Lopez-Ridaura, S., Frelat, R., van Wijk, M.T., Valbuena, D., Krupnik, T.J., Jat, M.L., 2018. Climate smart agriculture, farm household typologies and food security: an ex-ante assessment from Eastern India. Agricultural Systems 159, 57-68.

Mazoyer, M., Roudart, L., 2006. A History of World Agriculture: from the Neolithic Age to the Current Crisis. Monthly Review Press, New York.

Morel, K., Leger, F., 2016. A conceptual framework for alternative farmers' strategic choices: the case of French organic market gardening microfarms. Agroecology and Sustainable Food Systems 40, 466-492.

Morel, K., San Cristobal, M., Leger, F.G., 2017. Small can be beautiful for organic market gardens: an exploration of the economic viability of French microfarms using MERLIN. Agricultural Systems 158, 39-49.

Morel, K., San Cristobal, M., Leger, F.G., 2018. Simulating incomes of radical organic farms with MERLIN: a grounded modeling approach for French microfarms. Agricultural Systems 161, 89-101.

Navarrete, M., 2009. How do farming systems cope with marketing channel requirements in organic horticulture? The case of market-gardening in southeastern France. Journal of Sustainable Agriculture 33, 552-565.

Netting, R.M., 1993. Smallholders, Householders: Farm Families and the Ecology of Intensive, Sustainable Agriculture. Stanford University Press, Stanford, California, USA.

Pagès, J., 2004. Analyse factorielle de données mixtes. Revue de Statistique Appliquée Tome 52, 93-111.

Padel, S., 2008. Values of organic producers converting at different times: results of a focus group study in five European countries. International Journal of Agricultural Resources, Governance and Ecology 7, 63-77.

Perrot, C., Landais, E., 1993. Exploitations agricoles : pourquoi poursuivre la recherche sur les methodes typologiques? Cahiers de la Recherche Développement 33, 13-40.

RStudio Team (2016). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www.rstudio.com/ version 1.1.463.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/ version 3.5.3 (2019-03-11).

Rosset, P., Altieri, M., 1997. Agroecology versus input substitution: a fundamental contradiction of sustainable agriculture. Society & Natural Resources 10, 283-295.

Rosset, P., 2000. The multiple functions and benefits of small farm agriculture in the context of global trade negotiations. Development 43, 77-82.

Salou, T., Le Mouel, C., van der Werf, H.M.G., 2017. Environmental impacts of dairy system intensification: the functional unit matters! Journal of Cleaner Production 140, 445-454.

French Senate, 2019. Projet de loi de finances pour 2020 : Agriculture, alimentation, forêt et affaires rurales.

Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229-U113.

Sierra, J., Causeret, F., Chopin, P., 2017. A framework coupling farm typology and biophysical modelling to assess the impact of vegetable crop-based systems on soil carbon stocks. Application in the Caribbean. Agricultural Systems 153, 172-180.

Stanton, B. F., 1991. Farm Structure: Concept and Definition. Cornell Agricultural Economics Staff Paper, 91-6. Department of Agricultural Economies, Cornell University, Ithaca.

Therond, O., Duru, M., Roger-Estrade, J., Richard, G., 2017. A new analytical framework of farming system and agriculture model diversities. A review. Agronomy for Sustainable Development 37, 24.

van der Ploeg, J.D., 2018. The New Peasantries: Rural Development in Times of Globalization. Routledge.

van der Werf, H.M.G., Knudsen, M.T., Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nature Sustainability 3, 419-425.

Vincent-Caboud, L., Peigne, J., Casagrande, M., Silva, E.M., 2017. Overview of organic cover crop-based no-tillage technique in Europe: farmers' practices and research challenges. Agriculture-Basel 7, 42.

Ward, J.H., 1963. Hierarchical grouping to optimize an objective function. Journal of the American Statistical Association 58, 236-244.