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RESEARCH ARTICLE

A method to account for diversity of practices in Conservation Agriculture

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Abstract

Conservation Agriculture (CA) is actively promoted as an alternative farming system that combines environmental, economic, and social sustainability. Three pillars define CA: (i) minimum mechanical soil disturbance, (ii) permanent soil organic cover, and (iii) species diversification. The local context, constraints, and needs of the farmers influence the translation of the pillars into practices. Currently, there is no method for categorizing this diversity of CA practices, which hampers impact assessment, understanding of farmer choices and pathways, stakeholder communication, and policymaking. This paper presents a systematic method to identify and categorize the diversity of CA practices at the regional level, anchored in the three pillars and based on practices implemented by CA farmers. The classification method is grounded on the intersection of an archetypal analysis and a hierarchical clustering analysis. This method was used to study CA practices in Wallonia, Belgium, based on a survey of practices in a sample of 48 farmers. Combining the two clustering methods increases the proportion of classified farmers while allowing for the distinction between three CA-types with extreme and salient practices, and two intermediate CA-types comprising farmers whose practices fall between these references. The study reveals that three explanatory factors influence the implementation of CA practices in Wallonia: (i) the proportion of tillage-intensive crops and (ii) temporary grasslands in the crop sequence, and (iii) the organic certification. These factors lead to trade-offs that hinder the three pillars of CA from being fully implemented simultaneously. This new classification method can be replicated in other regions where CA is practiced, by adapting input variables according to context and local knowledge.

Keywords Farming practices · Organic · Trade-offs · Grassland · Tillage · Farm typology

1 Introduction

Agriculture is both affected by climate change and a significant contributor to greenhouse gas (GHG) emissions (Kassam et al. 2018). Conservation Agriculture (CA) has been highlighted as an alternative farming system that enables productive and profitable agriculture, improves soil and water conservation offering better adaptation to climate change, mitigates GHG emissions, and contributes to carbon sequestration in soils (Smith and Olesen 2010; Pisante et al. 2015; Powlson et al. 2016; González-Sánchez et al. 2017; Pasricha 2017; Meena and Jha 2018; Jug et al. 2018; FAO 2023a). In 2019, an estimated 14.7% of total global arable land was under CA (Kassam et al. 2022).

CA is based on three agronomic pillars (or principles): (i) minimum mechanical soil disturbance, (ii) permanent soil organic cover, and (iii) species diversification (FAO 2023a) (Fig. 1). While a pillar is considered a foundation of CA that distinguishes it from other farming systems, each pillar can be implemented through a variety of different practices (Sommer et al. 2014) tailored to the specific context and geographical location (FAO 2023b), as well as to the needs, constraints, and resources of each farmer (Vankeerberghen and Stassart 2016; Derrouch et al. 2020). The diverse range of practices encompassed by the CA pillars is mirrored in the guidelines provided by the FAO (2023b), ranging from no-till to periodic tillage that disturbs less than 15 cm wide or less than 25% of the cropped area, from over 90 to 30% soil cover, and rotation with a minimum of three different crop species.

The CA practices implemented influence its outcomes and sustainability (Scopel et al. 2013). Determining the diversity of CA practices helps to assess impacts, better

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Fig. 1 The picture on the left shows a cereal seedling with no-till on the left and plowing on the right. The middle image shows a cover crop consisting of several associated species. The image on the right illustrates the diversity of crops grown in Wallonia. Photos credited to Philippe Baret.

understand the farmers' choices, guide policy decisions, and improve communication within the scientific community or between scientists and field actors (Landel 2015).

Categorization is essential for studying CA. First, categorization bridges the gap between the concept of CA and the wide range of CA practices (Riera et al. 2023) and helps to distinguish different practices that actors commonly blend. Categorization helps to study and analyze the system's complexity (Alvarez et al. 2018; Mutyasira 2020) by creating a shared conceptual framework accessible and usable by all stakeholders (Dixon 2019; Riera et al. 2023). In addition, developing a typology not only improves the understanding of the decision-making processes farmers use to adopt specific CA practices but also fosters a sense of community and collaboration among farmers. This allows farmers to relate their practices to those of other farmers, facilitating sharing, exchanging concerns, identifying development pathways, and transferring technologies and strategies (Goswami and Bandopadhyay 2015; Alvarez et al. 2018; Riera et al. 2023). Finally, a typology can aid in identifying opportunities and constraints that can guide farm advisory services and policymakers in targeting or adjusting policy interventions (Alvarez et al. 2018).

The diversity of CA practices is widely recognized and reported in the scientific community (e.g., Lahmar (2010), Scopel et al. (2013), Craheix et al. (2016), Vankeerberghen and Stassart (2016), Brown et al. (2017), Cristofari et al. (2018), Derrouch et al. (2020), Bouwman et al. (2021)). However, there is currently no systematic method for categorizing the diversity of CA practices according to the three pillars implemented by farmers. Hauswirth et al. (2015) developed a typology on non-CA farms to facilitate the subsequent adoption of CA-types, and Husson et al. (2016) co-designed CA-types that farmers could implement. Scopel et al. (2013) presented CA-types in Brazil and France without explaining how the CA-types were identified. Bouwman et al. (2021) defined CA-types in Malawi based on the management of crop residues visualized by satellite imagery.

Farm typologies can be constructed using many tools. Cluster analysis uses algorithms to organize a multivariate data set (observations or individuals) into clusters (Alvarez et al. 2018; Alkarkhi and Alqaraghuli 2018). Cluster analysis has the advantage of classifying all individuals. However, it has the disadvantage of mixing, within the same cluster, farmers with salient practices and those with typical practices (Tittonell et al. 2020). Next to this common method, Tittonell et al. (2020) propose using archetypal analysis (AA) to construct farm typologies. AA is an unsupervised learning method designed to find extremal points in a multivariate data set, called "archetypes," by minimizing the squared error, such that all the individuals are represented as a convex combination of the archetypes (Cutler and Breiman 1994; Eugster 2012; Tittonell et al. 2020). An individual's proximity to an archetype is reflected by a coefficient that determines whether they should be assigned to that archetype. Unlike the traditional clustering method mentioned above, this approach classifies only individuals sufficiently close to an archetype. While this method allows for better identification of distinct practices, AA may result in a high percentage of unclassified farmers (e.g., 35% in Tittonell et al. (2020) and 43% in Tessier et al. (2021)).

This paper aims to enhance the understanding, analysis, and implementation of CA both within academic circles and among field practitioners. To achieve this goal, we present a novel classification method designed to categorize the diverse practices in CA on a regional scale. Our approach involves the intersection of the outcomes derived from an AA and a hierarchical clustering analysis. While the AA highlights CA-types that include farmers with atypical practices, the cross-tabulation with a hierarchical clustering analysis identifies intermediate CA-types comprising farmers whose CA practices fall between archetypes.

2 Materials and methods

The methodology combines a participatory approach and a new classification method to create a typology that captures the diversity of CA practices in a given area. The procedure consists of four steps described in the sections below (Fig. 2). First, the typology variables are selected by adapting the CA pillars to local knowledge (Section 2.2). Second, information on the variables is collected through interviews with farmers practicing CA (Section 2.3). Third, two classifications are performed: an archetypal analysis (AA) and an agglomerative Hierarchical Clustering on Principle Components (HCPC). Their results are then crossed to construct the typology (Section 2.4). Finally, the practices implemented on each of the three pillars within each CA-type are translated into scores (Section 2.5) and described (Section 2.6).

2.1 Geographical context of the case study

While the typology is reproducible to other geographical contexts, its potential is demonstrated by describing CA practices performed in Wallonia, the southern half of Belgium. Based on 2022 figures, the Walloon territory accounts for 12,670 farms, with an average area per farm of 58 ha (SPW 2023). The agricultural area covers 738,927 ha (SPW 2023), of which 12.4%—mainly grasslands (Antier et al. 2019)—is devoted to organic farming (Statbel 2022). Wallonia is divided into agricultural regions that are differentiated by their soil, geographical and climatic characteristics (Goidts 2009; Etat de l'environnement Wallon 2018), which influence the agro-economic potential of agricultural land and thus the type of farming that develops (Goidts and van Wesemael 2007).

2.2 Data selection

The implementation of the three pillars exhibits regional variation in practice. To categorize the diversity of CA practices on a regional scale, it is necessary to contextualize these pillars and tailor them to represent the underlying practices accurately. A study of the CA landscape within the south of Belgium is carried out to adapt the definition of the pillars and select the variables that will characterize the diversity of practices in each pillar.

Data collection focused on crop sequences, which varied in length among farmers. To account for this variability, the variables were averaged over one year or expressed as proportions (Table 1). See supplementary data S1 for details of the calculation.

The crop sequence can include three types of crops. Annual crops include crops grown for sale and fodder crops grown for less than one year. These crops are either winter or spring sown. Second, temporary grassland

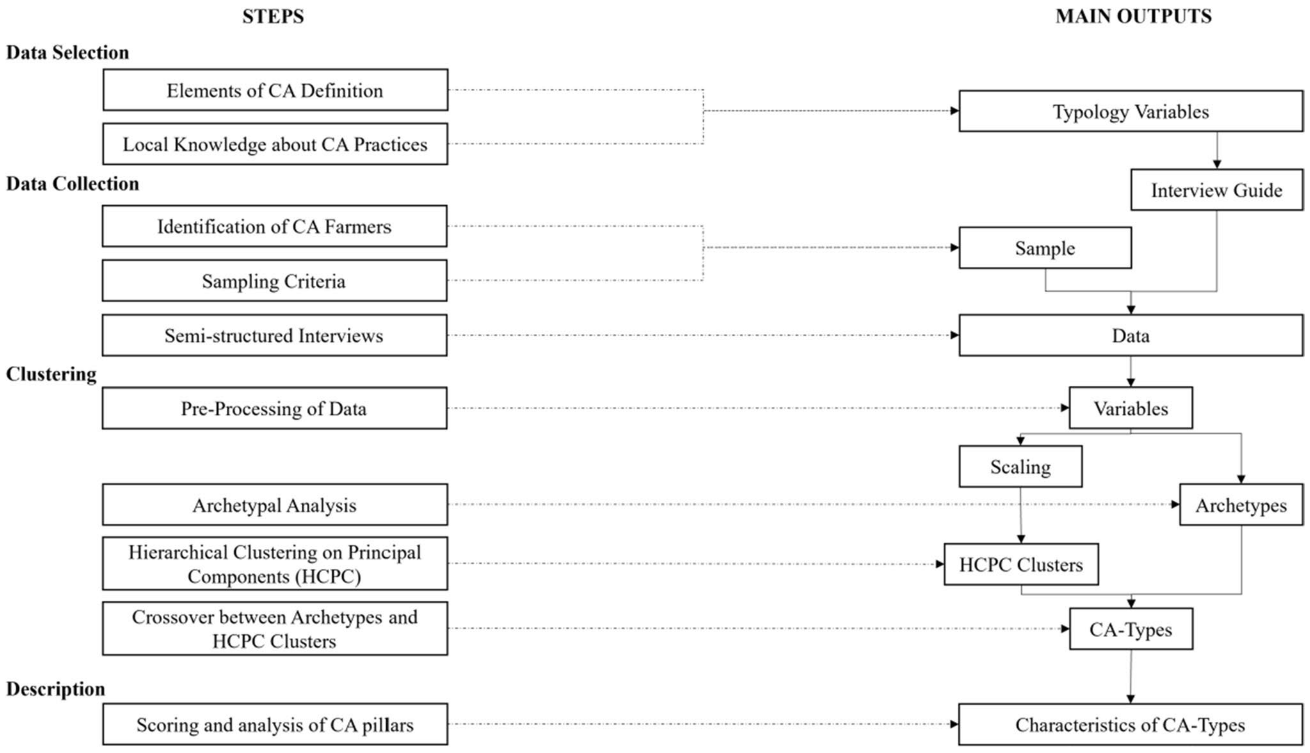


Fig. 2 Steps to build a typology capturing the diversity of Conservation Agriculture (CA) practices by categorizing them into CA-types.

Table 1 Variables used to characterize the pillars and gather data for the typology of Conservation Agriculture types. Legend: Erosion risk period (ERP), annual crops (A), temporary grassland (T).

Pillar	Variable	Detail
1. Minimum mechanical soil disturbance	Wheel traffic	The average annual wheel traffic for tillage operations (no. of tillage operations/year)
	Seeding	The proportion of seeding operations in relation to other tillage operations (%)
	Powered	The annual average of powered tillage passes (no. of powered passes/year)
	Plowing	The annual average of plowing (no. of plowing operations/year)
	Plowing depth	If horizons are turned over, the maximum depth of plowing (cm)
2. Maximum soil organic cover	Total cover	The average annual number of days the soil is covered (days/year)
	Living cover	The average annual number of days the soil is covered by a living mulch, i.e., crops, temporary grassland, or cover crops (days/year)
	Grassland cover	The proportion of days the soil is covered by temporary grassland (%)
	ERP cover	The proportion of days the soil is covered during the ERP, which in Wallonia is from May to September (%)
	Spring crops ERP cover	The proportion of days the soil is covered by spring crops during ERP, which in Wallonia is from May to September (%)
3. Maximum crop species diversification	Total species	The average annual number of different species in annual crops, temporary grassland, and cover crops (no. of different species/year)
	A+T species	The average annual number of different species except for cover crops, i.e., only annual crops and temporary grassland (no. of different species/year)
	A+T associations	The proportion of associations in annual crops and temporary grassland (%)
	A+T mixes	The proportion of mix of varieties in annual crops and temporary grassland (%)
	Tillage-intensive crops	The annual average number of tillage-intensive crops (no. of species/year)

is grass or forage that remains in place for at least one year and no more than five years. Finally, cover crops are unharvested crops grown to cover the soil between periods of regular crop production.

Pillar 1—minimum mechanical soil disturbance

To avoid confusion, we define "tillage" as any mechanical operation that fragments the soil, and "plowing" as a mechanical operation that inverts the soil horizons, usually to a depth of 30 cm in Belgium. We divided conservation tillage into three categories: (i) direct seeding (also called no-tillage or zero-tillage), defined as the planting of a crop without any soil preparation; (ii) non-inversion tillage, a soil preparation practice involving fragmentation, mixing and burial, without horizon inversion; and (iii) occasional inversion tillage, a tillage practice involving fragmentation, mixing, and burial with horizon inversion carried out by a plow at a reduced frequency or depth compared to conventional tillage. For some CA Walloon farmers, avoiding plowing throughout the entire crop sequence is challenging, for instance, due to unfavorable weather conditions or because the harvest occurred in very wet conditions. To accurately capture the practices of CA farmers, it was necessary to include occasional inversion tillage in conservation tillage practices.

Reducing mechanical soil disturbance can be accomplished by reducing the number of tillage operations (Kassam et al. 2009; Wauters et al. 2010) up to direct seeding (FAO 2023a).

Walloon farmers can practice CA with various seeders, ranging from conventional seeders to specialized direct-seeding seeders. The adoption of direct seeding in Belgium is low compared to the United States and South America (Vankeerberghen and Stassart 2016). As farmers can adjust seeder settings to change tillage intensity, it is useless to distinguish between seeders during data collection. Nevertheless, seeding remains one of the lightest tillage operations, yet one of the most essential. Therefore, it is important to distinguish this type of tillage from others.

Tools with high working depths and speeds, such as plows, disc harrows, and rotary cultivators, are avoided to limit effects on soil structural units' size, arrangement, and stability (Kassam et al. 2009).

Given that strip tillage is uncommon in Belgium (Ryken et al. 2018), we did not consider the proportion of soil disturbed within the cropped area by each tool.

The first pillar is defined by (i) the frequency of tillage operations, (ii) the proportion of seeding operations compared to other tillage operations, (iii) the frequency of use of powered tools, and (iv) the frequency of use of plowing tools and (v) the plowing depth (Table 1).

Pillar 2—maximum soil organic cover

Soil organic cover can be achieved using living (i.e., annual crops, temporary grasslands, or cover crops grown) or dead (e.g., crop residues, decaying leaves, bark, manure) ground cover. As living and dead mulch imply different management practices and impacts (e.g., carbon sequestration (Chenu et al. 2019)), it is interesting to differentiate them. According to FAO (2023a), a minimum soil surface coverage of 30% is recommended. The higher the soil cover, the lower the erosion risk (Erenstein 2002; Giller et al. 2009; Vanlauwe et al. 2014).

In the south of Belgium, since direct seeding remains limited, a permanent soil cover of at least 30% is rarely achieved. The term "maximum" has been chosen over "permanent" to convey the range of soil cover practices accurately.

The Belgian loess belt is known for its high rates of water-induced soil erosion (Cantreul et al. 2020). In Wallonia, cultivated land experiences an average estimated soil loss of 8.5 tons per ha annually (SPW 2022). The highest rainfall erosivity in Belgium occurs from May to September (Verstraeten et al. 2006). We called this timeframe the erosion risk period (ERP). In Wallonia, soil cover is particularly low for spring crops at the beginning of the ERP (Verstraeten et al. 2006; Laloy 2010; Clement et al. 2023). In practice, measuring the percentage of soil cover on a crop sequence over several years is challenging. This percentage can be estimated by calculating the amount of crop residue left on the plot. However, this information is only readily available for crops such as wheat, where farmers can intentionally set their combine harvester. Leaf Area Index (LAI) or Fraction of Green Vegetation Cover (FCOVER) can be estimated using growth models based on soil type, crop type, and sowing date. However, these models operate primarily on living mulch rather than dead mulch. Additionally, they are predictive models with inherent errors, and a reported FCOVER of 0.3 may not necessarily correspond to a field coverage of 30%. Furthermore, no data were available for the Walloon region in 2020. To overcome these limitations, we estimated soil cover through the number of days covered by living and dead mulch. This information is easily accessible during data collection and can be easily understood by all stakeholders.

Given that half of the Walloon farms are engaged in cattle farming (Statbel 2020), and recognizing the significant contribution of grassed areas in preserving soil structure and cover over extended periods (Hoeffner et al. 2021), it is essential to consider temporary grassland when assessing soil organic cover.

The second pillar is defined by (i) the total cover produced by all types of mulch, (ii) the cover produced by living mulch only (i.e., crops, temporary grassland, or cover crops), (iii) the cover produced by temporary grassland, (iv) the soil cover during the ERP, and (v) the proportion of days when spring crops cover the soil during the ERP (Table 1).

Pillar 3—maximum crop species diversification

Species diversification can be realized by rotations, crop associations, cover crops, or mixtures of varieties (FAO 2019, 2023a). FAO (2023a) states that CA cropping systems should include at least three different crop species to be considered diverse. To ensure consistency with the first two pillars, the term "maximum" has been added to the FAO definition, highlighting the significance of maximizing the number of crop species in CA.

In Belgium, some spring-sown crops such as beets, chicory, potatoes, maize, and other vegetables (e.g., carrots, onions, peas and beans) require a deeper soil preparation, a thin seedbed and/or can degrade the soil structure due to late harvesting (Poesen et al. 2001; Verstraeten et al. 2006; Agreste et al. 2014; Panagos et al. 2019). These crops will be referred to as tillage-intensive crops.

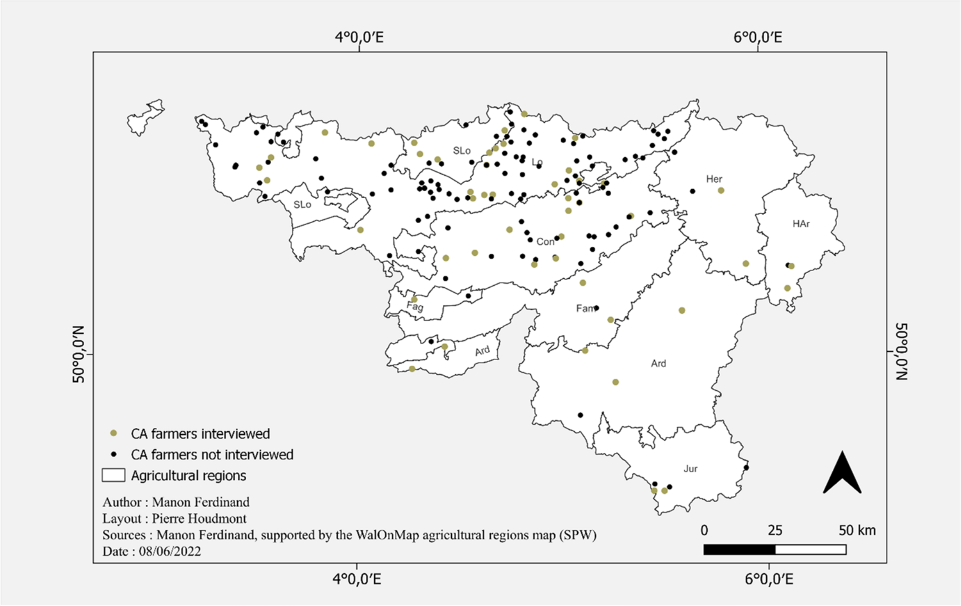
The assessment of species diversity considers the distinction between short-term income crops for the farmer (annual crops and temporary grassland) and cover crops.

The third pillar is defined by (i) the total number of different species grown (i.e., annual crops (A), temporary grassland (T), and cover crops), (ii) the number of different short-term income species (i.e., A and T), (iii) the crop associations in A and T, (iv) the mix of varieties in A and T, and (v) the number of tillage-intensive crops harvested (Table 1).

2.3 Data collection

2.3.1 Identification of the population of interest

The first step in collecting data involves identifying the target population. In Wallonia, there is no registry of farmers who implement CA. To recognize these farmers, we collaborated with 12 public and private institutions, eight farmers' associations, and two researchers from Belgian universities, through the use of the social network Facebook and by snowball method with CA farmers already met (method explained in Section 2.3.2). A verification of CA practice was conducted through telephone interviews and cross-referencing. As Walloon farmers who adopt CA typically begin by reducing or eliminating plowing practices (Vankeerberghen and Stassart 2016), only farmers who practice occasional inversion tillage, non-inversion tillage, or direct seeding were considered practicing CA. This audit reduced the number to 191 farmers, with 85% located in the sandy loam, loam, and Condroz regions (Fig. 3).



Author : Manon Ferdinand
Layout : Pierre Houdmont
Sources : Manon Ferdinand, supported by the WalOnMap agricultural regions map (SPW)
Date : 08/06/2022

Fig. 3 Geographical distribution of Walloon Conservation Agriculture farmers surveyed in 2020 by agricultural regions. Legend: Sandy loam (SLo), Loam (Lo), Condroz (Con), Herbagère (Her), Fagne (Fag), Famenne (Fam), Haute Ardenne (HAr), Ardenne (Ar), and Jurassic (Jur).

2.3.2 Sampling criteria

Farmers were selected using purposive sampling. Purposive sampling is a non-probability sampling in which the researcher selects the most relevant individuals to provide the information sought (Wauters and Mathijs 2013). This method highlights the existing diversity within the Walloon CA by focusing on inclusiveness rather than representativeness. Among purposive sampling techniques, snowball sampling enables to recruit new respondents based on the description of respondents who have already been interviewed (Tittonell et al. 2020; Tessier et al. 2021).

To guide the purposive sampling, assumptions were made regarding the factors driving and differentiating CA practices in Wallonia. The combination of CA and organic farming is practiced in Wallonia (Vankeerberghen and Stassart 2016; Boeraeve et al. 2022). Introducing organic certification in CA could result in higher soil preparation, lower soil cover, and higher species diversity. Besides, livestock could either complement (e.g., contributing to soil cover through the inclusion of temporary grassland, implementing forage breaks, engaging in cover grazing), replace (e.g., building soil organic matter, covering the soil with manure instead of crops or residues), or counteract (e.g., straw export, soil damage by trampling, overgrazing) some conservation practices (Kirkegaard et al. 2014). To ensure inclusiveness, four configurations resulting from the cross between organic certification and livestock farming were made: non-organic farmers (i) with livestock and (ii) without livestock, organic farmers (iii) with livestock and (iv) without livestock.

Although permanent grasslands are examples of well-managed agricultural land regarding tillage and soil cover, the study only focused on tillable areas occupied by crops or temporary grasslands. Small-scale horticulture is also excluded from the study.

The sample is spread over all main Walloon regions as agricultural regions have specificities.

Farmers with more than five years of CA experience were selected, as this is the minimum time for farmers to move beyond the adaptation period and begin to master the system (Derrouch et al. 2020). However, due to the limited number of CA farmers in the Famenne, Ardenne, and Haute Ardenne regions, this criterion had to be relaxed to interview at least two farmers per region. As a result, five farmers in the sample had less than five years of experience in CA or OCA.

2.3.3 Sample

Of the 191 farmers surveyed, 48 (25%) were selected based on the previously established criteria. Of these 48 CA farmers, 28 are non-organic (16 with livestock and 12 without) and 20 are organic (12 with livestock and 8 without livestock).

2.3.4 Semi-structured interviews

Data collection was carried out using a participatory approach, where the selected variables (as described in Section 2.2) were included in the interview guide. Semi-structured interviews were conducted between November 2020 and March 2021. Farming practices were characterized based on the crop sequence that best represents the farmer's CA practices, i.e., the crop sequence they practice most often or on the largest land area.

2.4 Clustering

2.4.1 Pre-processing of data

The data collected from the interviews were organized in a Microsoft® Excel spreadsheet and analyzed using R software to condense them into 15 variables. Each pillar was assigned equal weight, as no source justifies a specific hierarchy. Each variable was scaled to unit variance to perform the Principal Component Analysis (PCA), which will feed the Hierarchical Clustering on Principle Components (HCPC). The variables did not require prior scaling to perform archetypal analysis (AA).

Two of the 48 farmers interviewed were excluded from the analysis due to missing data.

2.4.2 Archetypal analysis

The method of carrying out the AA involved following the steps outlined by Tessier et al. (2021) and adhering to the guidance provided by Eugster and Leisch (2009). The R package "archetypes" was used to accomplish this. The algorithm was run for values of k (representing the number of archetypes) ranging from 1 to 10, 1000 times each, to avoid selecting a local minimum solution (Tessier et al. 2021). The best solution was determined by examining the residual sum of squares values and identifying the breaks (Tessier et al. 2021).

The assignment of farmers to an archetype is established through alpha coefficients that indicate their proximity to each archetype. For each archetype, each farmer has an alpha coefficient equal to or greater than zero, and the sum of these alpha coefficients per farmer amounts to one (Eugster and Leisch 2009). A membership threshold must be established to determine whether a farmer is close enough to be assigned to an archetype. A combined approach was used to select this threshold, drawing on the methods of Tittonell et al. (2020) and Tessier et al. (2021). Tittonell et al. (2020) proposed a criterion where farmers assigned to an archetype should have loadings above two-thirds, while Tessier et al. (2021) employed a graphical representation method. Farmers are assigned to an archetype if their alpha coefficient exceeds the chosen threshold.

2.4.3 Hierarchical clustering on principal components

The HCPC approach combines three standard methods to describe better the resemblances between individuals: PCA, hierarchical clustering, and the K-means algorithm (Husson et al. 2010).

First, PCA is a multivariate technique that extracts essential information from a dataset to represent it as a set of orthogonal variables called principal components (PCs) (Abdi and Williams 2010). Three methods were used to determine the number of PCs to include in the classification: (i) Kaiser's criterion with an eigenvalue greater than one (Kaiser 1960), (ii) the Cattell scree test (Cattell 1966), and (iii) a method based on the cross-validation criterion using the estim_ncp function (Josse and Husson 2012).

Then, an agglomerative hierarchical clustering with a K-means consolidation was performed on the PCA results using the HCPC function in the FactoMineR package in R (Lê et al. 2008).

The HCPC function uses Euclidean distance (root sum-of-squares of differences) to calculate the dissimilarities between individuals and Ward's agglomeration method to construct the hierarchical tree. Ward's method is used due to its ability to select at each step of the algorithm the cluster that corresponds to the smallest increase in group heterogeneity based on inertia (Härdle and Simar 2012) and its compatibility with principal component methods (Husson et al. 2010).

Finally, a K-means consolidation was performed. The K-means algorithm uses the tree cut partition obtained by hierarchical clustering as the initial partition (Husson et al. 2010), in contrast to classical K-means which starts with random centers. Consolidation improves the assignment of observations that lie on the border between clusters to produce a more stable and relevant result.

2.4.4 Crossover between archetypes and HCPC clusters

A cross-tabulation is performed in two steps to compare the results of AA and HCPC, following the method of Lebacq (2015) (see Table 3 in Section 3.4). First, the table is read based on the archetypes. The groups for which the AA and HCPC results match are defined as reference groups (Rg). Second, if the HCPC groups do not align with an archetype, they represent intermediate groups (Ig) located at the intersection of multiple archetypes.

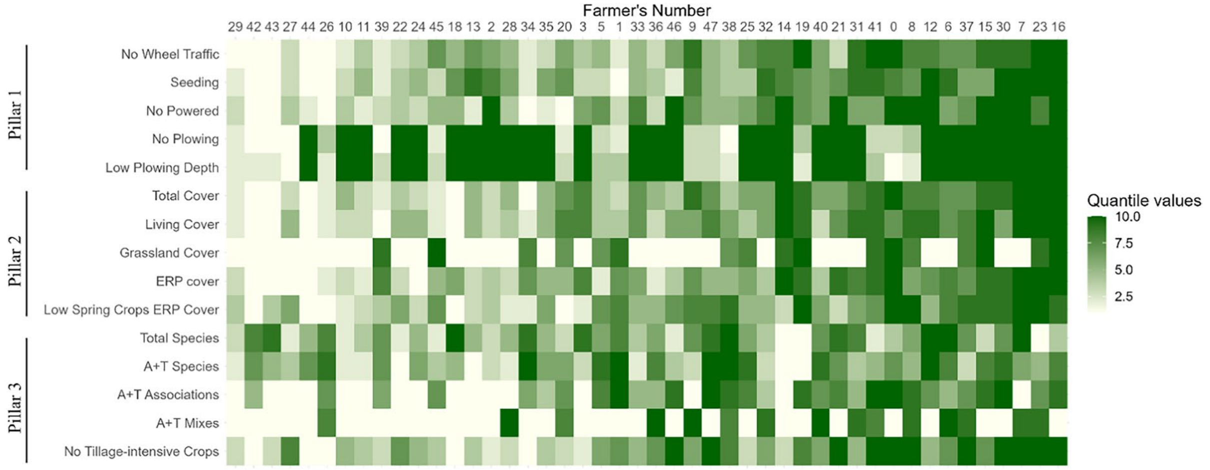
AA and HCPC are highly sensitive to outliers (Tessier et al. 2021). Following the method proposed by Tessier et al. (2021), the robustness of each group was evaluated by comparing the outcomes of the analyses when subjected to minor changes in the dataset. A group was deemed unreliable if it depended on a single variable or farmer. The resulting stable groups define the CA-types.

2.5 Transforming variables into scores

Each variable was scored on a scale from 1 to 10 to simplify the representation of data expressed in different units.

Initially, six variables ("Wheel traffic," "Powered," "Plowing," "Plowing depth," "Spring crops ERP cover," and "Tillage-intensive crops") showed negative correlations with

Table 2 Scoring table where the colors represent the score of the variable expressed in deciles (light green 0, dark green 10), and each column represents one farmer, inspired by Tessier et al. (2021). Their distribution is sorted according to the sum of the scores of all variables. Legend: Annual crops (A), erosion risk period (ERP), temporary grassland (T).



the CA pillars. To make all variables positively correlated with the CA pillars, these six variables were reversed (indicated by the addition of “No” or “Low” qualifiers next to them in the figures).

Afterwards, deciles were calculated for each variable, following the methods of Bijttebier et al. (2017) and Riera et al. (2020). Values below the first decile were given a score of “1,” while values above the ninth decile got a score of “10.”

2.6 Main features of CA-types

Characterizing the CA-types involves identifying the factors that distinguish practices between groups. A score analysis is carried out for each CA-type per variable, per pillar (obtained by summing the variables of each pillar), and for all variables (total score calculated by adding the variables).

3 Results

3.1 Overview of Conservation Agriculture diversity

As expected, each farmer has a unique combination of CA practices. Most farmers had both high and low scores for different variables. The 46 farmers were ranked from low total scores (left side of Table 2, table inspired by Tessier et al. (2021)) to high total scores (right side of Table 2). Farmers no. 29 and 16 had the lowest (32/150) and highest (131/150) scores, respectively.

Some practices are more common, while others are less practiced. While almost all Walloon CA farmers have abandoned plowing (29 farmers score 10 on the variable “No Plowing”), the establishment of temporary grassland and the use of variety mixes are less practiced (five farmers score 10 on the variables “Grassland cover” and the “A+T mixes”).

3.2 Archetypes

Four archetypes were identified using the relative evolution of the residual sum of squares as a decision rule. A simplex visualization illustrates each farmer’s proximity to the different archetypes through their alpha coefficients (Fig. 4a). While some farmers are very close to a particular archetype, others are at the intersection of two or more archetypes. To assign each farmer to one of the four archetypes, we set the alpha coefficient cut-off at 0.64. This threshold was chosen to be consistent with the two-thirds value proposed by Tittonell et al. (2020) and to ensure a plateau where membership remains stable across increasing thresholds, as in Tessier et al. (2021) (Fig. 4b).

52% of the farmers (24 out of 46) were assigned to one of the four archetypes since their alpha coefficient with one archetype is equal to or greater than 0.64. However, the remaining 22 unclassified farmers did not show significant proximity to any archetype, as all their alpha coefficients were below the threshold.

3.3 Hierarchical Clustering on Principal Components (HCPC) clusters

The first two principal components (PCs) accounted for 42.2% and 16.6% of the total variability. The variables most highly correlated with PC1 were wheel traffic and soil cover. The most influential variables for PC2 were

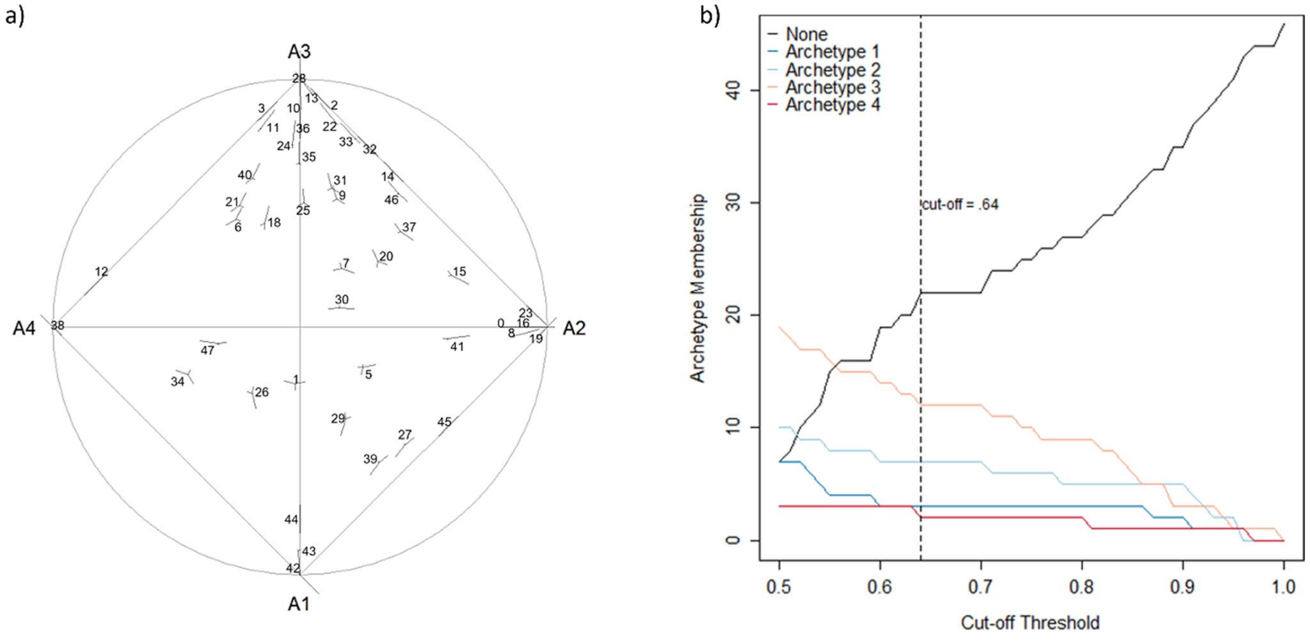


Fig. 4 **a** Simplex visualization of the farmers' proximity to the archetypes for $k = 4$. **b** The number of farmers belonging to the archetypes according to the cut-off threshold. Inspired by the figures presented by Tessier et al. (2021).

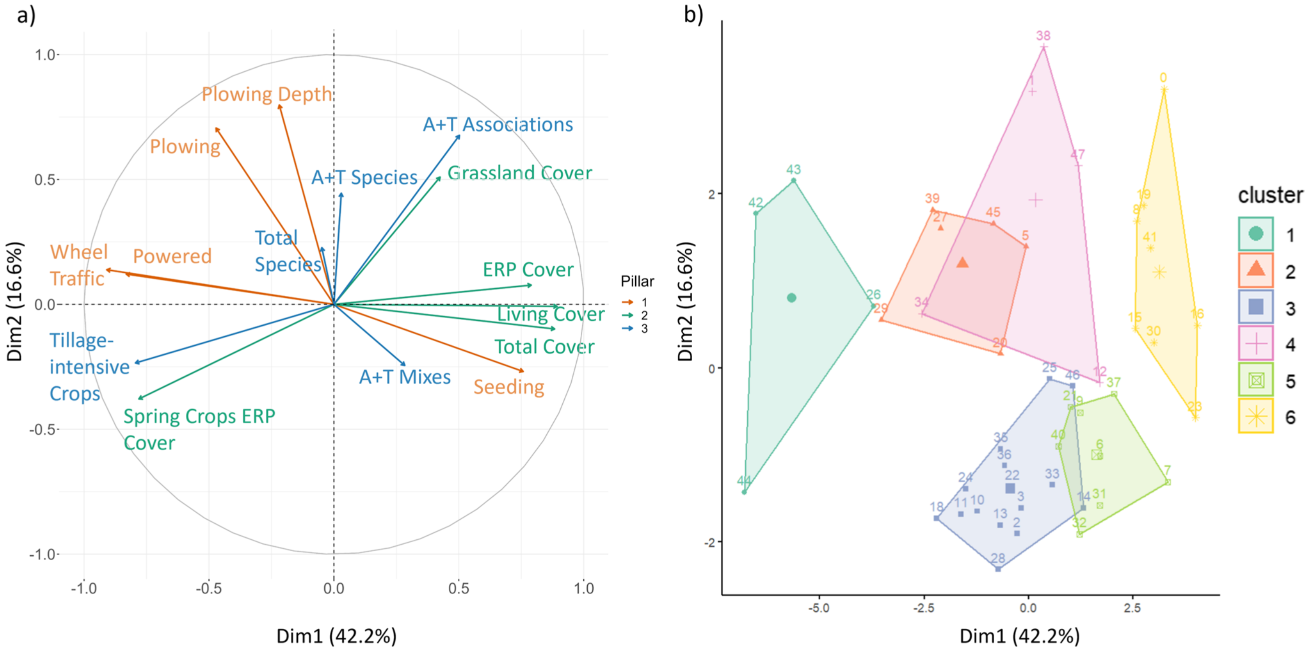
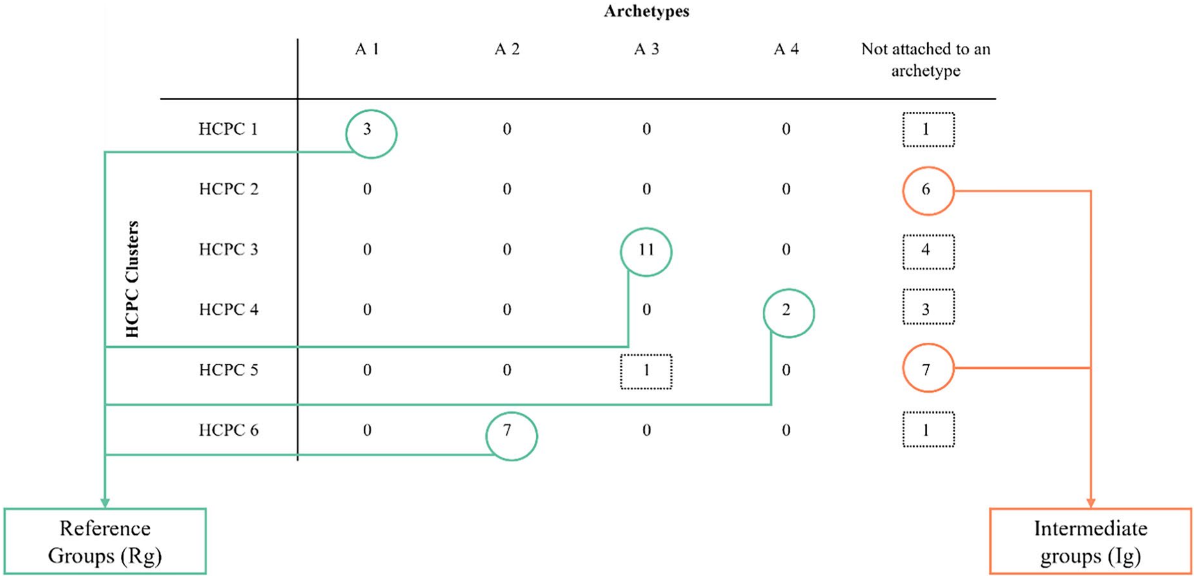


Fig. 5 **a** Graph of PCA variables. **b** Visualization of farmers on the first two dimensions of the PCA. Color code representing the hierarchical clustering results. Legend: Annual crops (A), erosion risk period (ERP), temporary grassland (T).

plowing and plowing depth (Fig. 5a). Five dimensions were retained using Kaiser's criterion, Cattell's scree test, and the R function estim_ncp, which explained 83.1% of the variability. PCA was used to identify the minimum number of clusters for the HCPC function, which was determined to be at least four. This decision was informed by distinctive agricultural practices observed in the first two dimensions of the PCA. The HCPC function from the FactoMineR package in R was then employed to conduct an agglomerative hierarchical clustering with K-means

Table 3 Cross-tabulation of clusters from Hierarchical Clustering on Principle Components ("HCPC") and archetypes from archetypal analysis ("A") results. The solid circles highlight six identified groups, while the dashed squares represent unclassified farmers. The groups derived from the archetypes are green and named "Reference groups" (Rg), and the groups from the HCPC only are orange and labeled "Intermediate groups" (Ig).



Archetypes

HCPC Clusters	A 1	A 2	A 3	A 4	Not attached to an archetype
HCPC 1	3	0	0	0	1
HCPC 2	0	0	0	0	6
HCPC 3	0	0	11	0	4
HCPC 4	0	0	0	2	3
HCPC 5	0	0	1	0	7
HCPC 6	0	7	0	0	1

consolidation, utilizing the outcomes of the PCA. The results of the HCPC have separated the 46 farmers into six clusters (Fig. 5b).

3.4 Crossover between archetypes and HCPC clusters

The groups for which the AA and HCPC results align are defined as reference groups (Rg) (Table 3). Second, all HCPC groups that do not match an archetype are defined as intermediate groups (Ig).

Of the twelve farmers assigned to the third archetype (A 3), eleven belong to HCPC group 3, and one belongs to HCPC group 5. The approach to deal with this isolated farmer in HCPC 5 was carefully considered. The first option was to merge this farmer with the eleven farmers at the A 3 – HCPC 3 intersection, but this option was rejected as it would contradict the classification performed by the HCPC. The second option was to combine this farmer with the seven farmers grouped in HCPC 5 who were not assigned to any archetype, but this was also ruled out as it would contradict the classification made by the AA. Since this farmer has a strong association with the third archetype, changing the group would risk shifting the characteristics of other farmers towards A 3. It was finally decided to exclude this farmer from all groups.

When AA and HCPC are aligned to form a reference group, the farmers in the HCPC clusters who do not belong to the archetype are not assigned to any group. The practices of these farmers show similarities to the reference group but do not meet the threshold for assignment. Their alpha coefficients, below the defined membership threshold of 0.64, position them at the intersection of two or more archetypes. Consequently, the practices of these farmers lack sufficient distinctiveness to warrant the formation of a new group.

Six groups, four Rg and two Ig (solid circles in Table 3), were identified by cross-referencing the AA and HCPC results. Ten farmers were not assigned to any group (dashed squares in Table 3).

Following the robustness test (explained in Section 2.4.4), the group formed by the intersection of the fourth archetype ("A 4") and the fourth cluster ("HCPC 4") was removed. Contrary to the other groups, deleting a single variable ("Total Species") caused both HCPC 4 and A 4 to disappear, eliminating the group formed by their intersection.

In summary, 34 of the 46 farmers in the sample were grouped into five CA-types, representing 74% of the sample.

3.5 Main features of CA-types

The analysis based on the combination of AA and HCPC identified five CA-types: three references (RgI, RgII, and RgIII) and two intermediates (Ig1 and Ig2). The comparison of the CA-types involved calculating the average scores (from 0 to 10) for each variable obtained from all the farmers within the CA-type. These scores are displayed on the radar charts in Fig. 6 and Table 4 (see supplementary data S8 for raw values).

The areas of the radar charts represent the degree of adoption of different CA practices. CA-types RgII and Ig2 have

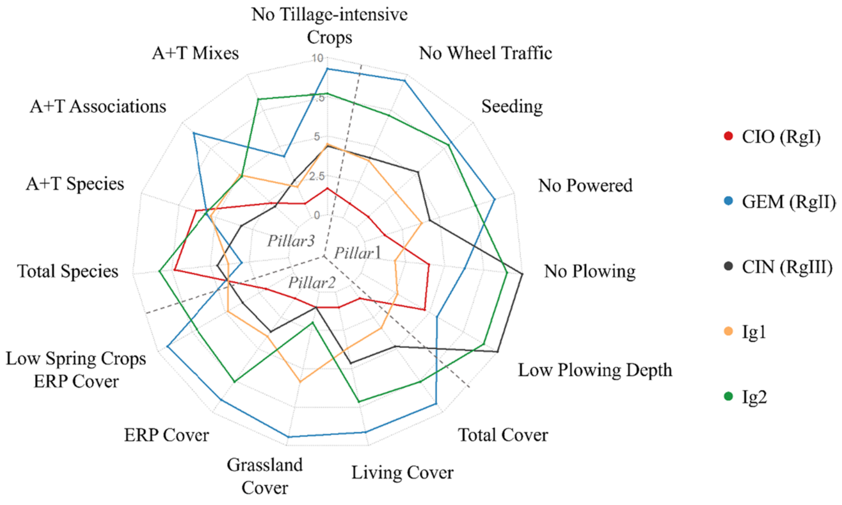


Fig. 6 Radar charts showing the average scores of Conservation Agriculture types for the 15 variables. Legend: Reference groups (RgI, II, and III), intermediate groups (Ig1 and 2), cash tillage–intensive crops organic farmers (CIO), cash tillage–intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with a mix of organic and non-organic farmers (GEM), erosion risk period (ERP), annual crops (A), temporary grassland (T).

Table 4 Average scores of each variable for each Conservation Agriculture type. See supplementary data S8 for raw values. Legend: Cash tillage–intensive crops organic farmers (CIO), temporary grassland and tillage-extensive crops with a mix of organic and non-organic farmers (GEM), cash tillage–intensive crops non-organic farmers (CIN), reference groups (RgI, II, and III), intermediate groups (Ig1 and 2), erosion risk period (ERP), annual crops (A), temporary grassland (T).

	CIO (RgI)	GEM (RgII)	CIN (RgIII)	Ig1	Ig2
Number of farmers	3	7	11	6	7
With organic certification	3	5	0	4	2
Pillar 1—minimum mechanical soil disturbance					
No wheel traffic	1	10	4	4	7
Seeding	1	8	5	3	8
No powered	1	9	4	4	7
No plowing	4	6	10	2	9
Low plowing depth	5	6	10	3	9
Pillar 1 sum	12	38	34	16	40
Pillar 2—maximum soil organic cover					
Total cover	1	9	5	3	8
Living cover	1	9	5	4	7
Grassland cover	1	9	1	6	2
ERP cover	1	9	4	4	8
Low spring crops ERP cover	2	9	4	5	7
Pillar 2 sum	6	46	18	22	31
Pillar 3—maximum species diversification					
Total species	7	3	5	4	8
A+T species	6	6	3	5	6
A+T associations	2	9	2	5	5
A+T mixes	1	4	3	2	8
No tillage-intensive crops	2	9	4	5	8
Pillar 3 sum	19	31	17	21	35
Sum of all pillars	37	116	68	58	107

large chart areas, indicating strong adoption of the CA pillars, in contrast to CA-types RgI and Ig1. The size of the radar charts varies between the CA-types, with some overlap for certain variables. Some CA-types have scores close to ten for certain variables and close to zero for others.

The reference types are distinguished by three explanatory factors used to label them: the labeling process involved considering the presence of temporary grassland in the crop sequence, the proportion of tillage-intensive crops, and the certification status of the farmers in each type. If the crop sequence includes a significant proportion of temporary grassland, the label starts with "G." If the crop sequence is based on cash crops (i.e., annual crops grown to be sold for profit), the label begins with "C." The following letter, "I" or "E," indicates whether tillage-intensive or tillage-extensive crops dominate the crop sequence. The last letter represents whether the CA-type comprises only organic (“O”), only non-organic (“N”), or a mix of both organic and non-organic farmers (“M”).

RgI, RgII, and RgIII were named CIO, GEM, and CIN, respectively, to reflect the three reference CA-types in southern Belgium: organic farmers with a significant proportion of cash tillage–intensive crops (CIO); non-organic farmers with a significant proportion of cash tillage–intensive crops (CIN); farmers (organic or non-organic) with a significant proportion of temporary grassland and tillage-extensive crops in their crop sequence (GEM). Ig1 and Ig2 have not been labeled because they do not have well-defined characteristics, being intermediate between the reference types. The main features of the CA-types are described below.

CIO. Tillage-intensive crops with organic certification

The CIO type consists of CA organic farmers with a high proportion of tillage-intensive crops in their crop sequence. These farmers have the least developed practices in Pillar 1 (mechanical soil disturbance). Frequent tillage operations and the regular use of powered tools characterize their crop sequences. The CIO type has the lowest scores for the Pillar 2 (soil organic cover) variables among all CA-types. Although crop species diversification is high, crop associations and variety mixtures are limited.

GEM. Temporary grasslands and tillage-extensive crops

The GEM type represents CA farmers with the least wheel traffic and limited use of powered tools. This type has the highest scores in Pillar 2. Temporary grassland plays an essential role in soil cover. Species diversity is the lowest of all CA-types. However, the use of crop associations is high. The proportion of tillage-intensive crops in their crop sequence is the lowest of all CA-types.

CIN. Tillage-intensive crops without organic certification

The CIN type consists of CA farmers who have stopped plowing. Their soil cover is average compared to the other CA-types, but with a lower share of cover by temporary grassland (as in CIO). This CA-type has the lowest species diversity in annual crops and temporary grassland, and limited use of crop associations and mix of varieties. Tillage-intensive crops comprise a significant part of the crop sequence, although less than in CIO.

Ig1. Intermediate group 1

Ig1, the first intermediate CA-type, consists of CA farmers with the highest plowing frequency and depth. The first pillar scores slightly above CIO, with less wheel traffic frequency. The second pillar score is close to that of CIN. The crop sequence is characterized by a significant proportion of tillage-intensive crops (close to CIN), and some farmers have temporary grassland in their crop sequence. Farmers associate crops but rarely mix varieties.

Ig2. Intermediate group 2

Ig2, the second intermediate type, consists of CA farmers with the highest Pillar 1 score, with slightly more operations and use of powered tools than GEM. These farmers no longer plow their fields (like CIN). The crops grown are mainly tillage-extensive (e.g., winter cereals, rapeseed) and allow a soil cover close to GEM without having temporary grassland in the crop sequence. This CA-type has the highest score for Pillar 3, with few temporary grassland and tillage-intensive crops, and a high mix of varieties.

4 Discussion

4.1 The diversity in Conservation Agriculture

Farmers adapt agricultural innovations based on their constraints and needs. As a result, the implementation of CA practices varies across farms (Table 2).

To characterize CA practices, the score for each pillar is derived by adding the scores of the five variables (Table 4). No single CA-type exhibits the highest scores for all three pillars, and no single CA-type obtains the lowest scores for all three pillars. Certain CA-types display both very high (10/10) and very low (1/10) scores on the variables. For instance, CIO scores low in all variables linked to the second pillar (soil organic cover) while obtaining high scores in the two variables related to species diversification (“Total species” and “A+T species”). In contrast, GEM has high scores in the second pillar’s variables but low scores in the two variables associated with species diversification.

The explanatory factors provide insight into how variables and pillars interact. Three factors were identified: (i) the share of tillage-intensive crops and (ii) temporary grasslands in the crop sequence, and (iii) the organic certification. The explanatory factors that influence the application of the CA pillars are expected to differ depending on the study area.

In terms of tillage practices, the highest number of operations and frequency of use of powered tools are observed in CIO, characterized by a combination of organic certification and a high proportion of tillage-intensive crops in the crop sequence. In contrast, non-organic farmers with a high proportion of tillage-intensive crops in CIN experience reduced wheel traffic and use of powered tools. Furthermore, all farmers in CIN have abandoned plowing, suggesting that herbicide access makes it easier for non-organic farmers to avoid plowing, regardless of the crop sequence. On the other hand, CA-types with a low proportion of tillage-intensive crops (such as GEM and Ig2)—and therefore a high proportion of tillage-extensive crops (e.g., winter cereals and rape) or temporary grasslands—show a significant decrease in both wheel traffic and the frequency of powered tools.

In relation to soil cover, CA-types with a high proportion of spring crops within their crop sequence (such as CIO and CIN) display lower total soil cover and lower soil cover during periods of erosion risk. In contrast, a high proportion of winter crops or temporary grassland in the crop sequence (e.g., Ig2 and GEM) provides an effective soil cover.

Regarding species diversification, organic certification encourages a longer crop sequence. Tillage-intensive crops can contribute to diversifying the annual crops. However, it is challenging to associate them with other species or grow them as a mix of varieties. Temporary grasslands lower the number of species grown annually but promote species associations. The most optimal species diversification is observed in crop sequences with a high proportion of tillage-extensive crops and does not include grassland, exemplified by the Ig2 CA-type.

4.2 Aim for perfection, settle for ambition

No farmer obtained the maximum score on all the variables. The highest overall score was 131/150 (as shown in the supplementary data S7). We have put forth two hypotheses, which can complement each other, to account for the imperfect implementation of all three pillars that we noted:

(i) Achieving the highest scores for each pillar and the variables constituting them is a long and challenging process. The widespread adoption of CA is relatively recent in Belgium. The Walloon farmers are still in a transitional phase and need more time, knowledge, and/or resources to perfect their technical itinerary and fully adopt the principles of CA.
(ii) Trade-offs among the three pillars make it challenging to achieve a complete and simultaneous implementation.

To check the first hypothesis, a new assessment of the diversity of CA practices in Southern Belgium in the future will determine whether they align more closely with the optimal standards defined by the FAO. Scopel et al. (2013) identified Brazilian situations in which all three pillars of CA were fully implemented. This could be attributed to longer experience with CA and better access to specific resources such as no-till seeders.

The second hypothesis is supported by the three explanatory factors. Firstly, organic certification tends to increase crop species diversity (represented by the third pillar, or P3), enhance soil preparation for weed management (first pillar, or P1), and decrease soil cover (second pillar, or P2) (P3 > P1, P2). Similarly, in Wallonia, tillage-intensive crops contribute to enhanced crop species diversity (P3) in the crop sequence, but are associated with increased soil preparation (P1) and reduced soil coverage (P3 > P1, P2). Temporary grassland, on the other hand, allows for a significant reduction in soil preparation (P1) and continuous soil coverage for several consecutive years (P2), but leads to a reduction in the number of different species cultivated annually (P1, P2 > P3). These factors, therefore, explain the occurrence of trade-offs among the three pillars of CA. Previous studies have already highlighted the partial adoption of the three pillars resulting from trade-offs confronted by farmers (e.g., Bolliger et al. (2006), Giller et al. (2011), Kirkegaard et al. (2014), Carmona et al. (2015), Bouwman et al. (2021)).

Pillar ideals (e.g., direct seeding, permanent soil organic cover, diversified rotations) are not always adequate in some regions (e.g., unavailability of herbicides, management of weeds, low yields insufficient for generating crop residues, competitive use of crop residues with livestock production, market conditions, etc.) (Bolliger et al. 2006; Giller et al. 2009, 2011; Kirkegaard et al. 2014; Bouwman et al. 2021).

4.3 A new method for categorizing the diversity of practices

This study presents a novel approach for categorizing diversity in CA practices, aligning with the broader aim of offering new classification tools in agriculture. In addition, this method has the potential for extension to various CA contexts and farming systems beyond the scope of this research.

This study focused on CA practices implemented by farmers for at least five years at the plot level. The categorization centered on the three pillars of CA and was evaluated over a crop sequence. Data collection from farmers was necessary for this participatory approach, which, albeit time-consuming, enabled capturing a broader range of elements.

This study's farming system characterization bears similarities to the approach used in the Tool for Agroecology Performance Evaluation (TAPE) (Mottet et al. 2020). The FAO framework is used by both methods to define the farming system and to break it down into pillars or elements. These pillars/elements are further disaggregated into variables or indices, and then converted into scores. Each pillar/element is assigned equal weighting.

Crossing an archetypal analysis (AA) with an agglomerative Hierarchical Clustering on Principle Components (HCPC) enabled categorizing 74% of the sampled farmers. This exceeded the results of Tittonell et al. (2020) (35%) and Tessier et al. (2021) (43%), who used only archetypal analysis. Unlike the approach of Tittonell et al. (2020) and Tessier et al. (2021), who did not consider intermediate groups, we utilized HCPC to reintroduce these farmers into the CA landscape. Through cross-referencing, we differentiated between reference and intermediate CA-types. This distinction eases the interpretation of the CA-types. While the reference types are characterized by particularly distinctive combinations of CA practices, making them easy to label, targeting intermediate types allows for identifying combinations of practices located between extreme practices.

The definition of CA proposed by the FAO provides a clear understanding of its foundational pillars. However, it has limited applicability in capturing the intensity of pillar implementation at the farm level (Brown et al. 2017). To account for region-specific nuances, it is necessary to operationalize the definition of CA to the specific context where it is studied. Wallonia, located in Southern Belgium, is an intriguing selection as a testing ground for the proposed method. This territory exhibits a rich diversity of agricultural practices and features farms with average sizes that fall between large-scale (> 200 ha) and small-scale farms (< 2 ha) (Statbel 2022).

In the first stage of the methodology, typology variables are selected based on the study context to ensure that the proposed methodology can be replicated and transferred to other regions where CA is practiced and to other farming systems. This methodology can be applied to conventional and organic farmers to compare their tillage, soil cover, and species diversification practices with CA farmers. In addition, the method can be used to categorize the diversity of other farming systems by adapting the input variables.

4.4 Perspective

Identifying and categorizing the diversity of CA practices is necessary to assess the potential of CA (Landel 2015). This understanding could be used in models, such as ARMOSA (Valkama et al. 2020), which quantify the long-term impacts of CA practices. Additionally, classifying the diversity of CA practices can facilitate understanding between the different stakeholders involved in the system, such as farmers, advisors, researchers, and politicians (Landel 2015; Huber et al. 2024). The heterogeneity observed in CA practices raises significant concerns regarding the transferability of commonly reported findings. For instance, it prompts the question of whether all CA-types possess carbon sequestration capabilities. In addition to the usual lack of consideration of the diversity of CA practices, many studies also present generalized results on CA by considering only a part of the pillars (e.g., in Thierfelder and Wall (2009), Paudel et al. (2014), Kassam et al. (2015), Gonzalez-Sanchez et al. (2015), Knapp and van der Heijden (2018), Perego et al. (2019)). These different interpretations of CA lead to conflicting results in experimental studies with different designs (Carmona et al. 2015) and extrapolation of results comparing CA with other farming systems, which are themselves diversified (Sumberg and Giller 2022).

The adoption of CA has been widely studied. However, given that CA may now be explicitly subdivided into CA-types, it would be more appropriate to examine adoption according to the specific CA-types rather than the general and diverse concept of CA. Understanding why a farmer practices a particular CA-type would help identify the factors influencing the barriers and incentives for farmers to switch to a CA-type or from one CA-type to another.

Farmers' practices evolve, and the paths of these changes differ depending on whether it is a non-CA farmer adopting a CA-type, a farmer moving from one CA-type to another, or a farmer adopting a new CA-type not yet established in Wallonia. As a result, the culmination and stability of the CA-types may vary. Over time, the CA-types could either remain stable or evolve into an existing or a new CA-type, leading to the eventual disappearance of some types.

These questions underline the need to shift away from viewing CA as homogeneous and instead focus on its diversity of practices, impacts, and pathways.

5 Conclusion

This paper introduces a novel method to categorize the diverse practices within a farming system. Focusing on the CA system in Wallonia, Belgium, we utilized a combination of archetypal analysis and hierarchical clustering to establish a categorization. By analyzing CA practices in Wallonia, the method successfully identified distinct CA-types, encompassing both extreme and salient practices called "references," and intermediate CA-types, displaying practices located between these extremes. Our method highlights explanatory factors that shed light on the interplay between CA pillars, revealing the trade-offs farmers face in their decision-making process. This innovative classification method can be adapted to other geographic contexts and farming systems.

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Authors' contributions The conception and design of the study were contributed by MF and PB. MF conducted data collection, cleaning, and analysis. MF wrote the first version of the manuscript, and both authors commented on later versions. All authors reviewed and approved the final manuscript.

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Data availability The data are available from the authors on reasonable request.

Code availability The gathered interview data was organized in a Microsoft® Excel spreadsheet and analyzed using R software. The codes (custom code) are available from the authors on reasonable request.

Declarations

Ethics approval Not applicable

Consent to participate Each farmer has signed a consent form declaring that all the information collected during the interview has been processed in compliance with the General Data Protection Regulation 2016/679, on the protection of natural persons regarding the processing of personal data and the free movement of such data, voted by the European Parliament and the Council on 27 April 2016.

Consent for publication Not applicable

Conflicts of interest The authors declare no competing interests.

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