UCLouvain
Faculté des bioingénieur·es

The Diversity of Practices in Conservation Agriculture

Categorization and Impact Assessment in the Walloon Region, Belgium

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Un proverbe africain nous rappelle qu'il faut tout un village pour élever un enfant. Alors qu'une thèse est souvent comparée à un enfant pour illustrer le long processus de gestation, s'étendant sur plus de quatre ans, et l'accouchement libérateur qui survient lors de la défense publique, j'aimerais ici plutôt vous parler de ce village qui a permis à cette thèse de voir le jour, d'exister, et de prendre son envol.

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« Les promoteurs de thèse ce sont comme des sage-femmes. Ce ne sont pas eux qui accouchent, mais ils savent comment c'est, comment il faut se mettre pour que ça se passe bien. Tu as porté le bébé, maintenant il va falloir accoucher. » (Philippe Baret, octobre 2023)

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Foreword

It was decided to write one chapter of the manuscript in French and the others in English. The choice of language was based on the language of the readers for whom each section is intended. Thus, the section presenting results that are specific to Wallonia and cannot be extrapolated is written in French, while those with an international scope are written in English.

Avant-propos

Il a été décidé de rédiger un des chapitres en français tandis que les autres sont en anglais. Le choix de la langue a été guidé par la maîtrise potentielle des lecteurs à qui chaque section est destinée. Par conséquent, les parties exposant des résultats spécifiques à la Wallonie et non extrapolables sont rédigées en français, tandis que celles avec une portée internationale sont rédigées en anglais.

Summary

Scientists and policymakers are promoting Conservation Agriculture (CA) to reduce soil erosion and greenhouse gas emissions. While numerous studies have already highlighted the diversity of CA practices, no method has been proposed for identifying and evaluating it.

This thesis proposes a multi-scale, interdisciplinary, participatory methodology to identify and assess this diversity.

In Wallonia, five CA-types have been identified and differentiated by organic certification, the presence of temporary grassland, and the proportion of industrial crops in the rotation. Analysis shows significant differences in soil structural stability and carbon content: CA-types that include temporary grassland in their rotation, even if they occasionally plow, have higher stability and carbon content than those that have abandoned the plow altogether and grow industrial crops in their rotation. Farmers' incentives to adopt these practices vary within the same CA-type, as do their prospects for changing CA practices.

This study highlights the diversity of CA practices at the regional level, the diversity of impacts, and the diversity of incentives and prospects for change within CA-types, with implications for other areas and farming systems. More generally, it questions the boundaries of farming systems and the policy choices associated with them.

Résumé

Scientifiques et politiques promeuvent l'Agriculture de Conservation (AC) pour réduire l'érosion des sols et les émissions de gaz à effet de serre. Cependant, tandis que de nombreuses études ont déjà souligné la diversité des pratiques agricoles existantes en AC, aucune méthode n'a actuellement été proposée pour l'identifier et l'évaluer.

Cette thèse propose une méthodologie multi-échelle, interdisciplinaire et participative, pour identifier et évaluer cette diversité.

Sur le territoire wallon, cinq types d'AC ont été identifiés, se distinguant par la certification biologique, la présence de prairie temporaire, et la part de cultures industrielles dans la rotation. Une analyse met en évidence des distinctions notables dans la stabilité structurale du sol et les teneurs de carbone : les types d'AC qui intègrent une prairie temporaire dans leur rotation, même s'ils ont recours à des labours occasionnels, affichent une stabilité et des teneurs de carbone plus élevées que ceux qui ont abandonné complètement la charrue et cultivent des cultures industrielles. Au sein d'un même type d'AC, les incitations des agriculteurs à adopter ces pratiques varient, de même que leurs perspectives de changement de pratiques AC.

Cette étude met en lumière la diversité des pratiques AC à l'échelle régionale, la diversité des impacts, et la diversité des incitants et des perspectives de changements au sein des types d'AC, offrant des implications pour d'autres territoires et systèmes agricoles. Plus globalement, elle conteste les frontières des systèmes agricoles et les choix politiques associés.

List of main abbreviations and acronyms – Liste des principales abréviations et acronymes

English	EN	Français	FR
Agricultural Machinery Cooperatives	/	Coopérative d'Utilisation de Matériels Agricoles	CUMA
Archetypal Analysis	AA	Analyse Archétype	AA
Belgian Statistics Directorate General	STATBEL	Direction générale Statistique de Belgique	STATBEL
CA farmers	/	Agriculteur pratiquant l'AC	ACiste
Carbon	C	Carbone	C
Cation Exchange Capacity	CEC	Capacité d'échange cationique	CEC
Common Agricultural Policy	CAP	Politique Agricole Commune	PAC
Conservation Agriculture	CA	Agriculture de Conservation	AC
Direct seeding	DS	Semis direct	SD
Erosion Risk Period	ERP	Période à risque d'érosion	ERP
European Conservation Agriculture Federation	ECAF	Fédération européenne de l'agriculture de conservation	ECAF
Food and Agriculture Organization	FAO	Organisation des Nations unies pour l'alimentation et l'agriculture	FAO
Genetically Modified Organism	GMO	Organisme génétiquement modifié	OGM
Greenhouse gases	GHG	Gaz à effet de serre	GES
Hierarchical Clustering on Principal Components	HCPC	Classification Hiérarchique sur Composantes Principales	HCPC
Organic Conservation Agriculture	OCA	Agriculture Biologique de Conservation	ABC
Organic Matter	OM	Matière Organique	MO
Permanganate Oxidizable Carbon	POXC	Carbone Oxydable au Permanganate	POXC
QuantiSlake Test	QST	QuantiSlake Test	
Soil Organic Carbon	SOC	Carbone Organique du Sol	COS
Soil Organic Matter	SOM	Matière Organique du Sol	MOS
Simplified Cultivation Techniques	SCT	Techniques Culturales Simplifiées	TCS

Utilised Agricultural Area	UAA	Superficie Agricole Utile	SAU
United States	US	Etats-Unis	/
Walloon Region	WR	Région wallonne	RW

Glossary

Topic	Term	Our definition
Crop	Annual crop	Crops grown for sale and forage crops grown for less than one year.
	Association	Two or more crop species grown simultaneously on the same plot, not necessarily sown and harvested at the same time.
	Cash crop	Crop grown to be sold for profit.
	Catch crop	Cover crop harvested for grain production, green fodder or silage.
	Cover crop	Fast-growing crop planted between the harvest and sowing of two main cash crops, usually unharvested, and used to protect soil or water resources. Also called intercrop, intermediate crop, or green manure.
Grassland	Temporary	Grass or forage that remains in place for at least one year and no more than five years.
	Permanent	Grass or forage that remains in place more than five years and is not typically included in a rotation.
Soil Cover	Dead mulch	Organic material spreads over the soil (crop residues, compost, decaying leaves, etc.) to protect it (e.g., from erosion) or enrich it.
	Living mulch	Crops sown to cover the soil, commonly known as cover crops.
Soil working	Direct seeding	The planting of a crop without mechanical soil preparation. The soil is only disturbed at the point where the seed is deposited. Also called zero-till or no-till.
	Non-inversion tillage	A soil preparation practice involving fragmentation, mixing and burial without horizon inversion.

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. It could also be called strategic inversion tillage.
Plowing	A soil preparation practice where the soil horizons are inverted, usually to a depth of 30 cm.
Simplified cultivation techniques	Refers to loosening and subsoiling operations, pseudo-plowing, shallow strip tillage, and surface cultivation.
Strip-till	A soil preparation practice consists of working only on the future seed rows to encourage crop start-up by creating fine soil while leaving the inter-rows untouched.
Tillage	Any mechanical operation that fragments the soil.

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Chapter 1 General Introduction

This introductory section focuses on the presentation of the chosen field of study: Conservation Agriculture (CA). We begin by examining its historical background, shedding light on its development, origins, and global spread.

After setting this context, we outline the existing gaps in CA research. Borrowing the English metaphor, we have identified not one, but three elephants in the room: firstly, a still ambiguous definition of CA that hinders its practical use; secondly, a well-known but unstudied diversity of CA practices; and thirdly, a diversity of outcomes arising from this diversity of practices, which remains largely unexplored. We identify research questions arising from these gaps and articulate the objectives that this thesis aims to achieve.

Next, we explore the methodological approach used to conduct this dissertation. Finally, we will unveil the structure of the thesis, providing a clear overview of the organizational framework. This preliminary presentation will serve as a guide for the reader, facilitating navigation through the various sections and chapters of the thesis.

1. Introduction to Conservation Agriculture

1.1. From Dust Bowl to carbon sequestration

The plow emerged in various locations throughout northern Europe during the early Christian era (Mazoyer and Roudart 1997) and rapidly became essential to modern farming practices (Goulet and Vinck 2012).

Unlike alternative soil cultivation methods, plowing involves inverting soil horizons, typically between 15 and 40 cm (Labreuche et al. 2014). This operation serves multiple purposes, including loosening the soil, removing crusts, reducing compaction, allowing weed management, promoting crop regrowth and residue burial, facilitating the incorporation of organic matter (OM), stimulating nutrient release via mineralization, aiding in pest and disease control, … (Hobbs et al. 2008; Derpsch et al. 2024).

After the World War I, agricultural practices began to transition toward industrialization, primarily in North America (Derpsch et al. 2024). This shift relied increasingly on agrochemical products and intensive soil cultivation, while diversified cropping systems were disappearing (Derpsch et al. 2024). In the 1930s, the combined effects of recurrent plowing, low soil cover, and overgrazing made Great Plains croplands particularly susceptible to wind erosion (Joel 1937; Hobbs 2007), resulting in numerous dust storms (Baveye et al. 2011). This phenomenon, known as the “Dust Bowl”, led to significant soil losses (Baveye et al. 2011) and prompted American farmers to implement soil conservation practices, such as reduced plowing and soil disturbance, as well as maintaining ground cover (Hobbs 2007).

After World War II, agricultural industrialization spread to European territories. Coupled with the Green Revolution, similar consequences as those experienced in the United States (US) emerged, including yield stagnation below agroecological potentials, high input costs, soil erosion, reduced soil resilience, and overall environmental and climatic degradation (Derpsch et al. 2024).

In 1998, following the global recognition of the soil erosion problem, the Food and Agriculture Organization of the United Nations (FAO) introduced and defined the concept of Conservation Agriculture (CA) (Kassam 2022). According to the FAO (2023a), CA is a cropping system founded on three pillars (or principles): i) minimum mechanical soil disturbance, ii) permanent soil organic cover, and iii) diversification of cultivated species.

At the outset, farmers implemented CA to mitigate soil erosion and degradation (Kassam 2022). Subsequently, CA has evolved into a strategy to reduce production costs while maintaining and enhancing soil health and fertility (Kassam 2022).

In December 2015, the COP21 in Paris launched the “4 per 1000” initiative (Minasny et al. 2017). The initiative aims to enhance the potential for sequestering atmospheric CO_2 by soils, particularly agricultural soils, to raise global soil organic carbon (SOC) stocks by 4 per 1000 (or 0.4%) annually. Its objective is to counterbalance global anthropogenic greenhouse gas (GHG) emissions, improve soil adaptation to climate change, and promote soil fertility (Chenu et al. 2019).

Studies have shown that no-till, cover crops, adding carbon inputs, and crop rotations, have the potential to sequester carbon (Minasny et al. 2017). However, causative links between these practices and carbon sequestration are now being questioned (Chenu et al. 2019). When plowing is interrupted, the increase in SOC stock is low, or even non-significant (Chenu et al. 2019). As for the potential sequestration related to the simultaneous implementation of the three pillars of CA, it varies among studies and still requires further in-depth research (Chenu et al. 2019).

Since 1998, the search for CA has been gradually expanded. To provide an overview of the scientific publications on CA, its three pillars, soil health, and carbon sequestration up to December 31, 2022, the Scopus database was searched by title (see legend in Figure 1). Figure 1 shows the results of the period from 1980 to 2022.

The earliest publications were from the 1950s for reduced soil tillage and soil cover, and the 1960s for crop diversification. Research on soil health began in 1907, while studies on soil carbon sequestration started in 1992. The studies specifically focused on carbon sequestration in CA began in 2009, six years before the launch of the "4 per 1000" initiative. Publications on these topics gained momentum mainly in the late 1990s. Publications on reduced soil tillage increased from 2005, a decade before those related to soil health. In 2015, the year of COP21, a significant surge in research on living soils and CA is observed.

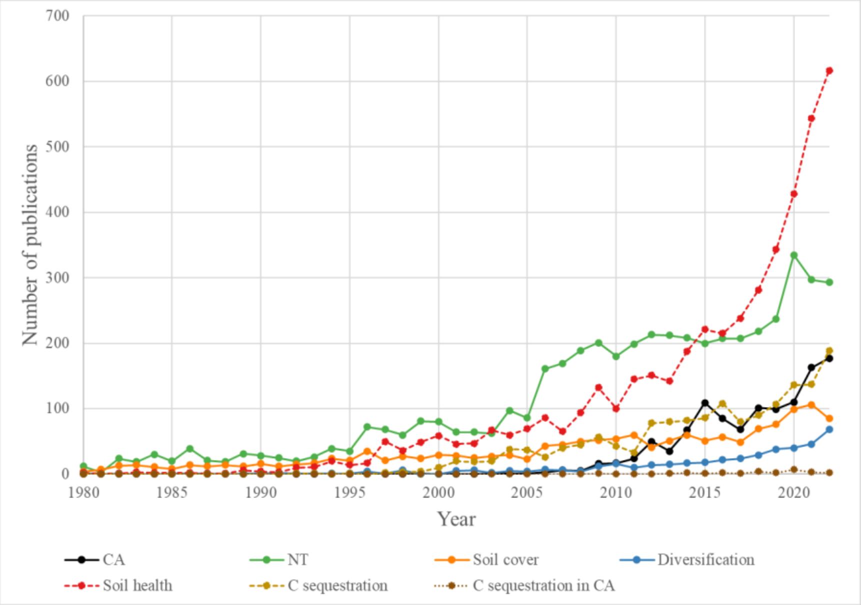

Figure 1 Scientific documents related to CA published between 1980 and 2022, according to the Scopus database

Explanatory notes on bibliographic text search:1. CA: TITLE("conservation agriculture"); 2.NT: TITLE("No-till" OR "reduc* till*" OR "direct seeding" OR "direct sowing" OR "direct drill"); 3. Soil cover: TITLE("soil cover*" OR "ground cover*"), 4. Diversification: TITLE("crop* diversif*" OR "specie* diversif*"); 5. Soil health: TITLE("living soil" OR "soil quality" OR "soil health"), 6. Carbon (C) sequestration: TITLE("carbon*" AND "sequestr*"), 7. C sequestration in CA: TITLE("carbon*" AND "sequestr*" AND "conservation agriculture").*

1.2. History of Conservation Agriculture

As presented in the previous section, the history of CA can be traced back to the adoption of no-till practices in the Great Plains after the Dust Bowl of the 1930s. This event serves as a warning to farmers, policymakers and citizens and stimulated the establishment of an institutional framework to investigate soil erosion and develop solutions, making the US became the cradle of the modern CA movement (Kassam 2022).

Afterwards, two technologies significantly influenced the development and adoption of no-till (Kassam 2022). Firstly, the development of chemical weed control to replace tillage. After the arrival of selective herbicides such as 2,4-D in the 1940s and atrazine in 1952, two non-selective herbicides, paraquat in 1958 and glyphosate in 1971, greatly influenced the adoption of no-till (Kassam 2022). The latter two herbicides allowed for quick termination of existing vegetation which made primary tillage for weed control unnecessary

(Kassam 2022). Secondly, the emergence of Genetically Modified Organism (GMO) herbicide-resistant crops in 1990s plays a crucial role in the transition to no-till for US farmers (Kassam 2022). In 2022, 94% of soybeans, 98% of cotton and 90% of corn acreages grown in the US are herbicide-tolerant (most significantly glyphosate) (Kassam 2022).

In contrast, the other two pillars of CA are still relatively underdeveloped in the US : cover crops are still in their infancy and are used on only 5% of the planted cropland, while crop diversity relies mainly on five crops: corn, soybean, hay, wheat, and cotton (Kassam 2022).

In 1972, CA was first introduced in Brazil before spreading throughout South America (Kassam 2022). The development, adoption, and success of no-till were initially led by farmers and the main drivers for adoption were the need to stop soil erosion and the advantages of savings fuel, labor and time (Kassam 2022).

In New Zealand, the initial experimentation with untilled soils for pasture renovation dates back to the 1950s (Kassam 2022). However, the substantial potential of no-till practices as a viable alternative to conventional tillage only began to emerge in the 1960s, coinciding with the availability of paraquat herbicide (Kassam 2022). Subsequent widespread adoption accelerated notably in the 1970s with the introduction of glyphosate (Kassam 2022).

The history of CA varies among European countries (Kassam 2022). The earliest instances of CA in Europe have emerged in the United Kingdom and Scandinavian countries (Lahmar 2010). Apart from Norway and Germany, which actively encourage and subsidize CA, adoption of this new agricultural system is primarily initiated and driven by farmers themselves (Lahmar 2010; Stroud 2020). In Wallonia, some farmers started practicing no-till agriculture in the 1980s (Vankeerberghen and Stassart 2016).

CA has been growing in Europe since the mid-1990s (Vankeerberghen and Stassart 2016). During this time, herbicides (Hunt et al. 2020) and new seeding technologies (Pittelkow et al. 2015b) has facilitated the implementation of no-till practices. The efficacy of no-till techniques among farmers is attributed to the benefits they confer in reducing costs, especially those incurred in fuel and labor expenses, while additionally mitigating soil erosion and retaining soil moisture (Holland 2004). Notably, water erosion is a prevalent form of soil degradation across the European Union (Panagos et al. 2022a).

1.3. Deployment of Conservation Agriculture

CA is practiced in diverse agricultural landscapes, spanning equatorial tropics to Arctic circles, at altitudes ranging from sea level to over 3000 meters, crossing regions with precipitation ranging from 3000 mm to less than 250 mm, and including soils with compositions ranging from 90% sand to 80% clay (Kassam et al. 2018). Moreover, CA pillars can be applied to the cultivation of all types of crops, including root and tuber plants (Kassam et al. 2018).

Since 2008, the worldwide area of arable land managed under CA has increased to approximately 10.5 million hectares per year (Kassam et al. 2018). In 2018/19, it reached 205.4 million hectares, which equals 14.7% of the total global cultivated land area (Kassam 2022). At the Eighth World Congress on CA in 2021, a will was formulated by the congress to increase the global CA cropland area to 50% of the total cropland by 2050, representing an area of 700 M ha (Kassam 2022). Currently, the largest proportion of cultivated land under CA is recorded in Australia and New Zealand (74.0% of cropland area is under CA in the region), followed by South and Central America (68.7%), North America (33.6%), Europe (5.2%), Russia and Ukraine (4.5%), Asia (3.6%), and Africa (1.1%) (Kassam 2022). Spain, France, Romania, the United Kingdom, and Italy are the top five European countries practicing CA (Kassam 2022).

The limited adoption rate of CA among European farmers can be attributed to various factors. Firstly, there needs to be more knowledge on CA and it management, which, coupled with the complexity of knowledge required for farmers, poses significant obstacles (Lahmar 2010; Cristofari et al. 2017). Additionally, the benefits of CA are context-dependent and only become apparent in the medium or long term (Cristofari et al. 2017; Varia et al. 2017). Moreover, the historical orientation of the Common Agricultural Policy (CAP) has encouraged farmers to maximize yields (rather than reduce production costs) (Cristofari et al. 2017). Furthermore, the need for external incentives and pressures to adopt novel agricultural techniques, in conjunction with the favorable agricultural conditions, could account for the reluctance to modify long-standing practices (Kassam 2022).

In Belgium, data regarding the extension of CA vary considerably depending on the sources. According to Eurostat (2020), at least 10% of Belgian arable land is reported to be under no-till cultivation, placing Belgium among the four European countries with the highest adoption of this technique. However, concerning the full implementation of the three pillars of CA, international data indicates that only 270 hectares (Kassam 2022) to 300 hectares (ECAF 2023) of Belgian arable land are cultivated using this approach. The data provided by Eurostat (2020) and Kassam (2022) are sourced from Statbel

(SPF Economie), and the methods employed for estimating these areas are not specified.

The discrepancies and uncertainties in estimating CA adoption are not exclusive to Belgium and have been highlighted in several studies (Brown et al. 2017; Prestele et al. 2018; Bouwman et al. 2021). This inconsistency can be attributed to several factors. Firstly, variations in the definitions of CA and the ambiguity regarding the interpretation of “practicing CA”, result in confusion when interpreting the data (Andersson and D’Souza 2014). For instance, some studies limit CA to no-till practices exclusively (Prestele et al. 2018; Bouwman et al. 2021). According to Prestele et al. (2018), between 9% and 15% of global arable land is managed under CA: 9% if CA involves the combined practice of no-till with crop residue management and crop rotation, and 15% if CA encompasses a broad range of reduced soil tillage operations. The variation ranges from 2.3% to 25% when applying the same rationale to European agricultural land (Prestele et al. 2018). Based on this information, it is reasonable to question the high percentages of land under CA in Australia, New Zealand, and the Americas, as presented by Kassam (2022) and mentioned above. It seems likely that these percentages reflect the adoption of no-till rather than the joint adoption of three pillars of CA.

Furthermore, many areas designated as “no-till” may correspond to fields where no-till is used only for certain crops in the crop sequence (usually cereals and rape), while the other crops grown on the same plot are subject to conventional plowing (Lahmar 2010). Additionally, numerous studies emphasize the lack of a standardized method and an official monitoring system to measure the extent of CA plots (Brown et al. 2017; Prestele et al. 2018). Finally, the precision of statistics and survey data must be improved (Prestele et al. 2018). Spain is one of the few European countries actively monitoring and generating official CA statistics (Carmona et al. 2015).

2. Three elephants in the room

The English expression “the elephant in the room” is often used to describe a situation where a crucial topic, important issue, or obvious problem is widely perceived but curiously avoided in discussion. In this thesis, we argue that not one, but three elephants occupy the space of thinking around CA. Despite they are obviously difficult to hide, no one has yet addressed them directly.

2.1. An ambiguous definition of Conservation Agriculture and the pillars

The definitions of CA and its three pillars exhibit discrepancies across scientific literature, resulting in a lack of clarity that impedes its consistent application. The concept of CA was developed to unify various soil conservation techniques under a common banner to promote these practices (Knowler 2015). While some researchers summarize CA into the first two pillars (e.g., Li et al. (2018)), others incorporate a fourth pillar (e.g., Vanlauwe et al. (2014)) or give specificity to one of the pillars (e.g., introducing legumes into the definition of the third pillar by Bohoussou et al. (2022)). As the pillars are not directly translated into agricultural practices, this offers flexibility in interpretation and application. Ambiguities persist regarding the meaning of “minimal” soil mechanical disturbance or the determination of the threshold for “permanent” soil cover (Sumberg and Giller 2022).

Questions also remain regarding the boundaries of the CA system and the selection of reference points for practice thresholds, whether compared to prevailing practices, farmers’ skills, self-defined limits, or achievable thresholds recognized in a specific context and within a given crop rotation. For accurate interpretation and comparison of CA studies, it is crucial to define its boundaries precisely. Coherence may ensure the comparability of studies assessing the extent of CA adoption (refer to the previous section) and evaluating impacts on crop yields, farm profitability, or environmental repercussions induced by these practices.

The definitions of CA and its three pillars must align with the conservation practices implemented by farmers globally while being easily understandable by all stakeholders on a regional scale. For example, specifying the second pillar that entails permanent soil cover (365 days a year) and a significant density (at least 30% of the soil covered) is only reasonable if this practice is currently or can be feasibly implemented in the field. Consolidating the definition of CA is imperative to ensure its robustness and practical applicability.

2.2. An understudied diversity of Conservation Agriculture practices

Various CA practices are observed not only between distinct geographic areas but also within the same region. The pillars of CA distinguish this agricultural system from others (Sommer et al. 2014), establishing its boundaries and limits. Each pillar can be implemented through various practices within these limits (Scopel et al. 2013). Although CA can be applied across diverse agricultural landscapes and land uses (Kassam et al. 2018; FAO 2023a), its implementation modalities depend on local constraints such as climate, soil type, socio-economic conditions, accessibility to tools and seeds, as well as the needs, resources, and goals of individual farmers (Coughenour 2003; Giller et al. 2009; Kertész and Madarász 2014; Vankeerberghen and Stassart 2016; FAO 2019; Derrouch et al. 2020). Farmers adapt and implement each pillar of CA according to specific constraints, leading to a diverse range of soil conservation practices (Sumberg and Giller 2022).

This flexibility in applying the pillars is apparent in the contours of the definitions provided for CA, as illustrated by the FAO (2023a)'s guidelines. These encompass various practices, ranging from periodic tillage to direct seeding, with 30% to over 90% soil coverage, and a rotation involving at least three different crops, with no maximum specified.

The diversity of CA practices is highlighted when researchers discuss the challenges of implementing all three pillars of CA simultaneously (e.g., Bouwman et al. (2021), Bohoussou et al. (2022)), or when explaining the range of terms and reduced tillage techniques associated with the first pillar (e.g., Baker et al. (2007)).

Although the scientific community has extensively acknowledged and reported the diversity of CA practices (e.g. in Lahmar (2010), Scopel et al. (2013), Pannell et al. (2014), Craheix et al. (2016), Vankeerberghen and Stassart (2016), Brown et al. (2017), Derrouch et al. (2020), Bouwman et al. (2021)), there is a lack of identification of the diversity of CA practices implemented by farmers, considering all three pillars on a regional scale. This has led to the exclusion of this diversity in CA analysis.

2.3. The hidden diversity of Conservation Agriculture outcomes behind the diversity of practices

CA has received significant attention in academic research due to its potential to address pressing global crises. According to Kassam (2022), CA systems plays a pivotal role in tackling various challenges, including "food insecurity, climate change, loss of biodiversity, environmental degradation, unsustainable diets and human ill health".

In contrast to tillage-based agriculture systems, CA could offer numerous environmental benefits. According to Derpsch et al. (2024), it provides important ecosystem services, such as improving surface water quality, reducing soil erosion, increasing soil moisture retention, enhancing water infiltration, improving soil tilth, creating wildlife habitats, reducing air pollution, and promoting biodiversity. Furthermore, CA helps to reduce greenhouse gas emissions by decreasing the release of carbon dioxide into the atmosphere and increasing carbon sequestration in the soil (Kassam 2022; Derpsch et al. 2024).

The economic aspect has also been one of the main benefits highlighted for farmers' transition to CA since the 1990s (Derpsch et al. 2024). Derpsch et al. (2024) identify several economic benefits, including reduced labor requirements, time savings, less wear and tear on machinery, substantial fuel savings (up to two thirds), and improved long-term productivity.

In addition, policies are promoting CA as a sustainable agricultural practice. Initiatives such as Carbon Farming, integrated into eco-schemes of the Common Agricultural Policy (CAP), highlight the importance of incentivizing land managers to adopt practices that promote carbon sequestration and biodiversity enhancement (European Commission 2022). The pillars of CA are recognized as effective carbon farming practices, aligning with the goals of sustainability and environmental stewardship.

Among the political issues at stake was also the renewal of glyphosate in November 2023, a renewal that seemed essential for maintaining soil conservation practices and motivated by the benefits attributed to these practices, deemed to outweigh the potential harmful effects of glyphosate on the environment (European Parliament 2023; Le Soir 2023).

However, these discourses do not integrate the diversity of practices in CA. The range of practices within CA is likely to result in diverse outcomes and potential benefits. The outcomes and sustainability of the system are significantly influenced by the specific CA practices that are implemented (Scopel et al. 2013). Depending on the type and intensity of CA practices employed, the benefits associated with CA, whether environmental or socio-economic, will be impacted (Cristofari et al. 2017, 2018).

Determining the diversity of CA practices permits an evaluation of their impact, enhances comprehension of farmers' decisions, guides policy-making, and improves communication within and between scientific communities and field practitioners (Landel 2015).

3. Research questions and objectives

The previous section outlines the necessity of defining the boundaries of CA to ensure consistency and comparability across studies, while facilitating the identification of practices on a regional scale. It also highlights the diversity of CA practices within each territory, and raises questions about its potential impact on economic, social, and environmental outcomes.

This research seeks to identify the diversity of CA practices on a regional scale and to assess how this diversity influences CA impacts. More specifically, this thesis aims to study the impact of the diversity of CA practices on soil quality indicators, as well as on farmers' transition processes.

This overarching objective addresses several research questions, each generating a thesis sub-objective (Figure 2) and requiring a specific methodology for resolution.

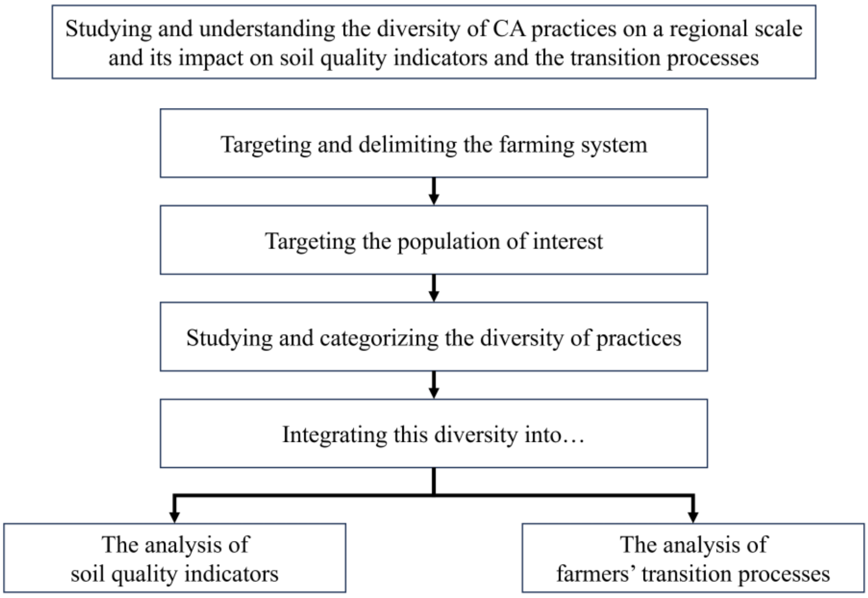

Figure 2 Sub-objective diagram to achieve the main objective of the thesis

1. What is a robust and operational definition of CA?

Our first sub-objective, linked to the taming of the first elephant in the room, is to build a practical definition of CA by defining the practices that delimit the system. This requires examining existing definitions for similarities and differences, using two primary sources: publications from the Food and Agriculture Organization of the United Nations (FAO), and research articles established as references in the CA field. Based on this analysis, we proposed an improved definition of CA that facilitates the identification of CA practices through guidelines broad enough to encompass CA practices worldwide and adaptable to local contexts.

2. Who are the CA farmers?

Our second objective is to delineate the population of CA practitioners within the study region. To achieve this, it is essential to understand this demographic to establish prohibitive criteria for identifying individuals as adherents of CA. Subsequently, an inventory of CA farmers is conducted in collaboration with local stakeholders. Finally, a thorough depiction of the CA landscape within the territory is presented, encompassing various facets and nuances of CA adoption and implementation.

3. **How can we highlight the diversity of CA practices?**

The third objective is to propose a systematic approach for categorizing various CA practices at a regional scale. Hence, a novel classification method has been devised to classify CA practices in a specific region. This method is based on the intersection of results from archetypal analysis and hierarchical classification. These two approaches enable the identification of salient and intermediate CA practices, as well as the factors that determine the groups.

4. **Do these different CA practices have different impacts on soil quality?**

We hypothesize that the type of practices implemented conditions the impact of CA. The fourth objective is therefore to integrate the diversity of practices identified in the CA assessment.

Our first approach focuses on soil quality, to assess and compare the impact of various types of CA on the latter. A comparative analysis is carried out based on several plots managed under CA, using soil structure, the Carbon:Clay ratio and labile carbon fraction indicators.

5. **Do farmers practicing different CA-types have different transition processes?**

As part of our goal to integrate the diversity of CA practices into the CA assessment, our second approach is to analyze and compare the diversity of drivers of change and the future changes in CA practices across CA-types. We intend to explore the incentives that motivate farmers to transition to CA and determine whether they vary according to the CA-type implemented. In addition, our study analyzes the stability of current CA practices and the future development or maintenance plans of farmers. The insights presented are based on semi-structured interviews conducted with farmers who practice CA.

4. Approaches used

The thesis employs a multi-scale and transdisciplinary approach. Tress et al. (2005) state that transdisciplinarity merges interdisciplinarity and a participatory method. This type of research mobilizes various disciplines and engages non-academic participants, such as farmers, to create new knowledge (Tress et al. 2005).

4.1. Multi-scale approach

Identifying and understanding the diversity of farming practices within a system, in this case CA, requires going beyond the farm level and exploring several scales. While the categorization of practices and the comparative assessment of soil qualities focus on the plot entity, the analysis of pathways simultaneously considers technical constraints at the plot and farm level, and sectoral constraints on a broader scale. This analysis is thus part of the overall landscape in which the farmer carries out his/her activity, integrating the various players with whom she/he interacts.

4.2. Participatory approach

During the Green Revolution, scientific research, particularly in chemistry and agricultural machinery, had a significant impact on agriculture. Since then, agricultural R&D is still commonly viewed as the primary source of innovation (Lamé et al. 2015). More recently, the top-down approach has been challenged by the recognition that innovation often originates on the farm (Salembier et al. 2021). Therefore, farmers are increasingly involved in innovation and knowledge production, bringing their empirical and technical knowledge (Lamé et al. 2015).

Designing farming systems that are economically, socially, and environmentally sustainable, while taking into account the multiple potential objectives of farmers, which are themselves conditioned by soil, climate, and socioeconomic contexts, is a uniquely complex undertaking (Quinio et al. 2021). By adapting their production systems to their specific constraints or opportunities, farmers innovate to improve their production systems (Lamé et al. 2015). Collaboration between researchers and farmers fosters the co-construction of innovative, field-applicable knowledge and technologies (Wauters and Mathijs 2013a; Pradhan et al. 2018; Stroud 2020; Aare et al. 2021). Considering field realities and farmers' knowledge can help to reduce the disconnects between the field, scientific research, and policy. This, in turn, can improve the dialogue between the various stakeholders and facilitate informed decision-making for the future of the agricultural sector, enabling the sustainable development of farming systems (Aare et al. 2021). To facilitate the adoption of sustainable farming systems, it is essential to characterize their performance and understand the conditions for success (Lamé et al. 2015).

Participatory research is commonly defined as the collaboration between academic researchers and non-academic stakeholders, such as farmers (Tress et al. 2005). This definition encompasses a range of approaches depending on the level of involvement of the farmers in the research (Chevalier 2022). Farmers can provide knowledge, serve as targets for learning or co-innovate with researchers (Lacombe et al. 2018). The relationship between farmers and researchers can be contractual, consultative, collaborative, or collegial[1] (Bigss (1989) as cited by Chevalier (2022)).

Farmers are rarely involved in all stages of the research process. Usually, collaboration with farmers is limited to evaluating the adoption of a particular innovation (Lacombe et al. 2018). However, in our situation, we started with innovations implemented by farmers. This approach required a different level of involvement and different methods. In this thesis, farmers were involved on three separate occasions (Figure 3).

First, 48 farmers were consulted through semi-directed interviews in order to trace their CA crop sequences to identify and categorize the diversity of CA practices implemented in Wallonia (cf. Chapter 4). Unlike studies that aim to design CA systems that are a priori adapted to local constraints (e.g. Djamen (2014), Hauswirth et al. (2015)), the aim here is not to design, but rather to identify what already exists. Farmers innovate and design knowledge that is adapted to their specific needs, capabilities and constraints - geographical, cultural, social or economic - under changing conditions such as climate change and fluctuating market prices (MacMillan and Benton 2014; Aare et al. 2021). Innovative practices adopted by some farmers are therefore more likely to be suitable for others (Aare et al. 2021; Queyrel et al. 2023).

Second, we collaborated with farmers to select the fields on which soil samples were taken to assess the impact of CA practices on soil quality indicators (cf. Chapter 5). The collaboration was carried out with farmers who had more than five years' experience of CA, which reduced the number of farmers from 48 to 28. The interviews were structured, i.e. based on closed questions. By working with the farmers, it was possible to select the plots that best met the sampling criteria for soil analysis. This methodology offers an in-depth analysis of the farming system's complexity, which is different from controlled experiments in test plots where only one factor is changed at a time (Aare et al. 2021). It allows a more realistic approach by exploring possible correlations between agricultural practices and their effects, and fits in with the emerging trend toward payment by results.

Third, farmers were consulted through semi-structured interviews to conduct a qualitative analysis of their drivers of change and future changes in CA practices (cf. Chapter 6). Only farmers whose CA practices were classified in one of the CA-types were analyzed, reducing the number of farmers from 48

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[1] (i) in the contractual form, a contract is signed between farmers and researchers to clarify the roles of each party; (ii) in the consultative form, researchers consult with farmers to obtain their advice on their research; (iii) in the collaborative form, researchers and farmers work together, but the project remains designed by the researchers; (iv) in the collegial form, researchers and farmers work as colleagues and develop the research together (Chevalier 2022).

to 34. Consultations with farmers effectively capture their reasoning, perceptions and knowledge based on their experiences (Aare et al. 2021). This sheds light on the incentives and barriers influencing their decision-making processes. The participatory approach provides a deeper understanding than closed surveys (Sovacool et al. 2018). It gives a holistic perspective on the issues that influence farmers' decisions. Given that new farming practices may involve agronomic, technical, social, and structural changes, this approach allows us to go beyond purely agricultural considerations. It facilitates an understanding of the influence of external actors on decision-making processes and cognitive interactions within the system and identifies existing pressures that are likely to block the system in its current state (Aare et al. 2021).

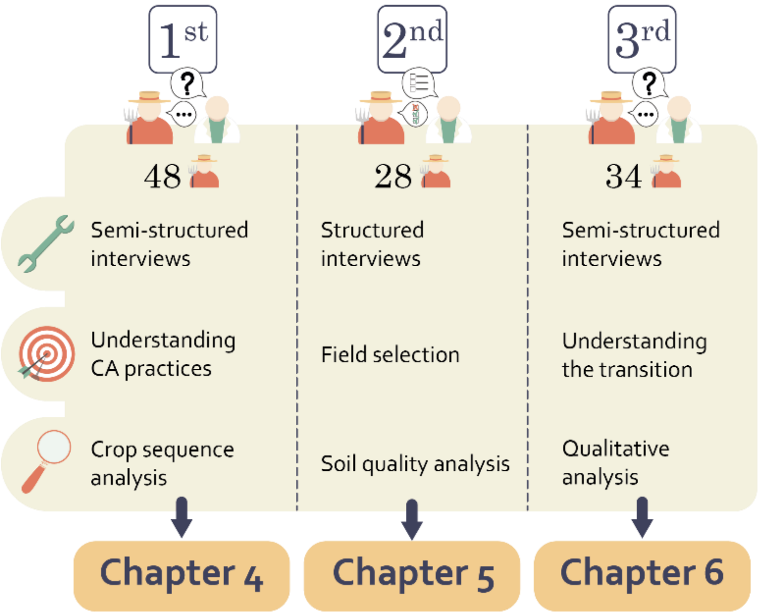

Figure 3 Steps of the participatory process, designed by Céline Chevalier (UCLouvain/Sytra)

4.3. Transdisciplinary approach

The transdisciplinary approach integrates a participatory approach into an interdisciplinary research (Tress et al. 2005). It is thus defined as an approach involving academic researchers and non-academic participants, integrating different disciplines (Tress et al. 2005). The aim is to generate new knowledge and theories that contribute to solving complex societal problems where there are no simple or definitive answers and where it is necessary to bring together different scientific disciplines and stakeholders (Tress et al. 2005; Arpin et al. 2023). For example, more than technological innovation is needed to meet the needs associated with the transformation of agri-food systems.

Calls for inter- and transdisciplinary research emerged in the 1970s and have gained momentum since the 1990s (Arpin et al. 2023). Despite its growing popularity (e.g. in National Academy of Sciences, Engineering, and Medicine (2019)), the adoption of this approach remains limited in academia, where evaluation and funding systems remain predominantly disciplinary (Jahn et al. 2012; Arpin et al. 2023). There are several reasons for this. First, because the scientific community remains mainly specialized in one discipline (Cochet 2011). Also, because it is difficult to produce high-quality results that meet the standards, approaches, and requirements of each of the mobilized disciplines (Jahn et al. 2012). Second, this approach requires more time, both for building trust and collaboration with stakeholders (the participatory dimension) and for learning and integrating new disciplines (the interdisciplinary dimension) (Polk 2015). Finally, transdisciplinary research involves stepping outside controlled situations, thus increasing the element of unpredictability, and tends to study more nuanced situations rather than sharp contrasts, making data collection, analysis, and interpretation more laborious.

In this thesis, the study of CA draws on agronomic knowledge to categorize the diversity of CA practices, pedological knowledge to compare soil quality in different CA-types, and social knowledge, to explore transition processes and farmers' trajectories shaped by external actors and elements of the socio-technical landscape. An interdisciplinary approach facilitates understanding the interactions between the different elements influencing farming practices.

5. Structure

Table 1 provides an overview of the thesis plan, detailing the chapters numbered 2 to 6 with their research questions, objectives, period and method of data collection, datasets, and associated types of analysis. Figure 4 illustrates the three elephants in the room that carry the different chapters.

Chapter 2 tackles the task of taming our first elephant in the room by providing a definition of CA that is both generalizable to allow comparison of studies, and regionally adaptable to allow identification and categorization of the diversity of CA practices. To this end, we carried out an analysis of the convergences and divergences between the most used definitions of CA.

Chapter 3, written in French, provides an overview of the CA landscape in Wallonia. Although it is not directly linked to one of the three elephants in the room, this chapter has made it possible to identify the Walloon CA population with the collaboration of about twenty stakeholders. This information was used to tackle the second and third elephants in Chapters 4, 5 and 6. Once the CA population has been identified, a sampling of some sixty CA farmers then enabled us to go into more detail and draw up the main characteristics of Walloon CA. The survey ran from 2018 to 2020 and reveals the scale of CA adoption by farmers, its geographical distribution, the place of livestock farming and organic certification in it, and a mapping of key CA actors.

Chapter 4 deals with taming the second elephant in the room by providing a systematic method to identify and categorize the diversity of CA practices at the regional level. Based on the definition of CA given in Chapter 2, and the CA population identified in Chapter 3, 48 Walloon CA farmers were interviewed to collect, analyze, and condense their practices into variables. From these, a hierarchical classification on principal components and an archetypal analysis were carried out. Cross-referencing these two classification methods resulted in the categorization into five CA-types, determined by three explanatory factors: the share of tillage-intensive crops in the cropping sequence, the presence of temporary grassland and organic certification.

Chapters 5 and Chapter 6 look at the third elephant in the room, by addressing the integration of the diversity of CA practices, which were categorized into CA-types in Chapter 4, to assess the impact of this diversity on CA analysis.

Chapter 5 assesses and compares the impact of the different CA-types on three soil quality indicators: soil structural stability, the carbon/clay ratio and the labile carbon fraction. To this end, soil samples were taken from CA fields and analyzed to compare these soil quality indicators between the identified CA-types. Our results showed significant differences in soil quality among the Walloon CA fields. Temporary grassland integration in the crop sequence emerged as the farming practice with the most significant impact, enhancing soil cover, reducing tillage, and stimulating carbon inputs. The results underline the need to move beyond simplistic dichotomies when assessing the impact of CA. CA cannot be reduced to a single pillar (tillage) or a single tool (the plow).

Chapter 6 analyzes the transition factors and future practice changes across different CA-types. Through qualitative analysis of semi-structured interviews with farmers representing different CA types, our findings reveal a nuanced array of transition factors, seemingly independent of the diversity of adopted CA practices. Furthermore, farmers within the same CA type may diverge in their aspirations or plans for adjusting their practices. While some strive to align more closely with CA principles, others opt to deviate, often to optimize farm profitability.

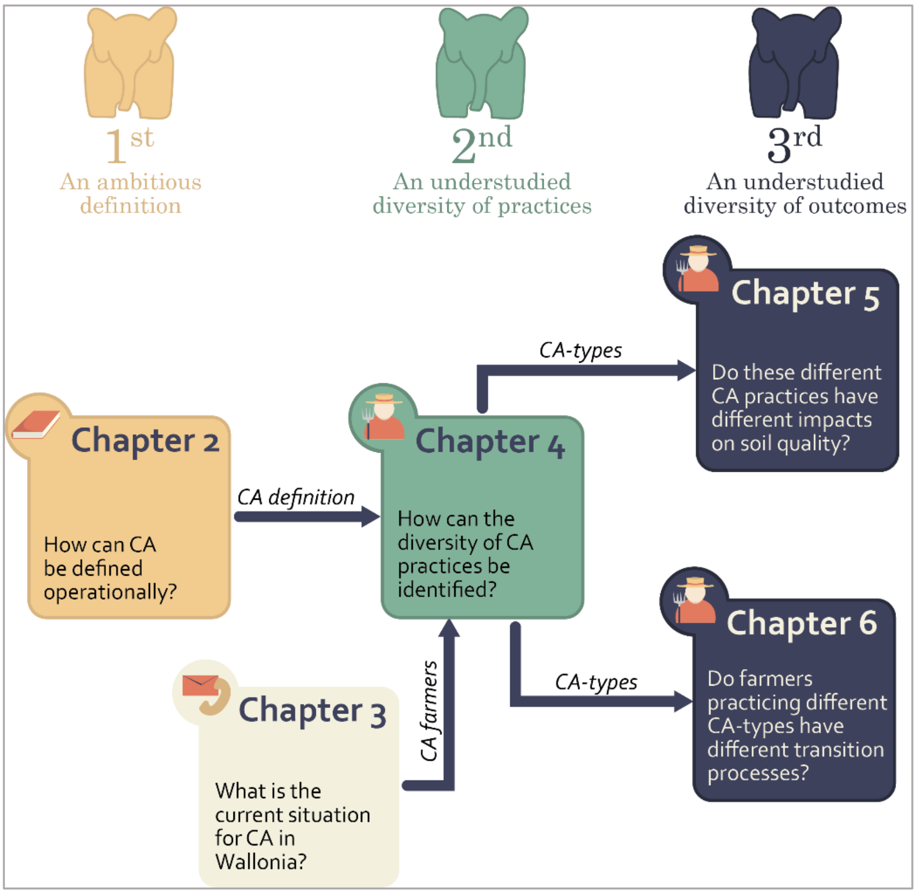

Figure 4 Organization of the thesis' chapters, designed by Céline Chevalier (UCLouvain/Sytra)

Table 1 Overview of chapter structure and content

Chapter Title	**Chapter 2** An operational definition of Conservation Agriculture	**Chapitre 3** L'Agriculture de Conservation en Wallonie	**Chapter 4** A method to account for diversity of practices in Conservation Agriculture	**Chapter 5** Digging Deeper: Assessing soil quality in a diversity of Conservation Agriculture practices	**Chapter 6** Transition in Conservation Agriculture: Integrating the diversity to explore the before and the after
Research question	How can CA be defined robustly and operationally?	What is the current state of CA in Wallonia?	How can the diversity of CA farming practices be identified?	Do these different CA practices have different impacts on soil quality?	Do farmers practicing different forms of CA have different transition processes?
Goal	Propose an operational definition of CA	Drawing up the CA landscape in Wallonia	Develop a method for categorizing the diversity of CA practices	Assessing and comparing the impact of different CA-types on soil quality	Understand and compare the transition processes of different CA-types
Data collection	**Apr. 2020**	**2018/20**	**Nov. – Mar. 2020/21**	**Nov. – Feb. 2021/22**: Sampling **Nov. – Aug. 2021/23**: Laboratory	**Nov. – Mar. 2020/21**
Datasets	FAO publications and scientific papers	Surveys of 12 public and private institutions, 8 farmers' associations, 2 university researchers, 2 natural parks, Facebook	Interviews with 48 CA farmers	Soil Analysis of 28 CA plots using three soil quality indicators	Semi-structured interviews with 34 CA farmers

		Semi-structured interviews with 62 CA farmers			
Analysis	Reading and comparison of CA definitions	Quantitative analysis of information gathered from stakeholders	Archetypal analysis and hierarchical classification	Descriptive statistics	Qualitative analysis of interviews using NVivo software

Chapter 2 An operational definition of Conservation Agriculture

In the introduction, we highlighted three major challenges, metaphorically referred to as three “elephants in the room”.

This chapter aims to tame the first elephant in the room by providing a comprehensive definition of Conservation Agriculture (CA). This definition delineates the general boundaries of the system at the global level and allows for its adaptation and implementation at the regional level.

To achieve this, we performed a comparative analysis of CA definitions found in various publications by the Food and Agriculture Organization of the United Nations (FAO), the organization that introduced the concept of CA in 1998. Our analysis revealed a number of elements, articulated in the form of questions, that hinder the construction of an operational CA definition. These questions were examined through articles that are considered as references in defining CA. Based on this analysis, we proposed an improved definition of CA that facilitates the identification and categorization of CA practices through guidelines broad enough to encompass CA practices worldwide and adaptable to local contexts.

1. Introduction

In 1930, dust storms emerged in the US due to intensive tillage, low soil cover, and overgrazing (Joel 1937; Hobbs 2007; Baveye et al. 2011). This phenomenon, known as the Dust Bowl, resulted in significant soil losses and prompted farmers to question their land management practices (Hobbs 2007). While wind erosion[2] has also severely affected other regions of the world over the past few years, such as northern China and India, water erosion, although less visible, is much more widespread (Handelsman 2021). Each year, water is estimated to displace from 20 to 50 billion tons of soil, a figure set to rise due to more frequent severe rainstorms linked to climate change (Handelsman 2021). In response to the global recognition of soil erosion as a critical issue, the Food and Agriculture Organization (FAO) introduced and defined the concept of Conservation Agriculture (CA) in 1998 (Kassam 2022). CA is based on three agronomic pillars, namely: (i) minimal mechanical soil disturbance, (ii) permanent soil organic cover, and (iii) species diversification.

The definition of CA and its pillars exhibit variation within the scientific literature, influenced by authors and the specific research context. Inconsistencies and discrepancies arise in terms of the number of CA pillars and the definition and guidelines associated with each pillar. The inconsistencies in defining and guiding the pillars can be attributed to the usage of terms such as “minimal,” “permanent,” or “diversify,” which can result in a range of interpretations (Sumberg and Giller 2022).

The study at the farming system level requires a comprehensive and practical definition of CA. CA is a transnational agrarian system (Vankeerberghen and Stassart 2016) where the translation of its pillars into practices is influenced by the individual constraints and objectives of farmers (Giller et al. 2009; Scopel et al. 2013; Hauswirth et al. 2015; Derrouch et al. 2020). A definition of CA with transparent guidelines is essential for effective communication and comparison among scientists and studies conducted in diverse contexts (Carmona et al. 2015). This definition should include the various CA practices implemented by farmers worldwide.

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[2] Erosion is the process of altering the soil surface by detaching and displacing soil particles (Morgan 2005). This topic covers a range of temporal and spatial scales, from the immediate impact of raindrops to the formation of landforms over millennia (Nearing et al. 2017). This thesis will only address erosion and soil degradation induced by intensive agricultural practices.

This chapter aims to provide a comprehensive definition of CA, suitable for practical application in the field, to facilitate the identification and categorization of CA practices. This definition serves to outline the boundaries of CA, i.e., distinguishing between practices that adhere to its pillars and those that do not. This entails formulating a definition with explicit guidelines that are sufficiently broad to encompass CA practices worldwide, while remaining adaptable to local contexts for the nuanced identification and study of CA practice diversity specific to each region.

To achieve this, we analyze the convergences and divergences among existing definitions by investigating two key sources: (1) publications from FAO and (2) research articles recognized as authoritative references in the definition of CA.

It is important to note that our research focuses on constructing a field-applicable definition of CA rather than providing a systematic and comprehensive review of the various definitions of CA.

2. Materials and methods

The methodology integrates two sources of information on CA definitions: FAO publications and reference articles on CA definitions in scientific literature (Figure 5).

FAO is a central hub for discussions on agriculture and food security (Loconto and Fouilleux 2019). The FAO was chosen as the starting point for analyzing CA definitions due to its foundational role in introducing and defining the concept of CA in 1998 (Kassam 2022). This definition has since been widely adopted across scientific literature.

The selection of multiple FAO publications was motivated by the desire to facilitate in-depth comparison and to develop a comprehensive definition of CA. This approach is based on the principle that an extensive analysis of various sources increases the wealth of information available. It also takes into account the fact that recent articles still refer to earlier FAO publications (e.g. in Jew et al. (2020) and Olawuyi and Mushunje (2020)).

An initial definition of CA is established by examining the FAO publications. The analysis has uncovered several unresolved queries and areas lacking clarification, referred to as “key questions.”

To address these inquiries comprehensively, authoritative articles within the field provide insights and responses, ultimately culminating in the formulation of a consolidated, operationally sound definition of CA.

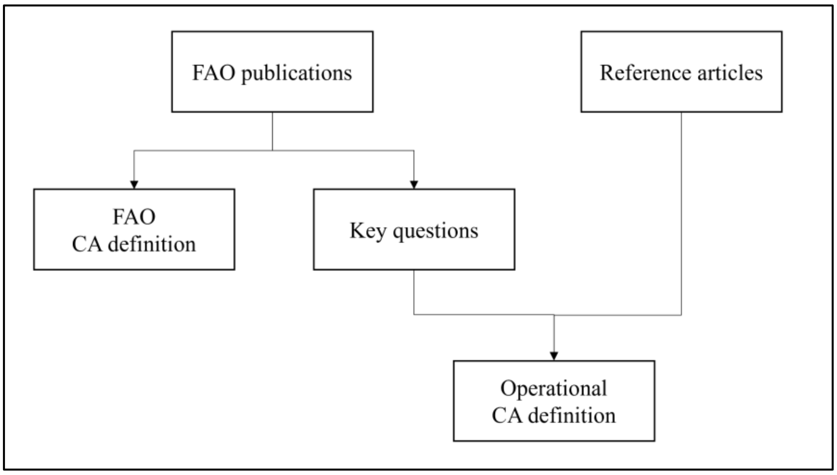

Figure 5 Steps to build an operational definition of Conservation Agriculture (CA)

2.1. Selection of FAO publications

For analysis, four FAO sources were selected (Table 2). The FAO (2023a)[3] source webpage is frequently cited in scientific articles and is the top search result on Google when searching for “conservation agriculture FAO” as of April 2020. Additionally, FAO (2014) and FAO (2017) were identified as relevant sources through the search engine. Furthermore, the latest FAO publication on CA, authored by Corsi et Muminjanov (2019) and referred to as FAO (2019), is accessible in the ‘Resources’ section of the FAO (2023a) website.

Table 2 The FAO sources analyzed to develop an operational CA definition

First author	Year	Type of document	Title
FAO	2014	Web page	Conservation agriculture: The 3 principles
FAO	2017	Leaflet	Conservation Agriculture
FAO	2019	Book	Conservation Agriculture: Training guide for extension agents and farmers in Eastern Europe and Central Asia
FAO	2023	Web page	Conservation Agriculture

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[3] This webpage was consulted in 2019 and although it has been updated since then, the content has not changed.

2.2. Selection of reference articles

The selection process involved identifying 42 papers published between January and April 2020 using Google Scholar, with “conservation agriculture” in their titles (Figure 6). From these papers, references used to define CA were extracted. FAO sources were excluded, and articles with “conservation agriculture” in their titles and cited more than 200 times were chosen. Additionally, the article by Sommer et al. (2014), which directly responds to one of the selected articles by Vanlauwe et al. (2014), was included (Table 3).

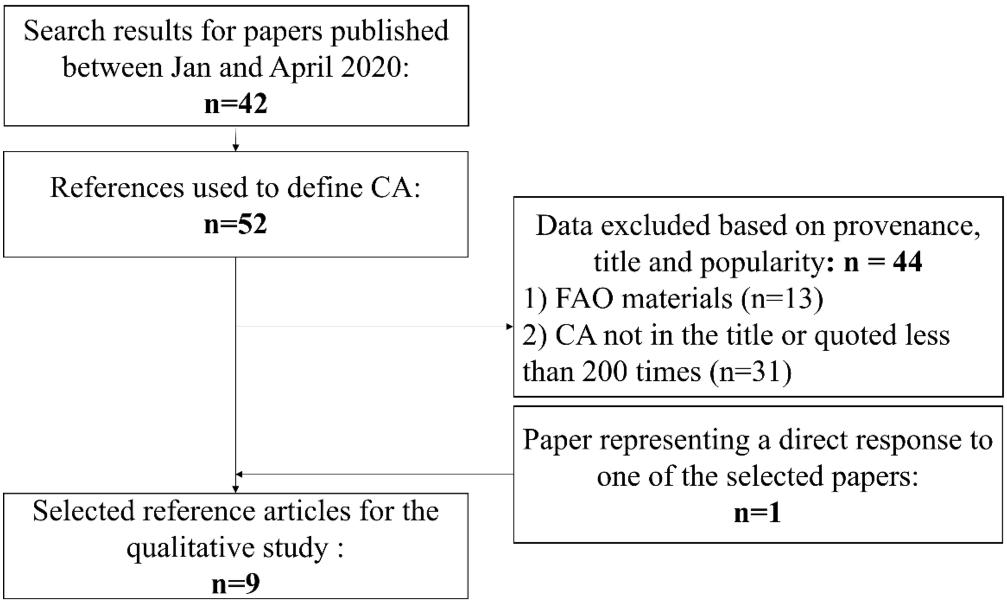

Figure 6 Selection of the reference articles to define Conservation Agriculture (CA)
Explanatory note: “n” represents the number of search records.

Table 3 Reference articles analyzed to build the CA definition

First author	Year	Title
Hobbs	2007	Conservation agriculture: what is it and why is it important for future sustainable food production?
Hobbs	2008	The role of conservation agriculture in sustainable agriculture
Kassam	2009	The spread of Conservation Agriculture: justification, sustainability and uptake
Giller	2009	Conservation agriculture and smallholder farming in Africa: The heretics' view
Thierfelder	2009	Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe
Friedrich	2012	Overview of the global spread of conservation agriculture
Vanlauwe	2014	A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity
Sommer	2014	Fertilizer use should not be a fourth principle to define conservation agriculture: Response to the opinion paper of Vanlauwe et al. (2014)
Pittelkow	2015	Productivity limits and potentials of the principles of conservation agriculture

3. Results

3.1. FAO definitions of Conservation Agriculture

All selected FAO sources define CA as a cropping system that rests upon three pillars: (i) minimum mechanical soil disturbance, (ii) permanent soil organic cover and (iii) species diversification (FAO 2014, 2017, 2019, 2023a). Moreover, FAO sources (2019, 2023a) highlight other practices, such as using quality seeds, integrated pest management and plant protection products and fertilizers. These practices, referred to as "additional practices" in this study, are associated with enhancing the sustainability of CA (FAO 2023b).

Minimum mechanical soil disturbance

The first pillar of CA, consistently defined by the selected FAO publications, emphasizes minimizing mechanical soil disturbance (FAO 2014, 2017, 2019, 2023a).

While previous FAO publications (2014, 2017, 2019) limit the first pillar to direct seeding only (constituting maximum tillage reduction), FAO (2023a) provides more specific instructions that allow for more types of tillage to be included. FAO (2023a) defines minimum soil disturbance as soil disturbance less than 15 cm wide or less than 25% of the cultivated area (whichever is lower), and allows for periodic- and strip-tillage within these defined thresholds.

Box 1. Definition of the first pillar of CA based on FAO publications

1. The first pillar of CA is defined by minimum mechanical soil disturbance;
2. Two approaches are suggested to achieve this objective:
    a. Strict approach: only direct seeding is allowed;
    b. Extended approach: periodic- and strip-tillage are allowed if the disturbed area is less than 15 cm wide or less than 25% of the cropped area.

Permanent soil organic cover

As per the selected FAO sources, the second pillar of CA highlights the importance of maintaining permanent soil organic cover (FAO 2014, 2017, 2019, 2023a). Two practices are used to achieve this: dead or living mulch. Dead mulch typically includes plant residues, but it can also encompass decomposing leaves, bark, or compost. On the other hand, living mulch refers to crops and cover crops.

Cover crops are recommended during extended periods between harvest and the next planting when crop residues alone do not provide sufficient soil cover (FAO 2023a).

Implementing the second pillar of CA should guarantee a minimum of 30% permanent soil cover (FAO 2017, 2023a). FAO (2023a) mentions three categories of soil cover: 30-60%, >60-90%, and >90%.

Box 2. Definition of the second pillar of CA based on FAO publications

1. The second pillar is defined by permanent soil organic cover;
2. The soil cover can be achieved by dead or living mulch;
3. A minimum soil cover of 30% is recommended;
4. There are three categories of soil cover: 30-60%, 60-90% and >90%.

Species diversification

The third pillar of CA is species diversification (FAO 2017, 2019, 2023a). Through a comprehensive examination of the FAO publications, it was established that species diversification could be achieved through four practices: (i) rotations (FAO 2014, 2017, 2019, 2023a), (ii) associations (FAO 2017, 2019, 2023a), (iii) cover crops (FAO 2014, 2019, 2023a), (iv) and mix of varieties (FAO 2019). According to FAO (2017, 2023a), species diversification involves at least three different crop species.

Box 3. Definition of the third pillar of CA based on FAO publications

1. The third pillar is defined by species diversification;
2. This diversification can be done through rotations, associations, cover crops or a mix of varieties;
3. Species diversification should involve at least three different crop species.

Additional practices

The most recent publications from the FAO introduce additional practices to complement the three fundamental pillars of CA (FAO 2019, 2023a). Although these practices are not explicitly outlined in the general explanation of CA and the pillars, they are regarded as essential for enhancing the sustainability of the CA system (FAO 2023a). The absence of specific details regarding the quantity or implementation of these practices implies a potential incompleteness in the provided list, highlighting its adaptability contingent upon contextual considerations.

The first additional practice mentioned is the use of quality seeds, specifically adapted varieties (FAO 2019, 2023a). However, it should be noted that the sources do not provide any additional information on this practice.

The second additional practice is the integrated management of pests, external inputs, weeds, and water (FAO 2019, 2023a). Pest management when transitioning to CA requires careful consideration due to potential changes in pest dynamics (FAO 2019). Integrated management of external inputs aims for targeted and optimal application (FAO 2023a). Weed management options in CA include rotations, associations – using fast-growing species to compete with weeds, or through allelopathy (FAO 2019, 2023a) – shallow tillage and herbicides (FAO 2023a). When using herbicides, proper understanding, calibration, and advice from experienced practitioners are essential (FAO 2019, 2023a).

Fertilizers are included as part of additional CA practices, with recommendations to address nutrient deficiencies through green manure or synthetic fertilizers before transitioning to CA (FAO 2023a). FAO (2019) highlights the potential issue of organic nitrogen immobilization in the early years of CA and suggests the application of mineral nitrogen.

To maximize CA benefits, farmers must acquire knowledge, experience, and suitable tools (FAO 2019, 2023a). Access to affordable and suitable equipment for sowing on covered soils, managing cover crops, residues, and weeds aids CA adoption (FAO 2019), while the learning phase helps integrate pillars and additional practices (FAO 2019, 2023a).

CA increases the possibilities for integration of production sectors such as crop-livestock association, integration of trees as well as pastures within the agricultural landscape (FAO 2023a).

Three anti-erosion methods were cited: (i) contour farming, (ii) hedgerows and windbreaks, and (iii) controlled grazing through restriction or supplementary feeding (concentrates or fodder) (FAO 2019).

Implementing measures to address potential compaction issues can be combined with the three pillars of CA. Two methods are mentioned: (i) the use of flotation tires on tractors and (ii) the controlled traffic system, which employs permanent lanes within fields to eliminate compaction outside of the traveled paths (FAO 2019).

Box 4. Additional practices in CA based on FAO publications

1. Use of quality seed;
2. Integrated pest, external input, weed and water management;
3. Preferential use of herbicides compared to intensive tillage;
4. Use of fertilizers;
5. Use of suitable tools;
6. Increased opportunities for integration of production sectors (livestock, agroforestry, grazing);
7. Measures to control erosion;
8. Measures to avoid soil compaction.

3.2. Analysis of key questions through authoritative reference articles

Although the latest FAO sources provide enhanced precision and guidance on the pillars of CA and additional practices, some areas still require clarification. To define CA accurately, we focus on thirteen key questions (Table 4) chosen for their ability to highlight information gaps that hinder the development of an operational CA definition applicable in field settings.

Table 4 Key questions raised by the analysis of FAO publications

Key questions	
Q1	Should the pillars be ranked?
Q2	How is a pillar different from an additional practice?
Q3	Pillar 1: does tillage mean plowing or soil working?
Q4	Pillar 1: is there a difference between direct seeding and no-till?
Q5	Pillar 1: which threshold: direct seeding or a soil preparation with a disturbed area less than 15 cm wide or less than 25% of the area?
Q6	Pillar 1: what is the scientific basis for defining the thresholds of 15 cm wide and 25% of the cropped area?
Q7	Pillar 1: what about the number of passes, the tools used, and the speed of the farm machinery?
Q8	Pillar 2: do soils need to be permanently covered?
Q9	Pillar 2: is the 30% coverage only for crop residues?
Q10	Pillar 2: on what scientific basis is the 30% threshold defined?
Q11	Pillar 2: is the importance of soil cover consistent throughout the year?
Q12	Pillar 2: on what scientific basis and for what purpose are the three coverage categories defined?
Q13	Pillar 3: on what scientific basis is the threshold of three crops defined?

Using the authoritative reference articles (see section 2.2. for their selection), we systematically address each question to refine and operationalize the definition of CA.

Q1. Should the pillars be ranked?

Some FAO sources sideline the third pillar of CA (species diversification), either by accepting monoculture[4] (FAO 2023a) or omitting it from the presentation of CA objectives[5] (FAO 2014).

Although Pittelkow et al. (2015a) mention that no-till is the « original and central concept of CA », no reference article explicitly prioritizes the three pillars. However, several references, such as Hobbs (2007), Kassam et al. (2009), Thierfelder et Wall (2009) and Friedrich et al. (2012), pay less attention to the third pillar compared to the other two. In contrast, Giller et al. (2009) and Pittelkow et al. (2015a) emphasize the central role of rotations in CA.

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[4] "However, repetitive wheat, maize, or rice cropping is not an exclusion factor for the purpose of this data collection, but rotation/association is recorded where practiced." (FAO 2023a)

[5] "Conservation agriculture systems utilize soils for the production of crops with the aim of reducing excessive mixing of the soil and maintaining crop residues on the soil surface in order to minimize damage to the environment." (FAO 2014)

As no reference article mentions or justifies a hierarchy of the pillars, equal importance is given to each pillar.

Q2. How is a pillar different from an additional practice?

A series of practices that do not fall under the three pillars of CA have been identified in the FAO (2019, 2023a) sources. These additional practices have sparked discussions regarding their inclusion as pillars in CA (in Vanlauwe et al. (2014) and Sommer et al. (2014)). Understanding the distinction between pillars and additional practices is crucial for defining CA. Two contrasting definitions of pillars exist. Vanlauwe et al. (2014) consider pillars as practices essential to the proper functioning of CA and the success of the farming system, while Sommer et al. (2014) define pillars as practices that distinguish CA from other farming systems.

We adopted the definition proposed by Sommer et al. (2014), where a pillar of CA is defined as practices that characterize the CA agricultural system and distinguish it from other systems. Additional practices are employed to enhance sustainability or facilitate the adoption of CA.

Q3. Pillar 1: does tillage mean soil preparation or plowing?

According to FAO (2023a), the implementation of first pillar should not involve periodic tillage that disturbs an area greater than 15 cm wide or 25% of the cropped area. The term “tillage” raises the question of whether it refers to any soil preparation or specifically plowing. Although the FAO website does not provide a clear definition of the term “tillage”, certain phrases suggest that it is synonymous with plowing. For instance, “Soil tillage is among all farming operations the single most energy-consuming [...]” or “Soil tillage is a traditional practice and thus presents some cultural barriers.” (FAO 2023a).

Additionally, in several reference articles, the terms “tillage” and “plowing” are used interchangeably, indicating their synonymity (Hobbs 2007; Hobbs et al. 2008; Giller et al. 2009; Thierfelder and Wall 2009). The term “tillage” is defined in two articles. Hobbs (2007; 2008) lists other names for tillage, such as plowing, cultivation, and digging. Kassam et al. (2009) explain that tillage often refers to the inversion plowing of topsoil over at least 20 cm, also known as conventional tillage. In their article, they chose to define tillage as “a generic term embraces all soil operations using plow, harrow and other farm tools or mechanical implements for seedbed preparation” (Kassam et al. 2009).

According to the information provided, it can be stated that the FAO (2023a) uses the term “tillage” as a synonym for plowing when defining the boundaries of the first pillar of CA.

To prevent confusion, we recommend that future definitions of the first pillar of CA use the term “tillage” to refer to any mechanical operation that fragments the soil, and “plowing” to refer to a mechanical operation that inverts the soil horizons.

Q4. Pillar 1: is there a difference between direct seeding and no-till?

The FAO (2023a) defines the first pillar as “minimum soil disturbance refers to low disturbance no-tillage and direct seeding”. Although the FAO (2023a) uses the terms “no-tillage” and “direct seeding” separately in this definition, on the same webpage dedicated to CA, they clarify that “direct seeding is understood in CA systems as synonymous with no-till farming, zero tillage, no-tillage, direct drilling, etc.” (FAO 2023a).

The definition of direct seeding as a synonym for no-tillage is also found in Kassam et al. (2009), who group no-till, zero-till, and direct seeding.

Based on these observations, it can be concluded that direct seeding, no-till, as well as zero-till are synonymous and defined as the planting of a crop without any soil preparation.

Q5. Pillar 1: which threshold: direct seeding or a soil preparation with a disturbed area less than 15 cm wide or less than 25% of the area?

The definition of the first pillar (minimum mechanical soil disturbance) varies between FAO sources. Some FAO sources (2014, 2017) limit the first pillar to direct seeding, while FAO (2023a) considers that soil disturbance can occur as long as it is “less than 15 cm wide or less than 25% of the cropped area (whichever is lower)”. In addition, according to FAO (2023a), it is crucial to adapt each CA pillar to reflect local conditions and needs.

The reference articles generally support a flexible definition, aiming to reduce tillage (i.e. plowing, cf. question no. 3), except for Pittelkow et al. (2015a), who solely consider direct seeding to implement the first pillar. According to Kassam et al (2009), the term minimum tillage is confusing and needs to be defined in parallel with the minimum possible tillage depending on the type of crop, the local context and the climatological and pedological characteristics.

To ensure the first pillar is configured to the local context, a flexible approach is necessary. We propose accepting soil disturbance, even periodic plowing or strip-tillage, as long as it is less than 15 cm wide or covers less than 25% of the cropped area. This contrasts with a definition where the first pillar is limited to direct seeding. Direct seeding is thus considered more of an end goal of the first pillar rather than a criterion for considering a farming practice as CA.

Q6. Pillar 1: what is the scientific basis for defining the thresholds of 15 cm wide and 25% of the cropped area?

The most recent FAO source (2023a) includes maximum thresholds for the disturbed soil area, which are less than 15 cm wide or less than 25% of the cropped area. However, FAO (2023a) lacks scientific justification for these two thresholds set.

Among the reference articles, only Kassam et al. (2009) and Friedrich et al. (2012) mention these two limits for defining acceptable soil disturbance within the first pillar. However, neither article explains the rationale behind these numbers. The only reference associated with these numbers is in the article by Friedrich et al.'s (2012) article, where they cite the 2011 version of the FAO website. The text has come full circle.

Two hypotheses have been proposed regarding the origin of these thresholds. The first hypothesis suggests that the thresholds were selected because they can be detected through remote sensing, as opposed to being based on a specific depth (F. Vanwindekens, personal communication, February 23, 2024). The second hypothesis proposes that the FAO established these thresholds based on field surveys. The data were collected in regions that may correspond to the case studies presented on the FAO website (2023a), namely Lesotho, China, Kazakhstan, the Indo-Gangetic Plains, Malawi and Zambia. It is worth considering whether these thresholds are applicable beyond these countries and can support the universal application of CA as advocated by FAO (2023a).

Additionally, these thresholds present several challenges.

First, the interpretation of the FAO (2023a) directive stating "less than 15 cm wide" raises questions. Although CA is primarily practiced in North and South America, the various FAO publications and case studies on CA appear to be more focused on smallholder farming systems, as illustrated by the examples used to define the first pillar of CA (Figure 7). In these systems, tillage tools can consist of a single element that is pushed by hand or animal traction, which helps to understand the meaning of "15 cm wide". However, in mechanized agriculture, the width of soil disturbance caused by the passage of a tool depends on several factors, including the width of the tool, the type and number of elements comprising the tool, and the forward speed. In this context, adhering to the "15 cm wide" threshold applied to the tool in its entirety effectively excludes nearly all implements used in mechanized agriculture, ranging from harrow to subsoiler, since most of these tools operate across the entire width during each pass (M.-H. Jeuffroy, personal communication, March 18, 2024).

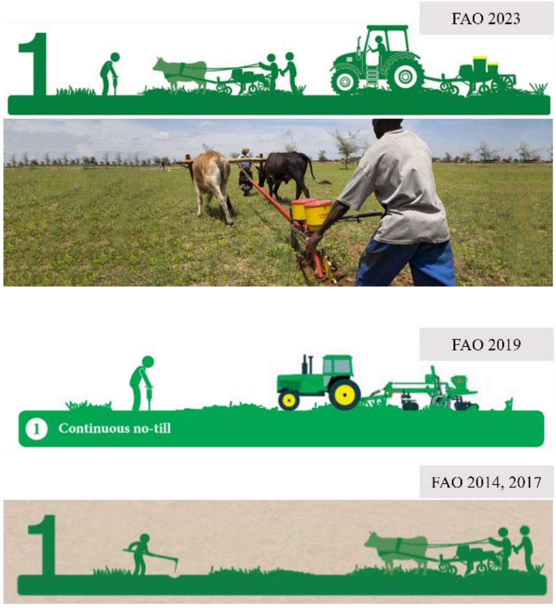

Figure 7 Illustrations from FAO publications used to define the first pillar of CA.

Secondly, according to the FAO (2023a), strip-till is allowed as long as soil disturbance remains below 15 cm wide or 25% of the cropped area. However, strip-till is typically defined as a system that minimizes the amount of soil disturbance to establish a crop, using specialized equipment to create rows that are usually 20–25 cm wide (Kassam et al. 2009).

Thirdly, according to the FAO (2023a), periodic plowing is allowed as long as the disturbed area remains below 15 cm wide or 25% of the cropped area. However, the plow, as used in industrialized agriculture, works on 100% of the cropped area and therefore on a width much greater than 15 cm. This raises the question of the meaning of the term "cropped area": does "area" refer to the plot or farm scale (M.-H. Jeuffroy, personal communication, March 18, 2024)? If the term "area" is interpreted as referring to the plot scale, then the exclusion of plowing in this respect is justified for the reasons given above. However, if "area" refers to the scale of the farm, plowing can be occasionally permitted on part of the area (M.-H. Jeuffroy, personal communication, March 18, 2024).

Finally, a unit of measurement that has not been addressed in FAO publications, but which seems relevant in distinguishing CA from other dominant farming systems, is tillage depth. This unit is used to define “reduced tillage”, classified in conservation tillage practices, by Kassam et al. (2009).

Therefore, while the term “minimum” used to define the first pillar is too vague to differentiate CA from other farming systems, restricting CA to direct seeding alone limits the application of CA to all regions of the world. Tillage thresholds can help create guidelines for data collection and analysis. The FAO (2023) proposes that soil disturbance in CA should be limited to a maximum of 15 cm wide or 25% of cropped area. However, none of the FAO publications or reference articles explain the rationale behind the use of width and percentage of area as reference units, nor what these thresholds mean and/how they should be interpreted (does width refer to the element or the tool, does percentage refer to the plot or the farm?). Furthermore, these thresholds, contrary to what the FAO claims, are difficult to reconcile with periodic plowing and strip tillage.

We therefore recommend that thresholds should be established to delineate the soil disturbance allowed in CA - whether in width, percentage of area, or tillage depth - and that these thresholds be defined to reflect existing or potential CA practices, depending on the area under consideration.

Q7. Pillar 1: what about the number of passes, the tools used, and the speed of the farm machinery?

Considering the objective of minimizing mechanical soil disturbance in the definition of the first pillar, it would be valuable to consider additional aspects such as reducing the number of interventions, differentiating tools according to their impact on the soil, and machinery speed[6]. These aspects are not covered in the various FAO publications.

Friedrich et al. (2012) highlight that reducing mechanical soil disturbance entails paying attention to harvesting operations, especially for root crops, and the circulation of agricultural machinery. Soil compaction can be mitigated by reducing farm machinery passing in the field (Hobbs et al. 2008; Kassam et al. 2009). Additionally, conventional tillage practices involving tools that cause soil horizon inversion and/or mixing, such as moldboard and disc plows, disc harrows, and rotary cultivators further disrupt soil structure compared to tools based on lifting, fracturing and/or compression (Kassam et al. 2009). According to Pittelkow et al. (2015a), the moldboard plow is the tillage practice that causes the most soil disturbance. None of the reference articles provide detailed insights into the effects of different types of tillage based on the tool composition and setting (M.-H. Jeuffroy, personal communication, March 18, 2024) or specifically investigate machine speed.

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[6] Operational speed of tillage equipment is one of the four components of the Soil Tillage Intensity Rating (STIR) numerical value, along with tillage type, tillage depth, and percent of the soil surface area disturbed (Lightle 2020).

Thus, it is enriching to include in the definition of the first pillar points of concern relating to the farm machinery traffic and harvesting operations of root and tuber crops, as well as the use of specific tools such as moldboard and disc plows, disc harrows, and rotary cultivators, given their greater soil-damaging potential.

Q8. Pillar 2: do soils need to be permanently covered?

FAO publications (2014, 2017, 2019, 2023a) define the second pillar as permanent soil organic cover. However, achieving permanent soil cover (i.e. 365 days a year) is only possible within direct seeding on permanent plant cover. The question arises whether a farmer who occasionally leaves plots bare should still be considered a CA practitioner.

To tackle this issue, Hobbs et al. (2007; 2008) suggest a more flexible definition of the second pillar. They propose that it should be characterized as "semi-permanent or permanent soil cover", with the latter being the ultimate objective. These articles refer to a 2006 FAO webpage that is currently unavailable, indicating that the FAO used to endorse greater flexibility in this regard. Other reference articles emphasize the importance of maintaining soil cover throughout the year (Kassam et al. 2009; Friedrich et al. 2012; Pittelkow et al. 2015a).

Given the close relationship between soil preparation and soil cover, and the decision to adopt a more flexible version of the first pillar allowing soil disturbance other than direct seeding and thereby leaving sometimes the soil bare (question no. 5), it seems reasonable to align the criteria of the second pillar with the flexibility allowed for the first pillar. Therefore, we propose redefining the second pillar as "maximum soil organic cover" instead of "permanent soil organic cover". The ideal scenario is still maintaining permanent soil organic cover.

Q9. Pillar 2: is the 30% coverage only for crop residues?

The FAO sources (2017, 2023a) appear to associate the 30% soil cover requirement with both dead (e.g. crop residues) and living mulch (e.g. cover crops). However, FAO (2019) and discussions with agricultural officers from FAO (Muminjanov and Beed, personal communication, 18 March 2020) indicate that the 30% soil cover requirement is specifically linked to crop residues. FAO (2023a) specifies that the measurement of soil cover should be taken immediately after the direct seeding operation, supporting the notion that the 30% limit applies only to crop residues and no other types of mulch.

The five reference articles that mention the 30% minimum limit (Hobbs 2007; Hobbs et al. 2008; Kassam et al. 2009; Giller et al. 2009; Vanlauwe et al. 2014) all cite crop residues as the means to achieve this coverage. No other type of mulch is mentioned to achieve at least 30% coverage of the plot area.

Kassam et al (2009) specify, as does FAO (2023a), that soil cover should be measured immediately after the planting operation.

Therefore, based on information from both FAO sources and reference articles, the 30% minimum soil cover requirement corresponds to the need for soil coverage by crop residues immediately after the seeding operation.

Q10. Pillar 2: on what scientific basis is the 30% threshold defined?

Although FAO publications (2017, 2023a) mention a minimum threshold of 30% soil cover , the rationale behind this specific threshold remains undisclosed. Discussions with FAO officers (Muminjanov and Beed, personal communication, 18 March 2020), reveal that the percentage of soil coverage requirement aims to accommodate diverse environmental, agricultural, and socio-economic conditions worldwide, allowing for variations in soil type, climate, crops, and farming practices. Farmers employ a range of practices, from utilizing crop residues as livestock feed to cultivating crops with limited residue production, such as wheat and rice. Additionally, regions experiencing cold and wet conditions may encounter challenges like delayed crop growth due to mulch cover affecting temperature and waterlogging. According to the FAO officers, the adoption of the 30% threshold enables all farmers to align with CA principles, irrespective of their difficulties in retaining crop residues (Muminjanov and Beed, personal communication, 18 March 2020). Nevertheless, the specific reasoning behind FAO’s selection of the 30% requirement remains ambiguous.

Reference articles suggest that to achieve an 80% reduction in erosion, at least 30% of the plot area should be covered with crop residues (Giller et al. 2009; Vanlauwe et al. 2014). The risk of erosion decreases as the soil cover increases (Allmaras and Dowdy (1985); Erenstein (2002), cited by Giller et al. (2009) and Vanlauwe et al. (2014)). This relationship is influenced by various factors such as soil type and foliage height, introducing a margin of error.

Therefore, it appears that the 30% minimum soil organic cover criterion was established to achieve the 80% soil erosion reduction target. Consequently, distinguishing between different types of mulch seems superfluous, suggesting that the 30% threshold can be applied universally to both dead and living mulch.

Q11. Pillar 2: is the importance of soil cover consistent throughout the year?

The FAO publications do not acknowledge the potential linkage between soil coverage requirements and temporal changes in soil erosion risks. This aspect was also not mentioned in the reference articles.

However, seasonal variation affects both rainfall erosivity and field erodibility by wind (Skidmore 2017; Panagos et al. 2017).

Therefore, we propose that exceeding or falling below the critical threshold of 30% soil cover should be correlated with the risk of soil erosion. This correlation depends on seasonal variations and must be delimited according to the geographical context studied.

Q12. Pillar 2: On what scientific basis and for what purpose are the three coverage categories defined?

The classification of soil cover into three categories (30-60%, 60-90%, and >90%) as mentioned in the FAO (2023a) publication lacks scientific justification. While Kassam et al. (2009) refer to these categories, they cite the FAO as an external source without providing additional scientific rationale. Consequently, neither FAO publications nor referenced articles have substantiated these categories.

Thus, we disregarded these categories due to their lack of empirical support, limited adoption in scientific literature, and limited utility in delineating and identifying CA practices.

Q13. Pillar 3: on what scientific basis is the threshold of three crops defined?

While FAO publications (2017, 2023a) recommend species diversification in CA by involving at least three distinct crop species, they do not provide explicit justification for this numerical requirement.

This threshold is also mentioned in the works of Friedrich et al. (2012) and Kassam et al. (2009), but the rationale behind the selection of three crops is unspecified in all sources.

Despite the lack of justification, this threshold has been upheld because of its usefulness in delineating CA practices.

To improve precision, we suggest including a temporal dimension linked to this threshold to better define its application. For instance, cultivating three different species over a five year cropping sequence differs significantly from cultivating three different species in association within a one-year period. This temporal dimension must be defined according to the local context where CA is practiced.

Moreover, to maintain terminological consistency with the first and second pillars, we recommend including the term “maximum” in the title of the third pillar. This emphasizes the goal of maximizing species diversity both spatially and temporally.

3.3. An operational definition of Conservation Agriculture

FAO publications have contributed to the development of the FAO definition of CA and have identified several obstacles to creating a definition that can be practically applied. By analyzing articles considered as references on CA, we propose an improved definition of CA that enables the identification and categorization of CA practices through guidelines that are broad enough to include CA practices from all over the world and adaptable to local contexts.

CA is based on three pillars: (i) minimizing mechanical soil disturbance, (ii) maximizing soil organic cover, and (iii) maximizing crop species diversification. Each pillar encompasses practices that define the CA agricultural system and differentiate it from other systems (Sommer et al. 2014). All three pillars are equally important and should be implemented simultaneously. The practices of these pillars can be adapted to reflect local conditions and needs (FAO 2023a).

Minimum mechanical soil disturbance

The first pillar of CA is defined as minimal mechanical soil disturbance.

To reduce confusion, we propose defining tillage as any mechanical operation that fragments the soil. Plowing, on the other hand, is specifically characterized as a mechanical operation that inverts the soil horizons.

Various forms of soil disturbance, such as periodic plowing and strip-tillage, are allowed within CA frameworks as long as they are below the prevailing practices in the study area. Thresholds can be utilized to identify and evaluate CA practices. The unit type, width worked, percentage of cropped area worked, or depth worked, should be adjusted to the region under study. For example, “the disturbed area must be less than 15 cm wide or less than 25% of the cropped area” (FAO 2023a) can serve as an indication.

Efforts are made in CA practices to minimize agricultural machinery traffic to mitigate soil compaction. In particular, attention is needed when it comes to harvesting tuber and root crops.

Additionally, equipment such as plows, disc harrows, and rotary cultivators is discouraged to prevent soil degradation.

The ultimate objective is to eliminate plowing and adopt direct seeding, also known as no-tillage or zero-tillage, which involves crop planting without soil preparation.

Box 5. Definition of the first pillar of CA

1. The first pillar of CA is defined by minimum mechanical soil disturbance.
2. The soil disturbance is allowed if it is below the prevailing practices in the study area. Thresholds can be used to identify and evaluate CA practices. The unit type (width, percentage of cropped area, and/or depth worked) and values should be adjusted to the studied region.
3. Traffic of agricultural machinery is minimized. Regarding harvesting, particular attention must be given to the harvest of root and tuber crops.
4. Tools such as plows, disc harrows, and rotary cultivators are avoided.
5. Direct Seeding is the end goal.

Maximum soil organic cover

The second pillar of CA aims to achieve maximum soil organic cover using dead (e.g., crop residues) or living mulch (e.g., cover crops).

It is recommended to maintain at least 30% of the plot area covered, which can be achieved using all types of organic mulch.

To ensure consistency with the seasonal variability of erosion risks, the coverage threshold should be evaluated in parallel with the seasons when erosion risks are highest. These seasons should be defined according to the region where the study is conducted.

The ultimate goal is to maintain year-round coverage of at least 30% of the plot area.

Box 6. Definition of the second pillar of CA

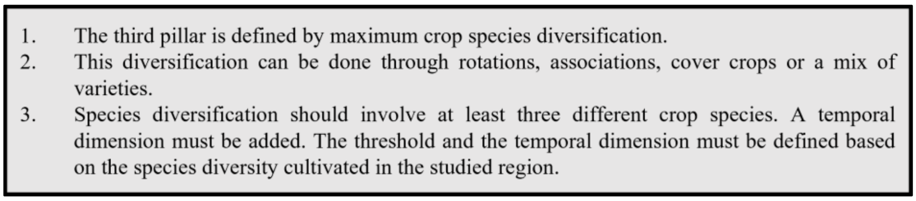
1. The second pillar is defined by maximum soil organic cover.
2. The soil cover can be achieved by dead or living mulch.
3. At least 30% of the plot area should be covered, which can be reached by all types of organic mulch.
4. To be consistent with the seasonal variability of erosion risks, the coverage threshold must be assessed in parallel with the seasons when erosion risks are highest, defined according to the region studied.
5. Permanent soil cover (365 days/year) of more than 30% of the plot area is the end goal.

Maximum crop species diversification

The third pillar of CA aims to achieve maximum crop species diversification. This can be achieved through crop rotations, crop associations, cover crops, or a mix of varieties. Species diversity can therefore be maximized both spatially, e.g. with associations, and temporally, e.g. through rotations.

According to FAO (2017, 2023a), species diversification should involve at least three different crop species. It is important to add a temporal dimension to meet this threshold. For instance, "species diversification should involve at least three different crop species within a two-year period". The threshold and temporal dimension must be defined based on the species diversity cultivated in the studied region.

Box 7. Definition of the third pillar of CA



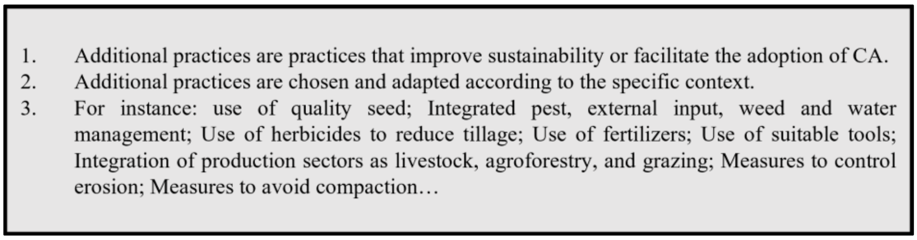
1. The third pillar is defined by maximum crop species diversification.
2. This diversification can be done through rotations, associations, cover crops or a mix of varieties.
3. Species diversification should involve at least three different crop species. A temporal dimension must be added. The threshold and the temporal dimension must be defined based on the species diversity cultivated in the studied region.

Additional practices

In addition to these three pillars, it is possible to implement additional practices that can be defined as practices that improve sustainability or facilitate the adoption of CA (Sommer et al. 2014).

Although FAO publications (FAO 2019, 2023a) already mention a list of additional practices (see Box 4), the number of these practices and their implementation characteristics depend on the context and therefore on the region studied.

Box 8. Additional practices to improve sustainability and/or facilitate CA adoption



1. Additional practices are practices that improve sustainability or facilitate the adoption of CA.
2. Additional practices are chosen and adapted according to the specific context.
3. For instance: use of quality seed; Integrated pest, external input, weed and water management; Use of herbicides to reduce tillage; Use of fertilizers; Use of suitable tools; Integration of production sectors as livestock, agroforestry, and grazing; Measures to control erosion; Measures to avoid compaction…

4. Discussion

4.1. Guidelines to identify Conservation Agriculture practices while embracing diversity

Establishing general thresholds for each pillar of CA facilitates cross-study comparisons, regardless of where CA is practiced. However, this approach highlights the need for standardized terminology to prevent confusion and ensure consistent naming of different CA practices. In addition, proposing general thresholds can lead to the exclusion of certain CA practices. The chosen thresholds may be perfectly suited to one region while excluding practices considered CA in other regions. This raises the question of who has the authority to define what CA actually is.

The definition of general thresholds is part of a top-down approach. External organizations, which may be disconnected from local realities, impose the boundaries of a farming system. This approach can prove complex to implement because soil conservation practices vary depending on the tools available, the crops and intercrops grown, the markets, and the possibilities for retaining crop residues on the plot. The use of a 100% top-down approach risks excluding the possibility of implementing CA in certain territories.

In contrast, the bottom-up approach uses local characteristics to assess the potential of conservation practices and define local thresholds associated with each CA pillar. While employing different thresholds and units of measurement can introduce bias into the assessment of CA practices (Y. Agnan, personal communication, February 23, 2024), this approach offers the advantage of comparing practices implemented within the same territory, which is more relevant than comparing CA practices between different regions of the world. For example, it would be inappropriate to compare a CA-type practiced on a family farm in Sub-Saharan Africa with a CA-type implemented on over 1,000 hectares in the Great Plains of the USA.

Our proposed definition of CA and its three pillars aims to reconcile the two approaches. The definition proposes a general framework with principles that can be implemented wherever CA is practiced. In addition, the definition enables studies that concentrate on implementing CA at the regional level to adjust the thresholds for identifying and comparing CA practices with other methods of managing agricultural land in the same area.

4.2. Unraveling the Complexity of Defining Conservation Agriculture Compared to Other Farming Systems

Constructing a comprehensive definition of CA for practical application in the field was challenging for several reasons. First, the terminology used in the pillar titles like “minimum”, “permanent”, and “diversify”, can lead to various interpretations (Sumberg and Giller 2022). Additionally, English terminology may lack the necessary nuance, leading to confusion between terms such as tillage and plowing, or direct seeding and no-till. Furthermore, the practices encompassed by CA are not always easily categorized as “on” or “off”, as is the case with organic farming where pesticide use is completely eliminated.

The challenge of defining an agricultural system is not exclusive to CA. Agroecology, which emerged in 1980, has undergone several changes in its definitions, including the addition of a new conceptual framework in 2019 (FAO 2024). Newton et al. (2020) have also noted that despite its increasing popularity, there is no widely accepted legal or regulatory definition of regenerative agriculture. Furthermore, Sumberg and Giller (2022) argue that the term “conventional agriculture” lacks analytical purchase and is used in a strategy to homogenize and normalize.

This approach, of attempting to delimit a farming system by constructing a definition that can be operationalized in the field, can therefore be echoed in farming systems other than CA.

4.3. Methodological limitations

Before concluding this chapter, it is important to identify the methodological limitations of the approach that has been adopted. Although rigorous, the method is based on arbitrary choices. A time bias is present in the selection process, as the FAO publications were chosen over a period of several years, while the reference articles were selected over a much shorter period, covering less than a year. Additionally, we focused on articles that are considered references in CA. We determined whether or not they belonged to the reference category based on a single criterion: the author’s number of citations. An author was considered a referent if they had more than 200 citations. To improve the analysis, it is suggested to consider broadening the selection period of articles to include multiple years, or even targeting key years in which CA has been widely discussed in scientific literature. Additionally, modifying or expanding the selection criteria for articles considered as CA references may be necessary.

However, even in the most frequently cited articles defining CA that we selected, the definitions of CA and its pillars remain generally succinct. They are often limited to a brief, general presentation of the three pillars of CA, without delving into specific farming practices. Therefore, we feel confident that we have not omitted from our selection an article that can present a comprehensive and widely used definition of CA.

5. Conclusion

This chapter aims to establish a comprehensive definition of CA suitable for practical application in the field, with the objective of facilitating the identification and categorization of CA practices on a regional scale.

The main challenge encountered was formulating a definition that is broad enough to encompass the diversity of CA practices implemented worldwide, while allowing for adaptation to local contexts to refine system delineation and facilitate comparison with other agricultural systems in the region.

Drawing from definitions provided by the FAO, which introduced and defined the concept of CA in 1998, we identified 13 points hindering the development of a universal and operational definition of CA. These points were addressed through the analysis of articles recognized as references in CA literature.

The proposed definition incorporates the three pillars (or principles) of CA, which can be supplemented with additional practices aimed at enhancing sustainability or facilitating CA adoption. For each pillar, a set of indicators is provided to differentiate CA from other agricultural systems, with some indicators adaptable to the region of implementation. Regarding additional practices, while a list has been provided, the number and types of additional practices are also context dependent. Therefore, this definition recognizes the diversity of practices in the field and offers greater flexibility than conventional definitions. It serves as a universal framework applicable to all CA systems worldwide. Adjustments to the pillar indicators, inclusion, or exclusion of additional practices, may be necessary depending on the specific context.

The endeavor to define a farming system by constructing an operationalizable definition applicable in the field resonates with other farming systems such as agroecology or regenerative agriculture, whose definitions are still evolving and thus not always easy to grasp.

Through this chapter, we have just tamed our first elephant.

Acknowledgements

We would like to extend our heartfelt gratitude to the members of the thesis committee for their invaluable guidance, not only on this chapter but throughout the entire thesis. A special acknowledgment is due to Marie-Hélène Jeuffroy (INRAE) for her second review. We are also grateful to Timothée Clément for the constructive discussions we shared regarding the FAO's definition of CA.

Chapitre 3 L’Agriculture de Conservation en Wallonie

Ce chapitre permet de réaliser la transition entre le premier « éléphant dans la pièce », traité dans le chapitre précédent (Chapitre 2) et portant sur la construction d'une définition opérationnelle de l'AC, et le deuxième « éléphant », traité dans le chapitre suivant (Chapitre 4), portant sur la catégorisation de la diversité des pratiques en Agriculture de Conservation (AC) à l'échelle régionale.

Ce chapitre a pour objectif d'identifier la population d'agriculteur·rices pratiquant l'AC – nommés ACistes – présente sur le territoire étudié, en l'occurrence la Wallonie, et de recenser les connaissances actuelles sur cette population. Au départ de la définition apportée au Chapitre 2, nous avons établi des critères pour identifier les ACistes wallon·nes. Ensuite, un inventaire des ACistes a été réalisé. Enfin, une description du paysage agricole wallon de l'AC est présentée, englobant les différentes facettes et nuances de l'adoption et de la mise en œuvre de l'AC.

Étant donné que les lecteur·rices les plus susceptibles d'être intéressé·s par ces résultats seront vraisemblablement francophones, ce chapitre a été rédigé en français.

Contrairement à l'anglais, la langue française masculinise les noms. Convaincu·es que la lutte contre les inégalités linguistiques est indispensable pour progresser vers un monde plus juste, qui plus est dans le cadre d'une thèse qui s'ancre dans une démarche globale de diversité et d'inclusivité, nous avons jugé essentiel de garantir la visibilité des agricultrices. En 2022, elles représentaient 29% de la main-d'œuvre agricole (SPW 2023a). Une écriture inclusive a été adoptée, tout en limitant au maximum le recours au point médian par souci de préserver la fluidité du texte. À cette fin, nous avons adopté la méthode de la philosophe Isabelle Stengers, consistant à accorder aléatoirement les mots, alternant entre le féminin et le masculin.

Certains verbatims ont été utilisés pour illustrer les résultats. Ces verbatims doivent, par définition, demeurer fidèles aux propos tenus et n'ont donc pas été reformulés en écriture inclusive.

1. Introduction

Pour bien comprendre la diversité des pratiques au sein d'un système agricole, tel que nous le ferons dans le chapitre 4, il est crucial de cibler et de délimiter ce système. Cette démarche a été entreprise dans le chapitre 2, où nous avons élaboré une définition opérationnelle de l'Agriculture de Conservation (AC). Par la suite, il est nécessaire de cibler la population d'intérêt, à savoir les agricultrices pratiquant l'AC, en agriculture biologique ou non, que nous désignons comme les ACistes.

En Belgique, comme dans la plupart des pays européens, il n'existe pas de base de données centralisée regroupant les ACistes (Carmona et al. 2015). Dans ce contexte, l'objectif de ce chapitre est double.

Tout d'abord, nous cherchons à identifier la population ACiste dans la région étudiée, à savoir la Wallonie, située dans la moitié sud de la Belgique. Il est important de souligner que notre but n'est pas de dresser une liste exhaustive des ACistes, car cette liste est susceptible d'évoluer au fil du temps. Notre intention est plutôt de dresser un état des lieux de la situation de l'AC tel qu'elle était en 2020.

Notre second objectif est de recenser les connaissances disponibles sur cette population afin de dresser le paysage de l'AC en Wallonie. À partir des données existantes et des informations recueillies auprès de diverses instances et d'un échantillon d'ACistes, ce chapitre vise à enrichir notre compréhension de la situation globale de l'AC en Wallonie. Nous chercherons à répondre à des questions telles que l'ampleur de son adoption, sa répartition géographique, l'intégration de la certification biologique et de l'élevage, ainsi qu’à mettre à jour la cartographie des acteurs clés dans ce domaine.

Il convient de noter que ce chapitre se démarque des autres en n'adoptant pas la structure et les méthodologies traditionnellement utilisées dans la recherche. Après avoir décrit la méthodologie utilisée, nous présentons successivement les résultats concernant le paysage de l'AC en Wallonie.

2. Méthodologie

La méthodologie utilisée se décompose en quatre étapes, détaillées dans les sections suivantes (Figure 8). Tout d'abord, nous avons défini les critères permettant de déterminer si un agriculteur est considéré comme ACiste, c’est-à-dire pratique l’AC ou l’Agriculture Biologique de Conservation (ABC). Pour ce faire, nous sommes partis de la définition établie dans le chapitre 2, tout en nous appuyant sur les connaissances actuelles sur l'AC en Wallonie. Ensuite, nous avons procédé au recensement des agricultrices potentiellement en A(B)C en collaboration avec des partenaires locaux. Cette collaboration nous a permis d'établir une première liste d'agriculteurs potentiellement ACistes, que nous avons ensuite validée en effectuant des appels téléphoniques et en croisant les informations provenant de différentes sources. À partir de cet inventaire d'ACistes confirmés, nous avons dressé un état des lieux concernant leur nombre, leur répartition géographique, ainsi qu'une première estimation de l'adoption de la certification biologique et de l'élevage en AC. Enfin, nous avons mené deux séries d'entretiens semi-dirigés (une en 2019 et une autre en 2020/21) auprès d'une soixantaine d'ACistes issus de l'inventaire. Les informations recueillies lors de ces entretiens ont permis de retracer l'historique de l'AC en Wallonie, d'estimer la Superficie Agricole Utile (SAU) dédiée à l'AC, de caractériser les pratiques de travail du sol en AC en Wallonie, et d'établir une cartographie des acteurs impliqués en AC.

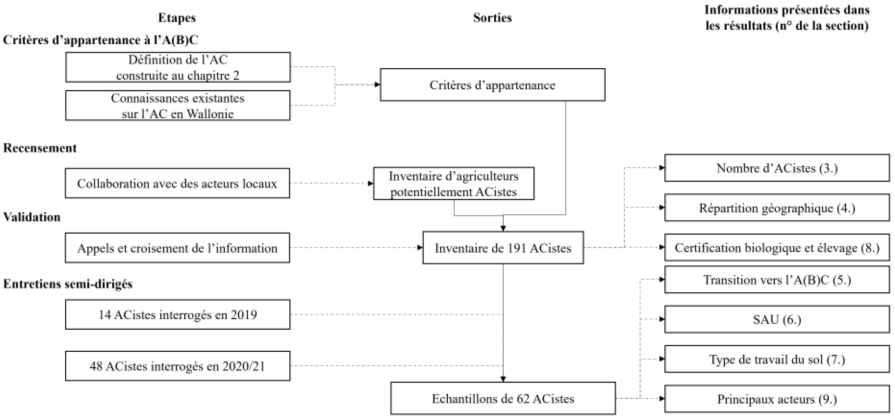


Figure 8 Etapes pour réaliser l'inventaire des ACistes et dresser le paysage de l'AC en Wallonie

2.1. Critères d'appartenance à l'A(B)C en Wallonie

Le chapitre 2 a abouti à l'élaboration d'une définition opérationnelle de l'AC, basée sur une analyse des publications de la FAO et des articles scientifiques jugés reconnus comme références en matière de définition de l'AC. Cette définition est conçue pour être applicable sur le terrain, quelle que soit la région étudiée. Elle fournit un cadre général permettant de distinguer l'AC des autres systèmes agricoles. Afin d'étudier l'AC au sein d'une région spécifique, il est essentiel d'adapter cette définition au contexte local. Étant donné que notre étude porte sur l'AC en Wallonie, il est nécessaire d'examiner les connaissances préliminaires sur l'AC dans cette région afin de clarifier sa nature spécifique et de définir des critères permettant de déterminer si un agriculteur pratique ou non l'AC.

L'étude wallonne la plus récente sur la transition des agricultrices vers l'AC, menée par Vankeerberghen et Stassart (2016), a montré que l'AC émerge selon un processus par retrait. Contrairement à l'agriculture biologique, qui émergea d’une opposition tranchée au modèle conventionnel, l'AC s'est insérée dans le paysage wallon en remettant en question une facette spécifique de l'agriculture conventionnelle : le labour. Le non-labour constitue ainsi la porte d’entrée vers l’AC pour les agriculteurs wallons (Vankeerberghen and Stassart 2016).

Vankeerberghen et Stassart (2016) suggèrent d’envisager l'innovation de l'AC en Wallonie comme un processus d'insularisation. Cette approche implique un éloignement progressif des pratiques AC du modèle agricole conventionnel. Cet éloignement débute par l'abandon du labour et la mise en place de techniques de travail de sol réduit. Bien que ces pratiques de travail du sol soient diversifiées et adaptées aux contextes et aux parcours individuels des agriculteurs, l’abandon de la charrue repose majoritairement sur une dépendance accrue aux herbicides totaux, tels que le glyphosate. Cette transition peut ensuite évoluer d'une péninsule partiellement connectée au modèle conventionnel, vers une insularisation complète. Cette phase avancée implique une transformation cognitive de la perception du sol, ouvrant la voie à l'adoption des deux autres piliers de l'AC et à l'intégration de pratiques additionnelles. Néanmoins, une tension émerge parmi les ACistes qui adoptent cette nouvelle vision du sol. Cette tension se situe entre la réduction du travail du sol et le désir de supprimer les pesticides, en particulier les herbicides, considérés le plus souvent comme indispensables pour la gestion des adventices et la destruction des intercultures en non-labour.

Certaines agricultrices wallonnes tentent de concilier l’AC et l'agriculture biologique, pour pratiquer l’ABC (Casagrande et al. 2016; Boeraeve et al. 2022). Boeraeve et al. (2022) soulignent le défi que représente l'ABC, qui consiste à éviter l'utilisation de la charrue et des herbicides pour la gestion des adventices. Cependant, leurs critères de sélection des parcelles en ABC ne précisent pas la place de la charrue : ces parcelles sont en travail du sol réduit (ou labour réduit, selon la signification donnée au mot « tillage ») ou en semis direct (SD, semis d'une culture sans préparation préalable du sol), les céréales sont cultivées en association de cultures et/ou des intercultures hivernales sont cultivées. Les parcelles conventionnelles pairées sont labourées régulièrement, mais la fréquence de labour n'est pas spécifiée.

Selon les études de Peigné et al. (2014) et Casagrande et al. (2016), les parcelles ABC européennes doivent répondre à au moins deux des trois critères suivants: (i) absence de labour, (ii) utilisation d'un système de travail du sol réduit, se référant à une méthode, soit sans retournement du sol (par exemple, l'utilisation d'un cultivateur lourd comme le chisel), soit avec un retournement des horizons, limité à une profondeur inférieure à celle pratiquée en agriculture conventionnelle (la profondeur n’étant pas spécifiée), (iii) mise en place d’intercultures. Seulement 27% des agriculteurs ABC interrogés ont déclaré ne plus pratiquer de labour, tandis que 89% ont indiqué réduire le travail du sol et que 74% ont signalé implanter des intercultures.

L’utilisation de la charrue semble donc autorisée en ABC. Cependant, des questions se posent quant à (i) la profondeur, comme mentionnée par Peigné et al. (2014) et Casagrande et al. (2016), sans qu’aucun seuil ne soit spécifié, et à (ii) la fréquence d’utilisation de la charrue. Concernant cette fréquence, Boeraeve et al. (2022) ont comparé des parcelles en ABC à des parcelles conventionnelles pratiquant un labour fréquent, mais à nouveau, aucun seuil de fréquence n'est défini.

Concernant la fréquence de labour en Wallonie, au sein de la région Hesbaye, 90% des terres arables labourables (hors prairies permanentes et temporaires) ont subi un labour au moins une fois entre 2015 et 2019 (Yue Zhou, communication personnelle, 1er mars 2024, résultats bientôt publiés). A l’échelle annuelle, les estimations sont compliquées à réaliser en raison d’un grand nombre de données manquantes : pour chaque année de la période 2015-2019, la proportion de parcelles (i) labourées varie entre 19% et 44%, (ii) non-labourées entre 24% et 49% et (iii) celles des parcelles sans information entre 30 et 32% (Yue Zhou, communication personnelle, 1er mars 2024).

En conclusion, il est observé que les études menées sur l’A(B)C sur le territoire wallon se concentrent principalement sur le premier pilier de l’AC, à savoir la réduction du travail du sol. Le second pilier (la maximisation de la couverture du sol) est pris en compte dans une moindre mesure, par la mise en place d’intercultures. Enfin, le troisième pilier (la diversification des espèces cultivées) ne semble pas faire l’objet d’un critère d’appartenance à l’A(B)C. Cette mise en avant du premier pilier peut être expliquée par l'historique de l'AC, puisque l’arrêt du labour constitue généralement le premier pas des agriculteurs lorsqu'ils décident de pratiquer l’AC (Vankeerberghen and Stassart 2016). De plus, le premier pilier est le seul sur lequel l'agricultrice exerce un contrôle direct, contrairement aux deux autres piliers qui sont souvent influencés par des facteurs externes.

Par conséquent, puisque le premier pilier constitue un critère facile à vérifier et reflétant pleinement le choix de l'agriculteur, nous l’avons sélectionné comme critère d'inclusion ou d'exclusion du système A(B)C. Pour les agricultrices non biologiques, nous les avons considérées comme faisant partie du système AC si elles ont cessé de labourer, en adoptant ou non le SD. Pour les agricultrices biologiques, pour être considérées comme pratiquant l'ABC, elles doivent avoir cessé de labourer systématiquement, et/ou maintenir une profondeur de labour inférieure à 15 cm. La profondeur de 15 cm a été choisie car elle est employée au sein de la littérature scientifique (p. ex. dans Kassam et al. 2009) et au sein de la BAE 5 de la PAC 2023-2027.

Pour terminer cette section, nous aimerions citer un agriculteur dont les propos illustrent la difficulté de définir l'AC de manière à englober la diversité des pratiques sur le terrain.

« Pour moi, l'AC, il faudrait déjà qu'on dise « c'est quoi l'AC ? ». Il y a des gens qui disent « je ne charrue plus, je fais de l'AC ». Si tu ne charrues pas, que tu ne mets pas d'engrais vert et que tu passes dix fois sur tes terres ou que tu fais quatre Roundup par an, ce n’est pas de l'AC... L'AC, il y a plein de façons. Alors, celui qui fait du semis direct pur, alors ok c'est même plus que de l'AC, c'est extraordinaire, ce qu'il fait. Mais on oublie alors les légumes, ces choses-là, ça ne fonctionne pas ! » (44)

2.2. Recensement

En 2020, un recensement des ACistes a été établi en collaboration avec douze institutions publiques et privées, huit comices agricoles, deux parcs naturels, deux chercheuses d'universités belges (Lola Leveau (UCLouvain) et Fanny Boeraeve (ULiège)), au travers de la méthode boule de neige[7] auprès des ACistes déjà rencontrés par l’équipe Sytra, ainsi que par l'utilisation du réseau social Facebook[8] (Table 5).

Table 5 Liste des instances et canaux employés pour la création de l’inventaire

Centre de recherche	**Instance publique**	**ASBL**	**Autre**
CRA-W ; UCLouvain ; ULiège.	SPW-Agriculture ; Collège des Producteurs.	Centre de Michamps ; Greenotec ; Regenacterre ; Natagriwal ; Agra-Ost.	Canopea ; ACistes déjà interrogés par Sytra ; GreenFarming ; Awé ; Comices agricoles ; Parcs Naturels ; Entrepreneurs agricoles ; Groupes Facebook.

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[7] La méthode boule de neige est une méthode d’échantillonnage raisonné permettant de sélectionner de nouveaux participants en fonction de la description donnée par les participants déjà interrogés (Tittonell et al. 2020; Tessier et al. 2021).

[8] Ceci dans le respect du RGPD de l’UCLouvain. L’accord des agriculteurices est indispensable en amont du partage de leurs informations.

2.3. Validation de l’inventaire

Après avoir dressé l'inventaire des agricultrices wallonnes potentiellement engagées dans l’A(B)C en collaboration avec diverses parties prenantes, une validation a été réalisée. Cette validation a été effectuée soit par des entretiens téléphoniques, soit par le croisement de source.

Lors des entretiens téléphoniques, la structure suivante a été adoptée : tout d'abord, une brève présentation de ma personne et du sujet de la thèse était effectuée. Ensuite, la question principale était posée : « Pratiquez-vous l’Agriculture de Conservation ? ». Les réponses des agriculteurs se divisaient en trois catégories : affirmative, négative, ou incertaine. En cas d'incertitude, une définition de l'AC basée sur ses trois piliers leur était fournie. Les agriculteurs développaient ensuite leurs pratiques agricoles, se focalisant généralement sur les aspects du travail du sol et de la couverture du sol. Finalement, c’est le travail du sol, et les seuils qui y sont associés (cf. section 2.1), qui a servi de critère d'inclusion ou d'exclusion pour considérer les agriculteurs de l’inventaire comme ACistes.

Les agriculteurs pour lesquels nous n’avions pas les coordonnées téléphoniques et dont l’emplacement géographique était inconnu ont été exclus.

Cet inventaire a permis de recenser le nombre d’ACistes en Wallonie (présenté dans la section 3) ainsi que leur localisation géographique (présentée dans la section 4).

Les appels téléphoniques et le croisement de sources ont également permis d’obtenir deux données supplémentaires : (i) la détention de la certification biologique, collectée pour 49% des ACistes, et (ii) la présence ou l’absence d’élevage, établie chez 61% des ACistes. Malgré l'absence d'une méthodologie rigoureuse dans leur acquisition, entraînant un nombre important de données manquantes, nous avons décidé de les inclure dans notre analyse (résultats présentés à la section 8).

2.4. Entretiens semi-dirigés

Des entretiens semi-dirigés (ou semi-directifs) ont été menés sur un échantillon issu de l’inventaire de la population ACistes (le guide d’entretien est présenté à l’Appendix A). Les informations recueillies lors de ces entretiens et utilisées dans ce chapitre portent sur la transition des ACistes vers l’A(B)C (présentée à la section 5), la superficie en hectares gérée en AC (section 6), les types de travail du sol (section 7), ainsi que les parties prenantes impliquées (section 9). Concernant ces acteurs, notre approche s'est focalisée exclusivement sur la perspective des ACistes, étant donné que ce sont elles qui implémentent les trois piliers de l’AC. Tous les acteurs mentionnés au cours des entretiens ont été répertoriés, qu'ils soient liés à l'implémentation des pratiques de l'AC, engagés dans des obstacles entravant son développement, associés à des choix de pratiques (sélection des cultures, intercultures, choix d'outils de travail du sol, utilisation d'intrants, etc.), à la mise à disposition de conseils ou de produits…

L'échantillonnage a été construit de manière à refléter la diversité inhérente du système AC. Pour ce faire, nous avons adopté la méthode de l'échantillonnage raisonné (ou « purposive sampling » en anglais), une approche non probabiliste visant à sélectionner délibérément les individus les plus pertinents pour fournir les informations recherchées (Wauters and Mathijs 2013b). Les critères qui ont orienté notre sélection étaient les suivants : (i) une répartition géographique diversifiée dans le but d'inclure des ACistes de différentes régions agricoles wallonnes, (ii) une variété sur le plan de la certification biologique, (iii) une diversité en ce qui concerne la pratique de l'élevage, et (iv) idéalement, une expérience en AC ou en ABC d'au moins cinq ans. 48 ACistes ont ainsi été sélectionné·es et interrogé·es entre novembre 2020 et mars 2021.

En complément des 48 ACistes, nous avons inclus quatorze autres ACistes, interrogés entre février et mars 2019. Ces entretiens avaient été réalisés dans le cadre d'un mémoire portant sur les stratégies de substitution au glyphosate en AC (Ferdinand et al. 2019). Lors de cette étude, nous avions collecté des informations similaires à celles recherchées dans ce chapitre, raison pour laquelle nous avons inclus ces ACistes pour enrichir l'analyse (les caractéristiques générales des ACistes interrogées sont présentées à l'Appendix B). Contrairement aux entretiens de 2020-2021, l'échantillonnage avait été réalisé exclusivement au nord du sillon Sambre-et-Meuse et la possession de l'élevage n'était pas un critère d'échantillonnage (seuls trois éleveurs font partie de cet échantillon).

3. Combien sont-ils ? Evaluer l'effectif des ACistes en Wallonie

Depuis 1980, l'adoption du non-labour s'est progressivement étendue en Wallonie (Vankeerberghen and Stassart 2014). Cependant, en raison de l'absence d'un système officiel de notifications, les données concernant cette adoption sont incertaines, présentent des variations en fonction des sources disponibles, et sont principalement axées sur le premier pilier de l'AC, à savoir la réduction du travail du sol et l'arrêt du labour (Prestele et al. 2018).

Selon l'ASBL Greenotec – impliquée dans l'expérimentation, la vulgarisation et le conseil sur les techniques de conservation des sols en Wallonie (ASBL Greenotec) – entre 15 et 25% des terres en froment d'hiver (soit entre 26 700 et 34 300 hectares), 10% des cultures de betterave sucrière, de colza d'hiver, de maïs grain et de pois de conserverie, ainsi que moins de 10% des autres cultures (moins de 19 000 hectares) sont conduites en non-labour en Région wallonne (ASBL Greenotec 2011; Vankeerberghen and Stassart 2016).

Selon Eurostat (2020), au moins 10% des terres arables belges sont semées en SD, faisant de la Belgique l'un des quatre pays européens avec la plus forte adoption de cette technique. En ce qui concerne l'adoption conjointe des trois piliers, les données internationales indiquent que seulement 270 hectares (Kassam 2022) et 300 hectares (ECAF 2023) de terres arables belges sont cultivés en AC. Cette situation positionne la Belgique au 55e rang mondial et au 15e rang européen en termes de superficie (exprimée en ha) dédiée à l'AC[9]. À noter que les données fournies par Eurostat (2020) et Kassam (2022) proviennent de Statbel (SPF Economie), et les méthodes employées pour estimer ces superficies ne sont pas renseignées.

Le recensement a permis d'identifier 220 agricultrices wallonnes potentiellement ACistes. La validation, finalisée en septembre 2023, a réduit ce nombre à 191 ACistes wallonnes[10]. En 2022, la Wallonie comptait 12 670 exploitations agricoles, dont 3 482 spécialisées en grandes cultures (SPW 2023a). L'AC serait donc pratiquée sur environ 1,5% des exploitations agricoles wallonnes, et 5,5% des exploitations wallonnes spécialisées en grandes cultures.

La réduction du travail du sol en Wallonie reste relativement restreinte, avec une progression modérée, une situation similaire à celle observée dans la plupart des régions européennes (Kassam 2022). L'adoption limitée de l'AC en Europe peut s'expliquer par le manque d'incitations et de pressions à adopter de nouvelles pratiques agricoles, étant donné que les conditions agricoles y sont relativement favorables et ne suscitent pas un besoin de changer les pratiques en cours (Kassam 2022). À l'échelle de la Belgique et concernant la pratique du travail du sol sans inversion, le nombre d'agriculteurs ayant l'intention d'adopter cette pratique dans un avenir proche dépasse celui des agriculteurs actuellement engagés dans cette pratique (Bijttebier et al. 2018). Ce constat renforce l'idée d'envisager une

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[9] A titre d'information, en 2018/19, les Etats-Unis, classés en première position, géraient 44 millions d'hectares gérées en AC, tandis que l'Espagne, classée onzième au niveau mondiale et première en Europe, comptait un million d'hectares en AC (Kassam 2022). Il pourrait être pertinent de rapporter ces superficies à la SAU de chaque pays afin d'évaluer la proportion des terres occupée par l'AC.

[10] Pour des raisons pratiques, étant donné qu'il n'était pas toujours possible de déterminer avec précision le nombre exact de personnes travaillant au sein d'une exploitation, chaque ACiste validé était associé à une seule exploitation agricole. Si plusieurs agriculteurices travaillent ensemble sur une même exploitation, comme leur nombre exact n'a pu être connu, ils ou elles étaient considéré·es comme un·e seul·e ACiste.

augmentation de la réduction du travail du sol et de l’AC en Wallonie dans les années à venir.

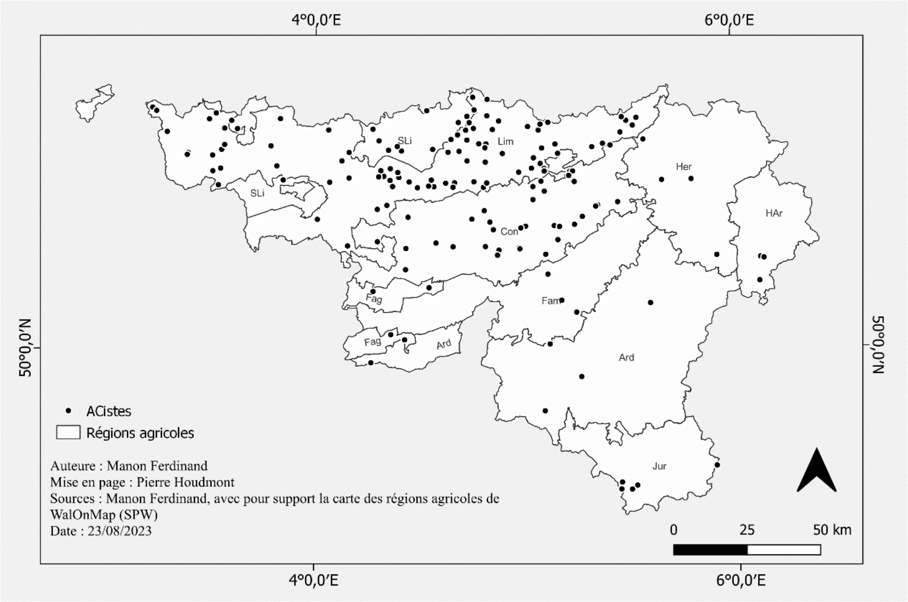
4. Où sont-ils ?

Depuis 1980, l’adoption du non-labour s’est progressivement étendue, principalement dans les régions de grandes cultures situées au nord de la Wallonie, telles que la Hesbaye, ainsi que dans les zones de culture-élevage, comme le Condroz (Vankeerberghen and Stassart 2014). Toutefois, d’après les données d’Eurostat (2020), la province du Luxembourg, située au sud de la Wallonie, est l'une des régions européennes avec une adoption du SD la plus élevée.

L’enquête a permis de positionner géographiquement les 191 ACistes identifiés (Figure 9). Malgré les efforts fournis, une faible proportion d’agriculteurs (12%) a été identifiée au sud et à l’est de la Wallonie. 88% des ACistes se situent au nord et à l’ouest de la Wallonie, dans les régions Limoneuses, Condrusienne et Sablo-Limoneuse.

« Le non-labour a démarré dans le Condroz. Ce sont les gars qui avaient les terres les plus difficiles qui ont commencé à réfléchir comme ça. » (11)

Aucune ACiste n’a été identifiée dans la région de la Campine Hennuyère, qui représente la plus petite région agricole de Wallonie (38 km^2) comptant uniquement 18 exploitations professionnelles et enclavée dans la région Sablo-limoneuse (SPW 2022a).



Auteure : Manon Ferdinand
Mise en page : Pierre Houdmont
Sources : Manon Ferdinand, avec pour support la carte des régions agricoles de WalOnMap (SPW)
Date : 23/08/2023

Figure 9 Répartition géographique des ACistes wallon·nes

Légende : Sablo-limoneux (SLi), Limoneux (Li), Condroz (Con), Herbagère (Her), Fagne (Fag), Famenne (Fam), Haute Ardenne (HAr), Ardenne (Ar), Jurassique (Jur).

Il est utile de rapporter le nombre d'ACistes au nombre total d'exploitations wallonnes de chaque région. Etant donné que les régions sablo-limoneuse et limoneuse s'étendent à la fois sur la Wallonie et la Flandre, nous avons plutôt calculé ce rapport en nous basant sur les cinq provinces wallonnes (Table 6). Nous remarquons à nouveau une concentration des ACistes au nord de la Wallonie.

Table 6 Analyse comparative du nombre d'exploitations ACistes par rapport aux exploitations wallonnes selon les cinq provinces

Source pour le nombre d'exploitations par province : Statbel 2022

Provinces wallonnes	**Nombre d'exploitations**		**Proportion des exploitations en A(B)C (%)**
	A(B)C	Total	
Brabant Wallon	34	1 031	3,30
Hainaut	63	3 896	1,62
Liège	41	3 056	1,34
Luxembourg	9	2 341	0,38
Namur	44	2 346	1,88
Somme	191	12 670	

Analyse géographique des incitants et freins à l’adoption de l’AC en Wallonie

Plusieurs raisons peuvent expliquer une adoption plus forte de l’AC dans le nord et l’ouest de la Wallonie (Figure 10).

Tout d’abord, les principaux acteurs impliqués dans l’encadrement, le conseil, et la recherche en AC sont principalement basés au nord et à l’ouest de la Wallonie (Dierick, communication personnelle, 21 octobre 2019).

De plus, les régions au sud et à l'est de la Wallonie sont principalement dédiées aux prairies (Maugnard et al. 2013; SPW Agriculture 2020), tandis que la majorité des grandes cultures sont cultivées dans le nord et l'ouest, en raison d’un statut acido-basique des sols optimal (Genot et al. 2009). Etant donné que l’AC concerne, conformément à la définition de ses trois piliers, davantage les grandes cultures que les prairies permanentes, il n’est pas surprenant de constater une plus grande concentration d’ACistes au nord et à l’ouest.

Les couverts végétaux (tels que les cultures intermédiaires piège à nitrates appelées CIPAN) sont moins fréquents dans le sud du pays en raison de l'absence d'obligations légales hors de la zone vulnérable[11] et des conditions climatiques plus froides qui entravent leur développement (Pr. Richard Lambert, communication personnelle, 21 octobre 2019).

La dégradation des sols préoccupe principalement le nord de la Wallonie, où une plus grande proportion de terres est cultivée en lignes (Wauters et al. 2010). Les régions sablo-limoneuse, limoneuse et condrusienne sont particulièrement touchées, présentant un état de dégradation parmi les plus avancés du territoire wallon (Bielders et al. 2003; Goidts and van Wesemael 2007; Wauters et al. 2010; Maugnard et al. 2013; Vanwindekens et al. 2018). Les agriculteurs confrontés à ces soucis d’érosion sont plus enclins à employer des mesures de lutte telles que des pratiques de conservation des sols (Bielders et al. 2003; Bijttebier et al. 2014). Bielders et al. (2003) ont montré qu’en région limoneuse et sablo-limoneuse la réduction du travail du sol était pratiquée par 24,7% des agriculteurs interrogés. A l’inverse, dans les régions agricoles situées au sud, les taux de MO sont généralement hauts, du fait de l’utilisation importante d’engrais de ferme et de la fréquence élevée de prairies temporaires au sein des rotations (Lambert, communication personnelle, 21 octobre 2019).

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[11] La zone vulnérable représente un périmètre de 9 596 km^2 (57% du territoire wallon) destiné à la protection des eaux souterraines et de surface contre les nitrates d’origine agricole afin de répondre aux exigences de la Directive Nitrates (SPW 2020).

Il existe néanmoins plusieurs arguments en défaveur d'une adoption de l'AC pour les agricultrices situées au nord et à l'ouest de la Wallonie. Des terres productives, qui assurent des rendements élevés sous labour, peuvent diminuer l'incitation des agricultrices à adopter des pratiques de réduction du travail du sol (Bijttebier et al. 2014). Sur un sol productif, les conséquences de certains problèmes édaphiques, comme un faible taux de MO, se répercutent moins sur les rendements, pouvant entrainer une plus faible remise en question des pratiques culturales et donc une plus faible adoption à de nouveaux systèmes agricoles comme l'AC. On pourrait dès lors s'attendre à un taux d'adoption plus faible dans les régions aux sols productifs – telles que les régions limoneuses, sablo-limoneuses et le Condroz – comparés aux autres régions.

De même, un système agricole avec un apport régulier en fumure organique, permettant de diminuer les conséquences d'une dégradation des terres liées à un travail du sol intensif, peut limiter l'adoption des techniques de conservation (Braibant et al. 2018). Certains agriculteurs des régions des grandes cultures considèrent néanmoins que l'apport d'engrais de ferme est une pratique qui va de pair avec l'application des pratiques AC pour augmenter le niveau de MO du sol (Braibant et al. 2018).

L'AC peut également être intéressante à pratiquer dans les systèmes agricoles situés au sud et à l'est de la Wallonie. Les zones les plus sensibles à l'érosion hydrique sont l'Ardenne et la Haute-Ardenne, en raison du relief accidenté et de l'intensité érosive des précipitations (Maugnard et al. 2013). Cette situation peut justifier la mise en place de pratiques AC dans les systèmes de culture où le sol n'est pas couvert en permanence, excluant donc les parcelles sous prairies permanentes.

Que ce soit au nord comme au sud de la Wallonie, des sols plus difficiles à travailler peuvent constituer un facteur d'adoption aux pratiques de conservation des sols (Vankeerberghen and Stassart 2013). Les sols hétérogènes, plus lourds (c'est-à-dire plus caillouteux et/ou plus argileux), plus collants et abrasifs pour le matériel agricole, sont plus compliqués à labourer. L'abandon de la charrue et son remplacement par des outils de travail du sol plus légers, voire le passage au SD, pourraient donc se justifier davantage sur ce type de sol (Braibant et al. 2018). En Wallonie, les teneurs des sols en argile et limon fin augmentent du nord au sud, avec une diminution dans la région Jurassique (Chartin et al. 2017).

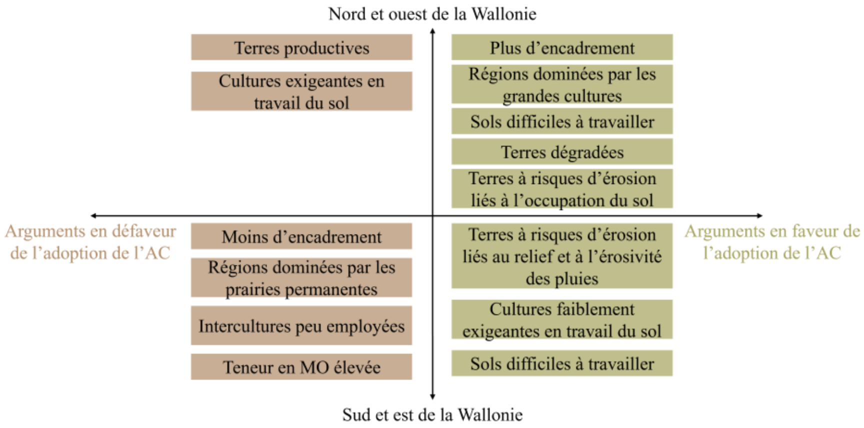

Figure 10 Synthèse des arguments expliquant la disparité géographique de l'adoption à l'AC en Wallonie

Sources d'incertitudes sur les données et leurs répercussions sur les pratiques de travail du sol

En comparant la localisation des ACistes (cf. Figure 9) avec les données d'Eurostat (2020), il est légitime de se demander comment Eurostat a pu conclure que la province du Luxembourg, située à l'extrémité sud de la Wallonie, figure parmi les régions européennes où la pratique du SD est la plus répandue.

« Il n'y a que moi, en province de Luxembourg, qui aie un semoir comme ça (semoir de semis direct, plus précisément le Sky). » (16)

Agriculteur n°19 : « Mais vous savez ici, en Ardennes, tout le monde fait de l'Agriculture de Conservation. » PhD : « En mettant des prairies ? » Agriculteur : « Oui, j'ai déjà des prairies permanentes, donc... »

L'erreur probable dans l'analyse des données d'Eurostat (2020) peut être attribuée à une mauvaise classification des parcelles, en particulier celles désignées comme prairies. Comme indiqué dans l'annexe C de l'article de Vandevoorde et Baret (2023), entre 2015 et 2020, les règles de déclaration pour les subventions de la Politique Agricole Commune (PAC), permettant de différencier les prairies temporaires des prairies permanentes, ont évolué. De plus, certains agriculteurs n'ont pas correctement déclaré leurs prairies permanentes afin d'éviter les restrictions relatives au labour des prairies (Vandevoorde and Baret 2023). En conséquence, il est possible que la catégorie « prairies temporaires » inclue des prairies permanentes « interrompues », c'est-à-dire qui sont déclarées comme d'autres cultures tous les cinq ans afin d'éviter d'être cataloguées comme permanentes (Vandevoorde and Baret 2023).

Ainsi, certaines parcelles sous prairies permanentes peuvent être incorrectement classées en tant que terres arables alors qu'elles restent constamment couvertes de végétation (puisqu'étant des prairies permanentes). Cela pourrait prêter à confusion en suggérant à tort qu'il s'agit de cultures arables gérées en SD (communication personnelle 18/04/2023, Noé Vandevoorde).

Cela remet en question la fiabilité du traitement des données d'Eurostat (2020), qui dépend des données fournies par Statbel. Statbel établit ses références à partir d'enquêtes agricoles menées tous les trois ou quatre ans, ainsi que de bases de données administratives (Statbel). Il n'est pas clairement précisé si Statbel intègre les déclarations de la PAC dans ce processus, et la méthodologie de traitement et de catégorisation des données n'est pas spécifiée.

A cette source potentielle d'erreur, s'ajoute le constat d'une différence notable entre les données issues de Statbel et celles provenant du Système Intégré de Gestion et de Contrôle (SIGEC) (Tableau présenté à l'Appendix C, communication personnelle 18/04/2023, Noé Vandevoorde).

Ces éléments divers mettent en évidence la difficulté actuelle de disposer d'une connaissance précise de l'utilisation des terres agricoles en Wallonie. Par conséquent, il est risqué de se baser sur ces recensements d'occupation des terres pour établir une déclaration concernant les pratiques de travail du sol en vigueur.

5. Depuis quand ? Le non-labour et l'AC, une histoire de plus de quarante ans

Les entretiens menés par Vankeerberghen et Stassart (2016) auprès de quinze agriculteurs ont révélé que les premiers adeptes du non-labour ont commencé leur transition dès le début des années 80. Quant à la mise en œuvre simultanée des trois piliers de l'AC, son développement en Europe a principalement débuté à partir du milieu des années 90 (Vankeerberghen and Stassart 2016).

Au sein de notre échantillon de 62 ACistes, la plus ancienne implémentation des piliers de l'AC, débutant par la remise en question et la réduction du labour, remonte également à 1980. Ce résultat concorde avec les informations recueillies par Vankeerberghen et Stassart (2016).

En moyenne, les ACistes ont adopté l'AC en 2002 (Figure 11). Parmi les 28 ACistes qui pratiquent l'ABC, les premières transitions de l'AC vers l'ABC remontent à 1998, avec une moyenne de transition en 2014. Six ACistes ont directement pratiqué l'ABC sans préalablement implémenter l'AC. Cette transition s'est réalisée en moyenne en 2015.

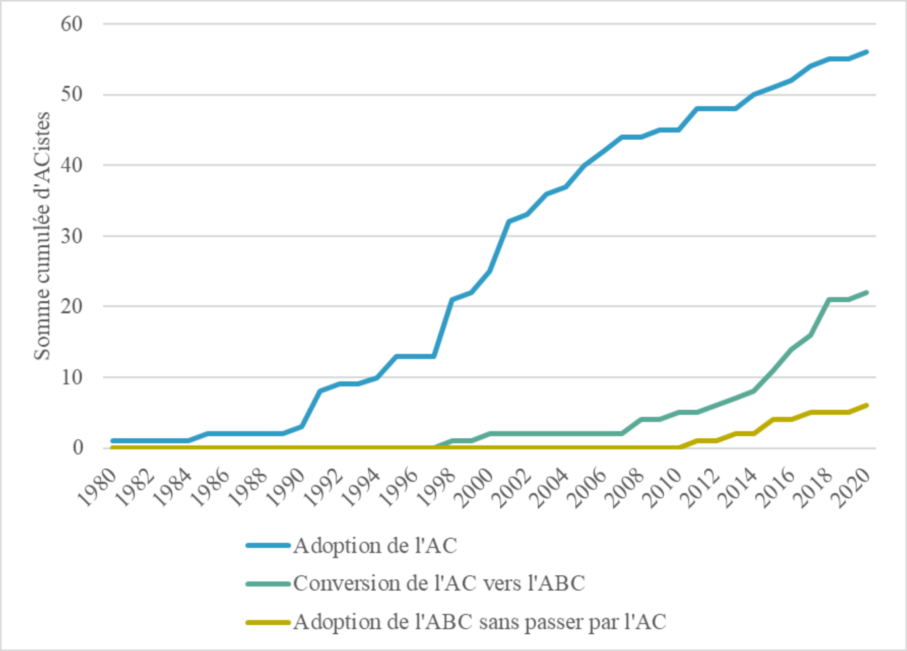

Figure 11 Évolution de l'adoption de l'AC et de l'ABC par les ACistes de l'échantillon

6. La superficie cultivée en AC

L’échantillon de 62 ACistes a permis d’évaluer les superficies agricoles gérées sous AC en Wallonie. En moyenne, les ACistes gèrent une superficie totale (prairies et cultures permanentes comprises) de 219 hectares, avec une médiane de 149 hectares, une valeur minimale de 45 hectares et une valeur maximale de 1 100 hectares (Figure 12).

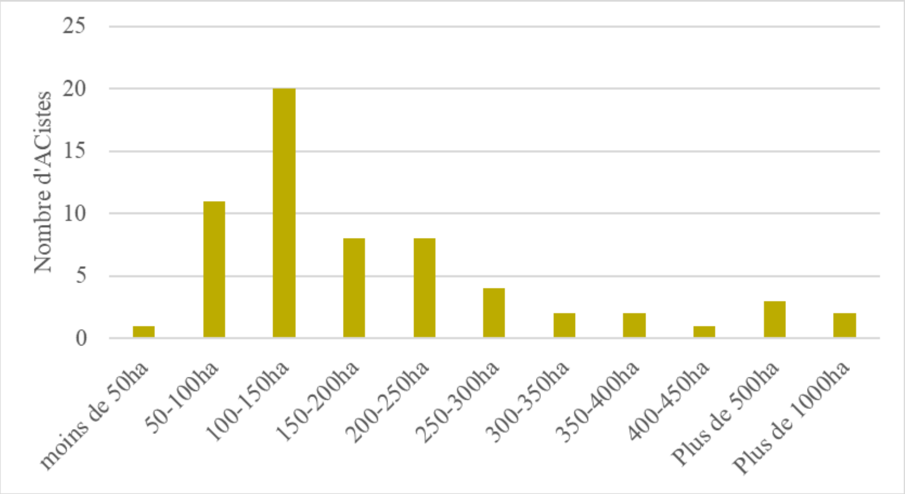

Figure 12 Superficies totales gérées par les ACistes de l’échantillon, exprimées en hectares

Note explicative : les prairies permanentes et cultures permanentes sont comprises dans la superficie totale.

La SAU totale de la Wallonie s'élève à 738 927 hectares, comprenant 249 432 hectares dédiés aux exploitations spécialisées en grandes cultures[12] (SPW 2023a). La superficie moyenne des exploitations wallonnes est de 58,3 hectares et de 71,6 hectares pour les exploitations spécialisées en grandes cultures (SPW 2023a).

En comparaison, la superficie agricole moyenne gérée par les ACistes de l’échantillon est trois fois supérieure à la moyenne régionale des exploitations spécialisées en grandes cultures.

En pratique, divers facteurs, tels que les cultures implantées, les conditions météorologiques et autres circonstances extérieures, influencent le degré

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[12] Le groupe des exploitations du type « spécialisées en grandes cultures » regroupe les exploitations « dont 2/3 au moins de la production brute standard totale provient de la valorisation des produits des grandes cultures. » (SPW 2023b). Pour information, au niveau des exploitations biologiques et des exploitations biologiques spécialisées en bovins laitiers, leur superficie agricole moyenne est de respectivement 46,5 ha et 74 ha (SPW 2023b).

d'intensité de la gestion des parcelles agricoles en AC. Cela se reflète à la fois dans l'étendue réelle des parcelles gérées selon les piliers de l'AC et dans l'intensité des pratiques AC mises en œuvre sur chaque parcelle. En raison de la variabilité interannuelle de ces facteurs, leur prise en compte n'a pas été possible.

Il a été choisi d'exclure les parcelles sous prairies permanentes et les cultures permanentes telles que les vergers. Cette décision découle du fait que les piliers de l'AC portent principalement sur les terres considérées comme « labourables », c'est-à-dire cultivées en cultures annuelles ou en prairies temporaires[13]. Par conséquent, la superficie moyenne gérée en AC est réduite à 199 hectares, avec une médiane de 130 hectares. Les superficies varient de 8 hectares au minimum à 1 100 hectares au maximum. Sur cet échantillon de 62 ACistes nous totalisons ainsi 12 367 hectares de terres « labourables » sous gestion en AC (les superficies totales, certifiées biologiques et sous cultures permanentes sont présentées à l'Appendix D).

En extrapolant la moyenne des superficies occupées à l'AC (hors cultures permanentes) par les ACistes de notre échantillon au nombre total d'ACistes répertoriés en Wallonie, nous pouvons estimer qu'environ 38 009 hectares (=199 ha x 191 ACistes) sont gérés en AC en Wallonie. Cela représente 5% de la SAU totale wallonne (= 38 009 ha / 738 927 ha) ou 15% de la SAU dédiée aux grandes cultures (= 38 009 ha / 249 432 ha). La dernière proportion est significativement supérieure aux estimations rapportées de 270 hectares (Kassam 2022) et 300 hectares (ECAF 2023) de terres arables belges gérées en AC.

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[13] Les prairies temporaires restent en place pour une durée de minimum un an et de maximum cinq ans.

7. Les types de travaux du sol

À la suite des entretiens, nous avons catégorisé les 62 ACistes en quatre systèmes de travail du sol (Figure 13) :

1. Le système « labour occasionnel », regroupant les ACistes qui labourent sur au moins une culture de l'assolement ;
2. Le système « non-labour », regroupant les ACistes qui ne labourent aucune culture de leur assolement ;
3. Le système « semis-direct » ou SD, rassemblant les ACistes qui ne labourent pas et réalisent un SD pour au moins une culture de l'assolement ;
4. Le système « hybride », rassemblant les ACistes qui labourent pour au moins une culture de l'assolement et sèment en direct pour au moins une autre culture de l'assolement.

Parmi les ACistes wallonnes, on observe une grande diversité dans les choix des systèmes de travail du sol. Le système le plus largement adopté est le non-labour, présents chez 42% des ACistes, suivi du labour occasionnel (34%), du SD (19%) et enfin du système hybride (5%).

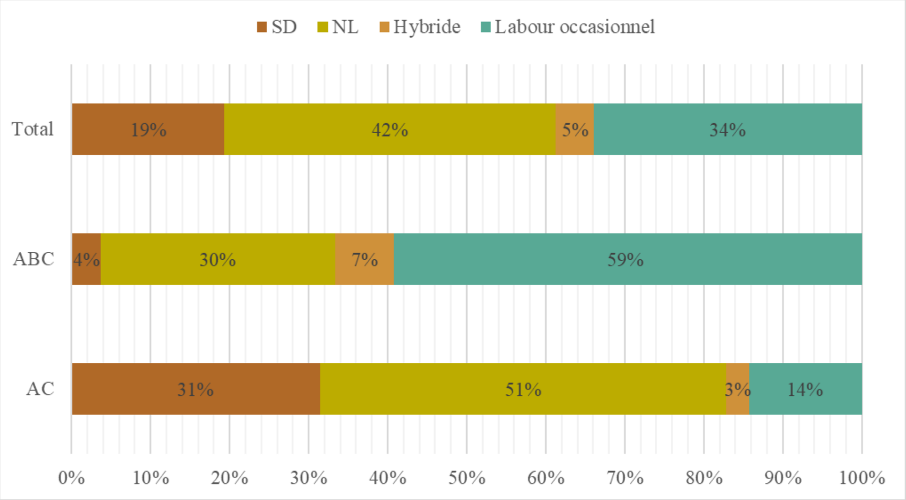

Figure 13 Répartition des ACistes de l'échantillon au sein de quatre systèmes de travaux de sol

Note explicative : (i) « SD » rassemble les ACistes qui ne labourent pas et réalisent un SD pour au moins une culture de l'assolement, (ii) « Sans inversion » regroupe les ACistes qui ne labourent pas, (iii) « hybride » rassemble les ACistes qui labourent pour au moins une culture de l'assolement et sèment en direct pour au moins une autre culture de l'assolement, (iv) « labour occasionnel » regroupe les ACistes qui labourent sur au moins une culture de l'assolement.

61% des ACistes (la somme des catégories NL et SD, respectivement de 42% et 19%) ont renoncé au labour, quelle que soit la culture implémentée. En revanche, 39% des ACistes (la somme des catégories labour occasionnel et hybride, respectivement de 34% et 5%) labourent pour au moins une culture de leur assolement.

Concernant la pratique du SD, souvent considérée comme l'aboutissement du premier pilier de l'AC, on remarque une tendance à son expansion par rapport aux conclusions des études antérieures qui suggéraient que le SD était peu répandu en Wallonie (Vankeerberghen and Stassart 2014; Braibant et al. 2018). Néanmoins, il est important de noter que nous sommes encore loin des prétendus 10% de terres arables en Belgique cultivées en SD, tel qu'avancé par Eurostat (2020).

« Le semis direct, ici en Belgique, il n'y avait que quelques pionniers il y a peut-être 10-15 ans. Mais que vraiment ça se développe, c'est ici, ces dernières années. » (40)

La répartition de ces différentes méthodes de travail du sol varie entre les ACistes non biologiques et les ACistes biologiques.

Parmi les ACistes non biologiques, 51% sont en non-labour sur l'ensemble de leur séquence culturale, comparé à 30 % des ACistes biologiques.

De plus, bien que la pratique du labour en agriculture non biologique ait été initialement considérée comme un critère d'exclusion à l'AC lors de la validation par téléphone, les entretiens semi-dirigés ont révélé que 14 % des ACistes non biologiques effectuent occasionnellement un labour pour au moins une culture dans leur rotation. Chez les ACistes pratiquant l'ABC, cette proportion s'élève à 59 %. Pour rappel, dans le cadre de l'ABC, le labour occasionnel, s'il n'est pas pratiqué pour toutes les cultures de la séquence culturale et s'il est réalisé à une profondeur inférieure à 15 cm, était considéré comme un critère d'inclusion à l'ABC (cf. section 2.1.).

La technique du SD est plus fréquemment utilisée par les ACistes non biologiques (31 %) par rapport aux ACistes biologiques (4 %).

Enfin, une petite proportion d'ACistes pratique à la fois le labour occasionnel et le SD dans leur rotation : 3 % parmi les ACistes non biologiques et 7 % parmi les ACistes biologiques.

8. La certification biologique et l’élevage

L’ABC avait déjà été observée chez quelques agricultrices wallonnes (Vankeerberghen and Stassart 2016; Boeraeve et al. 2022) mais restait fort limitée. En 2012, alors que Casagrande et al. (2016) souhaitaient inclure 30 agriculteurs pratiquant l’ABC en Belgique dans leur échantillon, ils n'ont su en identifier que neuf. À notre connaissance, il n’existe aucune donnée concernant l’étendue de l’adoption de l’ABC sur le territoire wallon.

L’élevage est particulièrement présent au sein du panorama agricole wallon. 47% des exploitations wallonnes sont spécialisées dans l'élevage bovin (SPW ARNE - DEMNA et al. 2022). Certains agriculteurs pratiquant l’AC adoptent un système polyculture-élevage, comme le démontre l’échantillon d’agriculteurs de Boeraeve et al. (2022). L'élevage peut soit complémenter (p. ex. en augmentant la couverture du sol grâce à l'intégration de prairies temporaires, ou en mettant en place des intercultures fourragères), soit substituer (en favorisant l'augmentation de la matière organique et la couverture du sol par l’emploi du fumier), soit entrer en contradiction avec (p. ex. par l’exportation des pailles ou par des dommages au sol dus aux piétinements) certaines pratiques de conservation (Kirkegaard et al. 2014). En Belgique, le non-labour est moins pratiqué par les agricultrices du secteur laitier (19%) que par les homologues spécialisées en grandes cultures (23%) (Bijttebier et al. 2018). Toutefois, aucune information relative à l’étendue de l’intégration de l’élevage en AC wallonne n’est connue à ce jour.

Les appels téléphoniques et le croisement de sources ont permis de recueillir deux données supplémentaires auprès d’une partie des ACistes : la certification biologique et la présence d’un élevage. Malgré que leur acquisition n’ait pas été systématique, entraînant de nombreuses données manquantes, nous avons décidé de les intégrer dans notre analyse. Sur les 191 ACistes, des informations relatives à la certification biologique ont été recueillies pour 94 d'entre eux (soit 49 %, Figure 14a), tandis que des informations sur la présence d'un élevage ont été obtenues pour 117 d'entre eux (soit 61 %, Figure 14b).

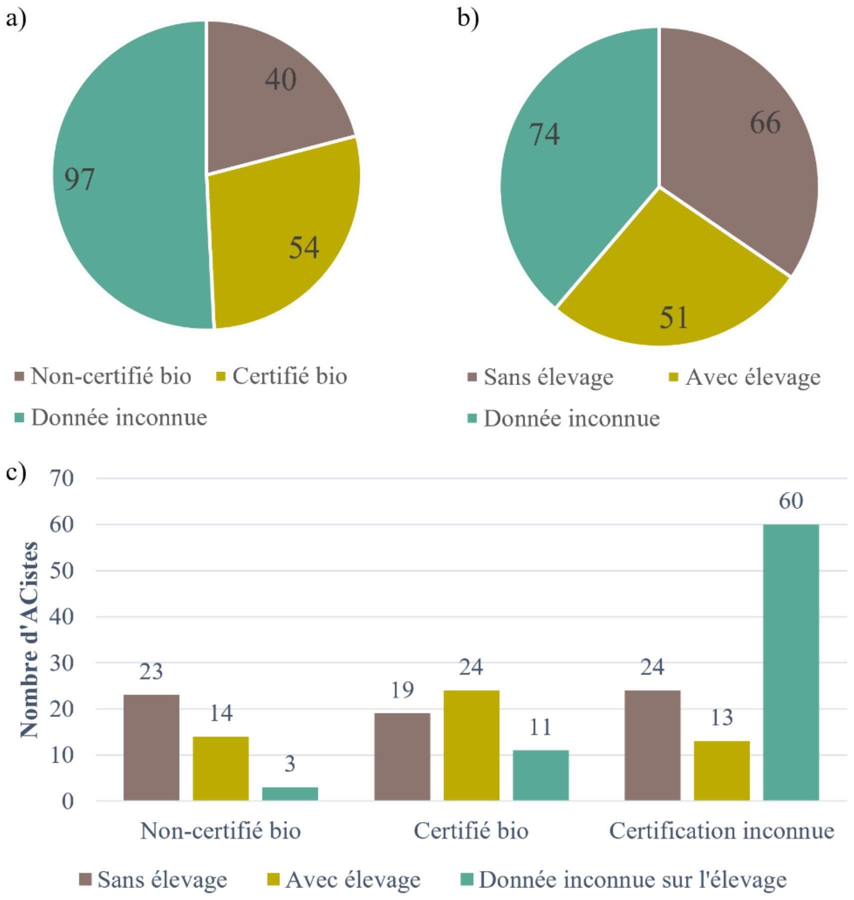

Figure 14 Part de l'élevage et de la certification biologique au sein de la population ACistes

Parmi les 94 ACistes pour lesquels nous avons obtenu une information sur la certification biologique, 54 (57%) possèdent la certification biologique. Les ACistes peuvent soit combiner l’AC et la certification biologique au sein d’une même parcelle, ce que nous qualifions d’ABC, ou bien gérer sur leur exploitation à la fois des parcelles en AC non biologique et des parcelles biologiques qui ne sont pas en AC. Pour éviter tout risque de déclassement dû à une dérive au champ de produits phytosanitaires, la plupart des ACistes wallons pratiquant l'agriculture biologique ne gèrent que des parcelles biologiques. Par conséquent, nous pouvons affirmer avec une relative certitude que l'ABC s’est largement répandue en Wallonie et concerne environ un ACiste sur deux. Ce chiffre est étonnant en regard du challenge que représente la mise en œuvre de l’ABC (Boeraeve et al. 2022) ainsi que le nombre restreint d’agriculteurs pratiquant l’ABC en 2016 en Belgique, qui s’élevait à neuf selon Casagrande et al. (2016). Il est possible que la pratique de l'ABC soit devenue plus accessible pour les agriculteurs aujourd'hui, en partie grâce à l'émergence de groupements d'agriculteurs engagés dans cette pratique, tels que la première communauté d'agriculteurs ABC créée en 2020 au sein de l'ASBL FarmForGood, ou encore le groupe de réflexion sur l'ABC formé en collaboration entre Greenotec et le CRA-W. La présence significative d'ABCistes est également à mettre en relation avec les critères d'inclusion choisis lors de notre étude (cf. section 2.1.).

Parmi les 117 ACistes pour lesquels nous avons pu recueillir des informations quant à la présence d'un élevage, il s'avère que 51 (44%) d'entre eux sont éleveuses en plus d'être cultivatrices. Par conséquent, il semble qu'une proportion importante des ACistes wallonnes soient éleveuses. Les éleveuses sont plus nombreuses au sein des exploitations pratiquant l'ABC par rapport à celles pratiquant l'AC. Cette constatation n'est pas surprenante étant donné que la certification biologique interdit l'usage d'engrais de synthèse (Figure 14c).

9. Cartographie des principaux acteurs impliqués

Les ACistes ne sont pas des acteurs isolés, mais évoluent dans un environnement complexe, constamment en interaction avec une diversité d'intervenants qui influent sur leurs choix d'adopter ou non des pratiques spécifiques. Ces interactions exercent un impact sur les décisions prises par les ACistes, leur accès aux connaissances, à un soutien matériel, aux marchés, et en fin de compte, sur l'adoption à un certain type d'AC. Les agricultrices qui s'orientent dans une phase de reconception de leurs pratiques mobilisent diverses sources d'information de manière à pouvoir les comparer afin d'améliorer et accélérer le processus d'apprentissage (Chantre and Cardona 2014).

Identifier les acteurs gravitant autour des ACistes représente une première étape pour comprendre les interactions en jeu. En Wallonie, une cartographie des principaux acteurs impliqués dans l'AC a été établie par Vankeerberghen et Stassart (2014) et lors du mémoire de fin d'études de Braibant et Morelle (2018).

Grâce aux entretiens avec les ACistes, nous avons pu recenser les acteurs influençant les décisions et les pratiques des ACistes. La Figure 15 illustre la diversité des acteurs qui entourent les ACistes wallons. Il est important de préciser que cette cartographie des acteurs reflète le point de vue des ACistes uniquement. Il convient également de noter que les ACistes peuvent eux-mêmes communiquer des informations aux différents acteurs et influencer les décisions et les interactions, bien que cet aspect ne soit pas étudié ici.

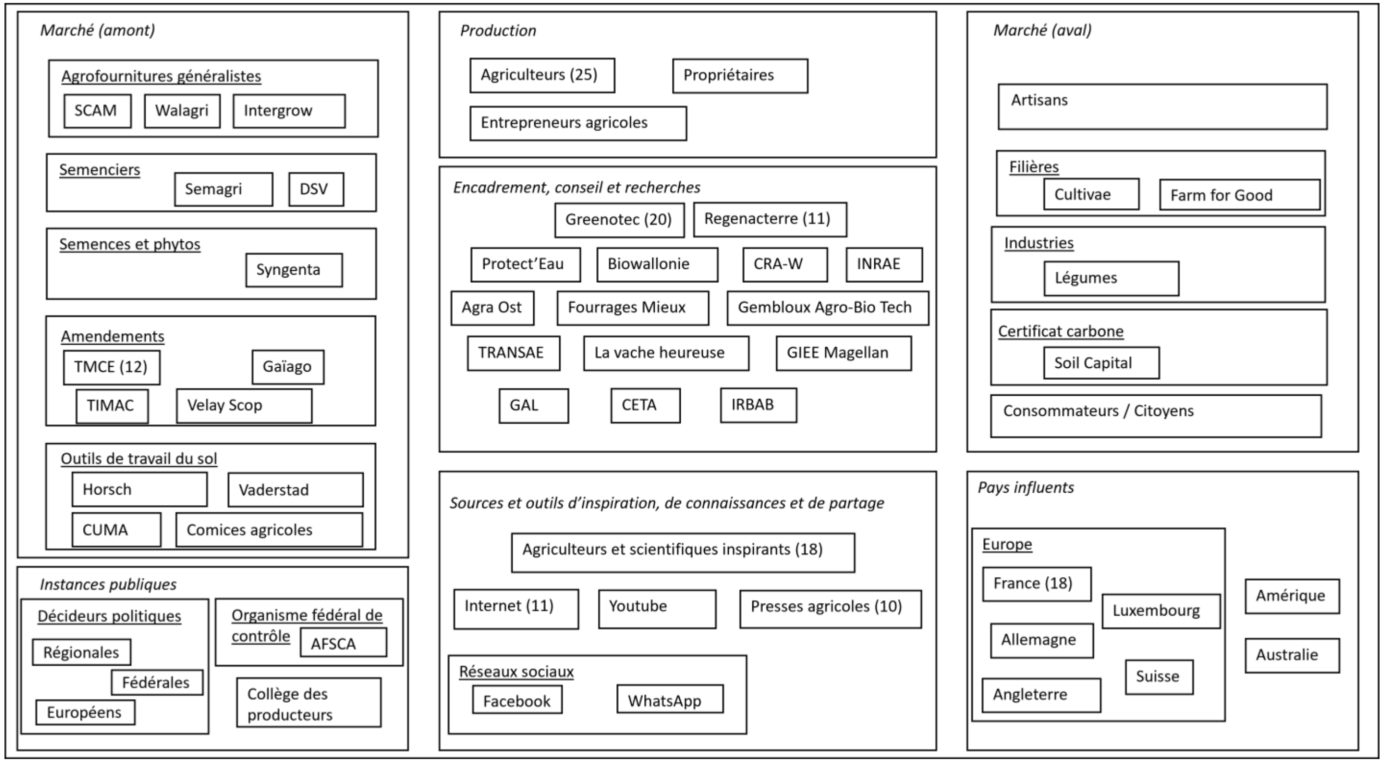

Figure 15 Principaux acteurs impliqués dans l’AC en Région wallonne

Note explicative : Les acteurs mentionnés par plus de dix ACistes sont ceux pour lesquels le nombre de mentions est spécifié entre parenthèses.

Avant d'entamer l'analyse des acteurs en fonction de leur position dans la chaine de valeur agricole, les entretiens ont mis en lumière le rôle prédominant de la France dans son influence exercée sur les ACistes wallons. Cette influence se manifeste à travers plusieurs aspects, que ce soit par le biais des organismes de recherche et de conseil, des entreprises privées, ou encore grâce à des personnalités inspirantes. Cette influence française est perceptible et expliquée au sein des paragraphes ci-dessous. Il est à noter que la France occupe une place particulièrement significative dans cette dynamique, étant donné que la majorité des ACistes se trouvent dans la partie nord-ouest de la Wallonie, à proximité de la frontière française. Les ACistes localisées à l'est, notamment celles et ceux de la région germanophone de la Wallonie, tendent à s'inspirer davantage des pratiques AC observées en Allemagne. La répartition géographique des ACistes influence donc la manière dont les ACistes wallonnes s'informent et se font conseiller sur leurs pratiques AC.

a. Les acteurs en amont

En amont de la chaîne de valeur, les entretiens ont permis de soulever les intervenants qui fournissent les intrants tels que les produits phytopharmaceutiques, les engrais et les amendements, ainsi que les semences et les outils de travail du sol utilisés par les ACistes. Ces dernières recourent fréquemment aux amendements pour améliorer les propriétés du sol, ayant pour principal conseiller et fournisseur la firme française TMCE (mentionnée par douze ACistes).

> *« Avec TMCE on a appris beaucoup de choses. Ils ne sont pas très vendeurs déjà. Ils ne vendent que des minéraux et ils ont une approche pratique extrêmement top. Ils font des coins de champs. Comme ils ne vendent pas de produit... C'est d'ailleurs à cause d'eux, par exemple, que je n'utilise plus les strobilurines et les SDHI. »* (28)

Au côté de ces sociétés, les instances publiques sont également présentes en amont de la production. Trois d'entre elles ont été mentionnées : les décideurs politiques (quelle que soit l'échelle), l'AFSCA et le Collège des Producteurs.

Le Collège des Producteurs est principalement évoqué pour son rôle de partenaire, en collaboration avec le CRA-W, dans le projet visant à établir des partenariats entre les agriculteurs et les éleveurs ovins pour le pâturage des couverts hivernaux (RwDR 2019).

b. Les agricultrices et entrepreneuses agricoles

L'émergence de l'AC sur le territoire wallon a été initiée par les agriculteurs locaux. Cette dynamique perdure avec une collaboration et un échange continu de connaissances au sein de cette communauté agricole. En effet, parmi les ACistes de l'échantillon, vingt-cinq ont mentionné qu'ils partagent activement leurs expériences, les résultats de leurs essais, des conseils pratiques couvrant à la fois l'AC et l'ABC, ainsi que du matériel agricole, avec leurs pairs ACistes. Cette culture de l'entraide et du partage semble être au cœur de l'évolution des pratiques AC en Wallonie.

« En fait, le point de départ (vers l'AC), c'est ma propre réflexion et la collaboration avec un des membres de la CUMA, qui est arrivée un peu plus tard, vers 2010 je crois. » (13)

« Et puis alors, en 2012 ou 2011, il y a un arrêté qui est sorti comme quoi, après les cultures de pois de conserverie, on était obligé d'implanter un couvert végétal. Pour les azotes, pour le lessivage. Et là, je me suis dit : "Ouh, ça va être compliqué. Si on se retrouve avec un grand couvert qui, après pois, bénéficie beaucoup d'azote, donc on va avoir une grosse masse végétative". Je me suis dit : "Comment est-ce qu'on va faire pour semer ça sans devoir labourer ?". Moi je ne voyais pas d'autre solution que de broyer, relabourer et bon ça me faisait beaucoup de travail pour pas grand-chose. Alors j'ai un peu fouillé sur Internet et j'avais vu qu'il y avait des gens qui faisaient du semis direct comme ça dans des couverts. Je me suis dit pourquoi pas. Donc j'ai un peu cherché à me renseigner là-dessus et j'ai trouvé un genre de CETA, groupement dans le nord de la France où les gens pratiquaient déjà un peu ça. » (6)

Outre les ACistes, les entrepreneurs jouent un rôle crucial. Ils ou elles peuvent offrir divers services aux ACistes, tels que les travaux de sol, permettant ainsi de réduire la nécessité d'acheter l'ensemble des équipements nécessaires. Cependant, cela peut également avoir des implications négatives, les agriculteurs exprimant un sentiment de perte de contrôle sur les pulvérisations (les quantités et les types de produits utilisés deviennent plus flous) et les travaux de sol. Ces derniers sont planifiés en fonction de la disponibilité de l'entrepreneur, plutôt qu'au moment optimal considéré pour limiter la perturbation du sol.

Enfin, les propriétaires fonciers, qui confient la gestion de leurs terres à des agricultrices, peuvent également exercer une influence sur les modèles agricoles adoptés. Quelques cheffes de cultures interrogées nous ont indiqué avoir adopté l'AC ou l'ABC à la demande des propriétaires.

c. L'encadrement, le conseil et la recherche

L'AC, tout comme tout système en quête d'amélioration, d'adaptation et d'innovation, compte sur l'encadrement, le conseil et la recherche. Plusieurs ASBL, telles que Greenotec, Regenacterre, Protect'eau, BioWallonie, Agra Ost et Fourrages Mieux, contribuent à fournir des conseils et un encadrement aux ACistes.

Parallèlement, les centres de recherche, tels que le CRA-W et l'université de Liège Gembloux Agro-Bio Tech, se consacrent à la recherche pour générer de nouvelles données bénéfiques aux agriculteurs. L'IRBAB mène également des recherches et des essais dans les parcelles des agriculteurs pour réduire l'utilisation de certains produits phytosanitaires.

De plus, certains éleveurs pratiquant l'AC font référence à des acteurs tels que « La Vache Heureuse », une société de conseil indépendante française.

En outre, le GIEE Magellan, une association d'agriculteurs français axée sur la maitrise du SD sous couvert végétal permanent, partage des techniques pour la mise en place du SD et fournit des outils, tels qu'un tableur, pour aider les agriculteurs à créer des mélanges de couverts végétaux.

Certains Groupes d'Action Locale (GAL) offrent également des semences aux agricultrices pour qu'elles ou ils puissent réaliser des essais d'intercultures et de couverts permanents.

De plus, les Centres d'Études Techniques Agricoles (CETA) fournissent une aide technique personnalisée aux agriculteurs pour améliorer leurs pratiques en matière d'AC ou d'ABC.

Enfin, les ACistes ont également évoqué le projet Transae, qui vise à promouvoir l'agroécologie en s'appuyant sur un réseau d'agriculteurs pionniers en Belgique et en France.

> *« Alors je fais partie d'un CETA (de Thuin) qui nous a déjà fait fort avancer. »* (28)

Parmi les acteurs les plus cités par les ACistes, Greenotec et Regenacterre se distinguent en tant qu'ASBL particulièrement actives dans la promotion de l'AC et le conseil aux ACistes wallons, citées respectivement par vingt et onze ACistes.

Fondée en 1995 à l'initiative et à l'intention d'agriculteurs désireux de partager et d'améliorer leurs techniques de conservation des sols, l'ASBL Greenotec joue un rôle central dans le déploiement de l'AC (ASBL Greenotec). L'association s'organise autour de trois types d'activités : l'expérimentation, la vulgarisation et le conseil. Les entretiens ont mis en évidence la pertinence de la partie « conseil » : Greenotec intervient notamment pour aider dans la sélection d'espèces d'intercultures, la mise au point de techniques de SD sous couvert, ou encore de rechercher des alternatives (p. ex., la production de betteraves sans néonicotinoïde).

Bien que l'ASBL Greenotec soit souvent évoquée comme un acteur clé dans l'adoption de l'AC en Wallonie, certaines critiques pointent un retard dans ses conseils et essais pour les ACistes ayant déjà plusieurs années d'expérience en AC. Néanmoins, Greenotec favorise la création de groupes d'agricultrices, facilitant ainsi les échanges et le partage d'expertise. De plus, l'association organise des conférences visant à diffuser les résultats des essais et à partager l'expérience de cultivateurs inspirants.

« Alors ce qui est bien maintenant, c'est que c'est vrai que l'information diffuse. Enfin moi je suis administrateur chez Greenotec, mais on a des groupes qui permettent d'avoir des échanges et éviter des erreurs. Parce que je veux dire ces erreurs-là, on les communique et ça permet de raccourcir quand même une expérimentation. » (28)

« Greenotec c'est très bien ce qu'ils font, ils sont là pour la promotion du truc. Les trois-quarts des agriculteurs sont toujours en conventionnel donc il faut des organismes comme Greenotec pour les accompagner dans leur transition. » (6)

Regenacterre joue également un rôle central dans la promotion des pratiques de conservation des sols. Les entretiens ont mis en évidence que les ACistes apprécient leurs conseils sur le choix des intercultures et la coordination d'achats groupés de semences. De plus, l'organisation propose la location d'un semoir pour le SD, permettant aux ACistes de pratiquer cette technique sans avoir à investir dans l'achat du matériel. Regenacterre fournit également des conseils sur la réduction des produits phytosanitaires, y compris des techniques de bas volume, et facilite la mise en place de réseaux d'agricultrices afin de stimuler le partage de connaissances.

Cependant, les mêmes critiques que celles adressées à Greenotec sont soulevées concernant Regenacterre : un certain retard par rapport aux connaissances des ACistes wallonnes les plus expérimentées en matière d'AC.

« Mais alors, par mon adhésion à l'ASBL Regenacterre, ils font la location d'un semoir de semis direct, et donc ça m'a permis de semer en direct une partie de mes céréales aussi. » (13)

d. Le partage de connaissances

Afin d'aider à l'élaboration d'itinéraires techniques, de prise de décisions éclairées et pour limiter les éventuelles erreurs, les ACistes wallons s'appuient sur de multiples sources et outils.

D'abord, ils s'inspirent de nombreux agriculteurs et chercheuses du monde entier, tels que Frédéric Thomas (agriculteur français, la personnalité la plus souvent mentionnée, citée par neuf agriculteurs), Elaine Ingham (microbiologiste américaine), Konrad Schreiber (ingénieur français), Pascal Boivin (professeur suisse), Christine Jones (agronome australienne), Dominique Soltner (agronome français), etc.

De plus, Internet, cité par onze ACistes, est une ressource essentielle pour fournir des conseils spécifiques sur l'AC. Des plateformes comme YouTube, notamment la chaîne "Ver de Terre Production", ainsi que les revues agricoles telles que le Sillon Belge, le PleinChamp, et surtout les revues françaises comme la France Agricole, Cultivar, et la revue spécialisée TCS consacrée aux techniques de conservation des sols, sont largement consultées par les ACistes.

« Non, on est quand même abonné à deux, trois revues, principalement des revues françaises d'abord parce qu'il y a la langue, mais aussi parce qu'en France il y a quand même des choses qui existent, les TCS notamment. » (3)

Les ACistes ont évoqué les réseaux sociaux tels que Facebook et WhatsApp comme des moyens de communication et de partage d'expériences entre pairs.

Les pratiquants de l'AC en Wallonie tirent également leur inspiration de divers pays, qu'ils soient européens comme la France, l'Allemagne, la Suisse, l'Angleterre et le Luxembourg, ou situés de l'autre côté des océans, comme les Amériques (tant du nord que latines) et l'Australie. À l'inverse, la Flandre (nord de la Belgique) n'a été mentionnée que par un seul ACiste, soulignant la rareté des systèmes d'AC dans cette région.

e. Les acteurs en aval

Les agricultrices ont pour objectif ultime de commercialiser leur production pour en tirer une rémunération, idéalement la plus juste possible. Pour ce faire, elles interagissent et collaborent avec les parties prenantes qui achètent leurs produits. Ces interactions peuvent influencer leurs choix de pratiques, y compris l'adoption de pratiques AC. À titre d'exemple, certains artisans, meuniers ou boulangers, peuvent accepter ou refuser certaines variétés ou associations de cultures en céréales, influençant les pratiques liées au troisième pilier de l'AC.

L'intégration de cultures légumières dans les rotations offre aux ACistes l'opportunité d'accroitre leur rentabilité, puisque ces cultures sont généralement plus rentables. Parmi ces ACistes, certaines ont été encouragées par des acteurs de l'industrie des légumes, comme Hesbaye Frost, à inclure davantage de légumes dans leurs rotations. Ces entreprises exercent souvent une influence sur des aspects décisionnels tels que la densité de semis, les pulvérisations à effectuer (les agricultrices n'ont parfois pas accès aux fiches de culture) et les pratiques de travail du sol. Plus spécifiquement en ce qui concerne l'AC, la rétention des résidus de culture en surface peut poser des défis pour certaines entreprises de légumes, qui parfois préfèrent, voire imposent le labour.

« Ils (Hesbaye Frost) ont des machines qui cueillent et qui aspirent, et donc eux, ils ne veulent pas qu'il y ait de la végétation en surface parce qu'ils disent que la végétation qu'on va avoir en surface, elle va monter dans la machine et ils vont l'avoir à l'usine. Donc ça les ennuie. Et en plus de ça, ils viennent avec leurs semoirs, parce que ce sont des semoirs bien spécifiques. Et leurs semoirs ne passent pas. Dès qu'il y a un débris de paille, ça bourre et ça ne fonctionne pas. Donc eux, actuellement, ils nous ennuient tous. Mais bon, ils sont tellement forts qu'on ne sait pas faire grand-chose contre eux malheureusement. [...] Et donc pour eux on est obligé, si on n'utilise pas le Roundup, et même si on l'utilise, on est obligé de travailler plusieurs fois la terre pour qu'il n'y ait presque plus de végétaux en surface, qu'ils soient mélangés au sol et qu'il n'y en ait presque plus en surface. Et donc évidemment, eux, ils prônent le labour. Comme ça ils sont sûrs qu'il n'y a pas un débris de paille. » (44)

« Dans certaines cultures de légumes si. Mais moi je travaille avec Noliko qui est une coopérative qui est assez ouverte à ce niveau-là. Mais il y a l'industrie ici tout près, qui s'appelle Hesbaye Frost, qui eux sont beaucoup plus exigeant, et qui exigent justement le labour avant certaines cultures en tout cas. » (13)

Les ACistes ont également mentionné le réseau Farm for Good et la coopérative Cultivae, qui incitent les agricultrices à adopter des pratiques vertueuses à obtenir des labels.

En outre, Soil Capital rémunère les agriculteurs pour leur stockage de carbone dans les sols.

Finalement, les citoyens wallons témoignent d'un intérêt croissant pour les enjeux et les pratiques agricoles. Bien que cela puisse encourager les adeptes de l'AC à adopter de nouvelles pratiques de gestion des sols, ils/elles font parfois face à un sentiment d'incompréhension et éprouvent des difficultés à trouver leur place dans le débat souvent simplifié entre les « conventionnels » perçus comme les « méchants » et les « biologiques » considérés comme les « gentils ».

« Ce que j'ai beaucoup de mal moi, c'est d'expliquer mes pratiques face aux gens, parce qu'ils ont une vision de la chose. Et en général, quand tu essayes de parler de ça, de leur expliquer, ils ne comprennent pas toujours. Ils ne t'écoutent pas, ou ils pensent qu'ils ont compris et que c'est facile, qu'il n'y a qu'à [...]. » (24)

10. Conclusion

Ce chapitre a permis d'éclairer plusieurs aspects. Tout d'abord, nous avons recensé 191 ACistes, représentant 1,5% des exploitations agricoles wallonnes, et 5,5% des exploitations wallonnes spécialisées en grandes cultures. Parmi ces ACistes, 88 % sont localisées dans les régions limoneuses, condrusienne et sablo-limoneuse.

Étant donné que la superficie moyenne gérée par les ACistes est de 199 hectares, nous pouvons estimer que l'AC s'étend sur une superficie totale de 38 009 hectares, ce qui équivaut à 5% de la SAU totale ou 15% de la SAU dédiée aux grandes cultures.

Les entretiens semi-dirigés ont permis de dégager une estimation de l'adoption des différents systèmes de travail du sol parmi les ACistes : 42 % ne labourent plus, 19% pratiquent le SD, 34% labourent occasionnellement pour une culture de la rotation, et 5% combinent le SD et le labour occasionnel au sein d’une rotation. Pour explorer plus en détail les autres aspects du premier pilier, ainsi que les deuxièmes et troisièmes piliers, une analyse plus approfondie des pratiques agricoles des ACistes est réalisée au chapitre suivant (Chapitre 4).

Remerciements

Nous remercions sincèrement et profondément tous les partenaires repris au sein de la Table 5 ainsi que les agriculteurs et agricultrices qui ont accepté de collaborer avec nous. Merci pour votre confiance et votre intérêt. Sans vous il n’aurait pas été possible de dresser ce paysage de l’AC.

Chapter 4 A method to account for diversity of practices in Conservation Agriculture

This chapter is published as:

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Chapter 2 has tamed our first elephant in the room, by providing a definition of CA that both delimits the system to include all types of CA practiced worldwide, while allowing it to be adapted for use on a regional scale.

Chapter 3 focused on the CA population in Wallonia, the southern part of Belgium, based on membership criteria defined in local literature. The analysis of this population was used to describe the Walloon CA landscape.

This chapter deals with the second elephant in the room: the study of the diversity of CA practices on a regional scale, which stems from the variety of local contexts, constraints and needs of individual farmers.

Currently, there is no method for categorizing the diversity of CA practices, which hampers impact assessment, understanding of farmer choices and pathways, stakeholder communication, and policymaking.

This chapter 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.

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) minimizing mechanical soil disturbance, (ii) maximizing soil organic cover, and (iii) maximizing crop species diversification (Figure 16). Each pillar can be implemented through a variety of different practices (Sommer et al. 2014) tailored to the specific context and geographical location (FAO 2023a), as well as to the needs, constraints, and resources of each farmer (Vankeerberghen and Stassart 2016; Derrouch et al. 2020).

Figure 16 Illustration of the three pillars of Conservation Agriculture in Wallonia
Explicative notes: 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.

The outcomes and sustainability associated with CA, whether environmental or socio-economic, depend on the type and intensity of CA practices implemented (Scopel et al. 2013; Cristofari et al. 2017, 2018). Determining the diversity of CA practices helps to assess impacts, better 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 the diversity of CA practices, and more broadly for exploring diversity within a farming system. 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)). A methodology for categorizing CA practices enables a systematic analysis of this diversity. By making rigorous methodological choices, it can facilitate communication, comparison, and evaluation among studies and stakeholders. 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 of farms that do not practice CA to facilitate the subsequent adoption of CA-types a priori adapted to existing constraints and opportunities in northern Vietnam. Husson et al. (2016) designed CA-types that farmers could implement in Madagascar, Lao PDR, and Cambodia. Scopel et al. (2013) presented CA-types in Brazil and France without explaining how the CA practices were categorized. 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 chapter aims to propose a method for categorizing the diversity of CA practices on a regional scale, based on CA practices implemented by farmers. 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. The purpose of this chapter is not to provide an exhaustive account of all practices across every pillar of each CA-type identified in the studied region.

The chapter is structured as follows: firstly, a description of the CA landscape in Wallonia is provided, followed by an explanation of the methodology used. Subsequently, the results are presented, followed by a detailed discussion.

2. The CA landscape in Wallonia

Beginning with the general definition of the pillars (Chapter 2 summarized in section 2.1) and a brief presentation of the Walloon agricultural context (section 2.2), the definition of CA is adapted to the Walloon CA landscape (section 2.3). This definition is then used to select the variables that will characterize the diversity of practices in each pillar (section 3.1).

2.1. The general definition of CA

Chapter 2 provided an operational definition of CA based on a cross-referencing of FAO publications and articles that are considered benchmarks for defining CA. This definition offers guidelines broad enough to encompass CA practices from various regions worldwide and adaptable to local contexts. CA is therein defined as grounded on three pillars, which are considered fundamental elements distinguishing CA from other farming systems. Each pillar is of equal importance.

The first pillar of CA entails minimal mechanical soil disturbance. While soil disturbance is allowed within CA frameworks, it should remain below prevalent practices in the study area. Units (width, depth, percentage, etc.) are to be adjusted to the study zone. Reduction of soil disturbance can be achieved by minimizing agricultural machinery traffic. Harvests of root and tuber crops must be integrated differently from harvests of other crops, because of their impact on soil structure. Furthermore, the use of equipment involving soil horizon inversion and/or mixing, such as plows, disc harrows and rotary cultivators, is discouraged to prevent soil degradation. Direct seeding represents the ultimate reduction in tillage.

The second pillar of CA aims to attain maximum soil organic cover through the utilization of dead (e.g., crop residues) or living mulch (e.g., cover crops). It is advisable to uphold a minimum of 30% coverage across the plot area. To ensure alignment with the seasonal variability of erosion risks, the coverage threshold should be assessed concurrently with peak erosion-risk seasons, which ought to be determined based on the regional context of the study. The ultimate goal is to maintain year-round coverage of at least 30% of the plot area.

The third pillar of CA endeavors to maximize crop species diversification. This goal can be accomplished through practices such as crop rotations, crop associations, cover crops, or the mix of diverse crop varieties. The number of crop species implemented (at least three according to FAO (2023a)) should be considered in conjunction with a specified time frame.

Alongside these pillars, additional practices may be implemented to enhance the sustainability of the system or facilitate the adoption of CA. These practices depend on the context and may include aspects such as integrated input management, livestock integration, or agroforestry.

2.2. The Walloon agricultural context

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 hectares (SPW 2023a). The agricultural area covers 738,927 hectares, of which 13%–mainly grasslands (Antier et al. 2019)–is devoted to organic farming (SPW 2023a).

Wallonia is divided into ten 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).

2.3. The definition of CA adapted to Wallonia

2.3.1. Pillar 1 – Minimum mechanical soil disturbance

The literature reviewed for the targeting of the CA population in Chapter 3 emphasized that the first pillar, through its challenge to conventional plowing practices, serves as the gateway for farmers to embrace CA (Vankeerberghen and Stassart 2016). In Wallonia, CA is practiced by both non-certified and certified organic farmers, the latter being called Organic Conservation Agriculture (OCA) (Casagrande et al. 2016; Boeraeve et al. 2022).

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 organic CA farmers, plowing is difficult to stop completely because of the absence of herbicides for weed management (Boeraeve et al. 2022). As a result, these farmers sometimes still carry out occasional inversion tillage (i.e. not applied to all crops in the rotation) and/or shallow plowing to less than 15 cm depth. For non-organic CA farmers, the plow may also be taken out of the shed in exceptional cases, for example due to unfavorable weather conditions or because the harvest of spring crops took place in very wet conditions. To accurately capture the practices of CA farmers in Wallonia, it was necessary to include occasional inversion tillage in conservation tillage practices.

The adoption of direct seeding and strip tillage is uncommon in Belgium (Vankeerberghen and Stassart 2016; Ryken et al. 2018).

2.3.2. Pillar 2 – Maximum soil organic cover

In the south of Belgium, since direct seeding remains limited, a permanent soil cover of at least 30% is rarely achieved.

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 hectare annually (SPW 2022b). The highest rainfall erosivity in Belgium occurs from May to September (Verstraeten et al. 2006). We called this time frame 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).

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.

2.3.3. Pillar 3 – Maximum crop species diversification

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.

3. 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 (Figure 17). First, the typology variables are selected based on the CA definition adapted to the local context (section 3.1. 3.1. Data selection). Second, information on the variables is collected through interviews with farmers practicing CA (section 3.2. 3.2. Data collection). 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 3.3. 3.3. Clustering). Finally, the practices implemented on each of the three pillars within each CA-types are translated into scores (section 3.4. 3.4. Transforming variables into scores) and described (section 3.5. 3.5. Main features of CA-types).

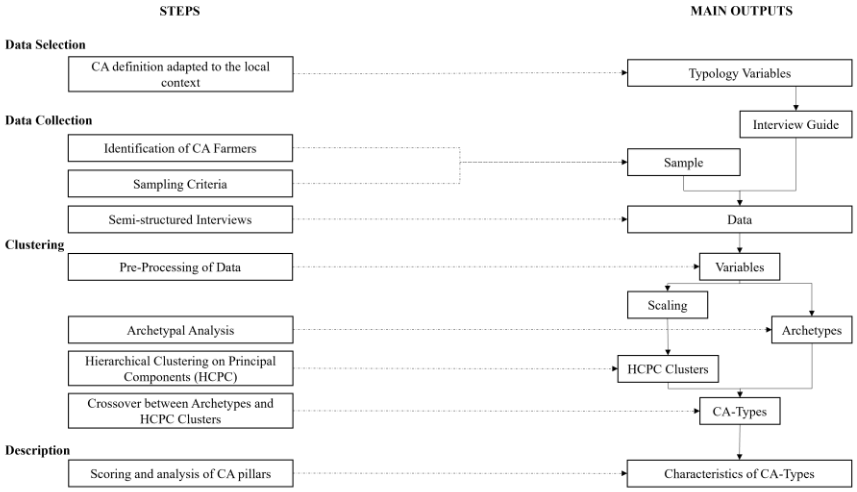


Figure 17 Steps to build a typology capturing the diversity of Conservation Agriculture (CA) practices by categorizing them into CA-types

3.1. Data selection

To compare CA practices, it is essential to establish a standardized reference system and time scale. The chosen frame of reference is the crop sequence, which exhibits variability in length across different farmers. To accommodate this variability, the variables were averaged over one-year period or expressed as proportions (Table 7). See Appendix E 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 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.

3.1.1. Pillar 1 – Minimum mechanical soil disturbance

Reducing soil disturbance can be achieved by minimizing agricultural machinery traffic and restricting the use of tools such as plows and animated tools (section 2.1). In Wallonia, plowing is still occasionally practiced in CA but its frequency and depth are reduced. Conversely, strip-tillage is uncommon (section 2.2). Therefore, the most suitable measurement unit for categorizing the first pillar revolves around frequency and depth rather than the proportion of tilled area.

Farmers can practice CA with various seeders, ranging from conventional seeders to specialized direct-seeding seeders. 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.

The speed of agricultural machinery was not considered as it was not identified as a component within the definition of the first pillar of CA. In addition, collecting this data would have been time consuming as the crop sequence is spread over several years with several tractor passes per year.

The first pillar is characterized 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, (iv) the frequency of use of plowing tools and (v) the plowing depth (Table 7).

3.1.2. Pillar 2 – Maximum soil organic cover

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.

The second pillar is captured 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 7).

3.1.3. Pillar 3 – Maximum crop species diversification

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 characterized 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 7).

Table 7 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).
Note: See Appendix E for details of the calculation.

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)

3.2. Data collection

3.2.1. Identification of the population of interest

The first step in collecting data involves identifying the target population (cf. Chapter 3). In Wallonia, there is no registry of farmers who implement CA. To recognize these farmers, we collaborated with twelve public and private institutions, eight farmers' associations, 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 3.2.2.). A verification of CA practice was conducted through phone 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 88% located in the Sandy Loam, Loam, and Condroz regions (Figure 18).

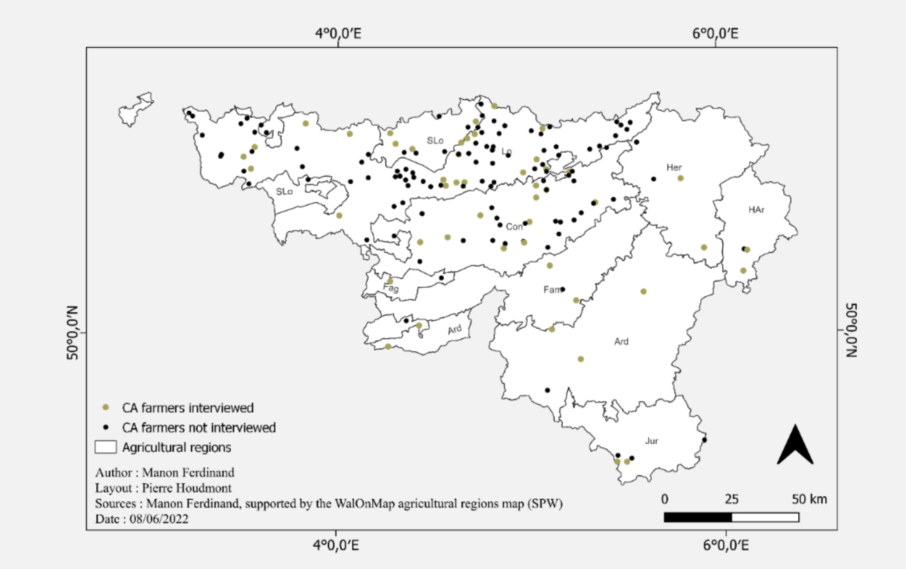


Figure 18 Geographical distribution of Walloon Conservation Agriculture farmers surveyed in 2020 by agricultural regions

Legend: Sandy Loam (SLo), Loam (Lo), Condroz (Con), Herbagère (Her), Fagne (Fag), Famenne (Fam), Haute Ardenne (HAr), Ardenne (Ar) and Jurassic (Jur). See Appendix F for details on sample characteristics.

3.2.2. 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 2013c). 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. Introducing organic certification in CA by practicing OCA, 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 coverage, 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.

3.2.3. 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).

3.2.4. Semi-structured interviews

Data collection was carried out using a participatory approach, where the selected variables (as described in section 2.2. 3.1. Data selection) were included in the interview guide (cf. Appendix A). 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.

3.3. Clustering

3.3.1. 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 fifteen 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 (numbered 4 and 17 in Appendix G) were excluded from the analysis due to missing data.

3.3.2. 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, every 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.

3.3.3. 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 reduces the dimensionality of the data set, allowing classification to be performed on the result of this analysis rather than on the original data. 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). These methods, each based on a different selection process, provide a variety of perspectives that strengthen the assessment of the optimal number of PCs to include in the analysis.

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.

3.3.4. 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 9). 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 our CA-types.

3.4. 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 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”.

3.5. 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), as well as for all variables (total score calculated by adding the variables).

4. Results

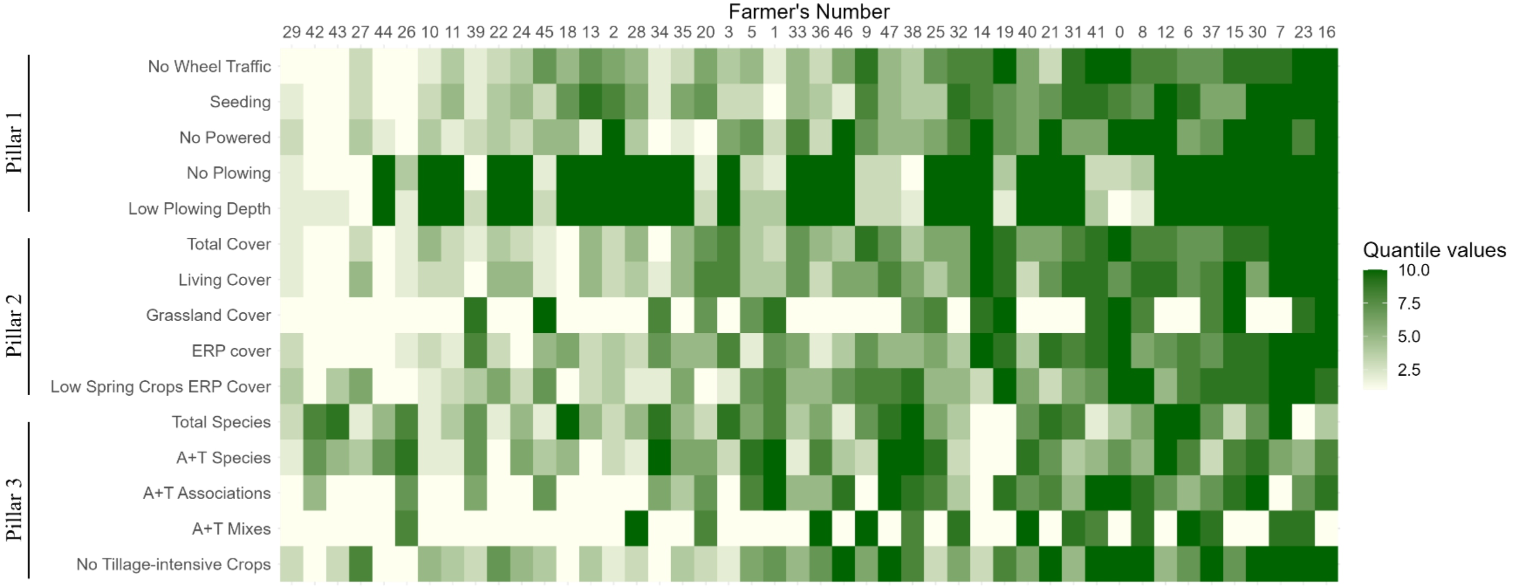
4.1. Overview of Conservation Agriculture diversity

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 8) to high total scores (right side of Table 8, table inspired by Tessier et al. (2021)). 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”).

Table 8 Scoring table where the colors represent the score of the variables expressed in deciles (light green 0, dark green 10), and each column represents one farmer

Explanatory notes: This table is inspired by Tessier et al. (2021). The distribution of farmers is sorted according to the sum of the scores of all variables. See Appendix H for details of each farmer's scores. Legend: Annual crops (A), Erosion risk period (ERP), Temporary grassland (T).



4.2. 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 (Figure 19a). 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) (Figure 19b).

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 (as shown in the Appendix I). However, the remaining 22 unclassified farmers did not show significant proximity to any archetype, as all their alpha coefficients were below the threshold.

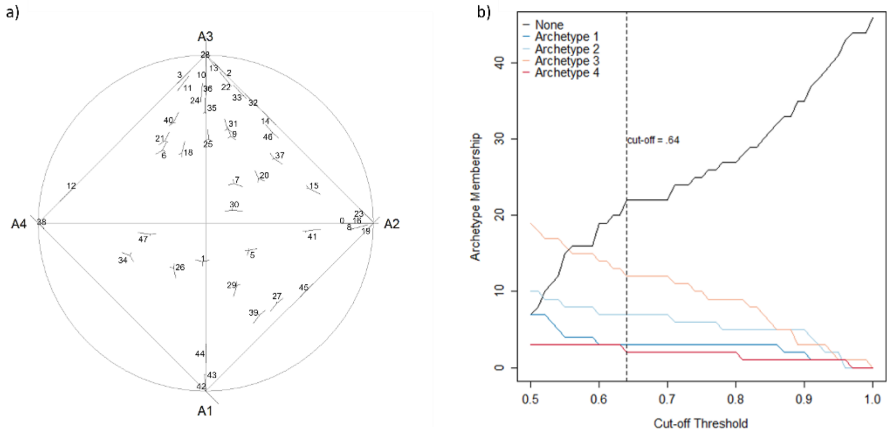


Figure 19 (a) Simplex visualization of the farmers’ proximity to the archetypes for k=4. (b) The number of farmers belonging to the archetypes according to the cut-off threshold

Explanatory note: These figures are based on those presented by Tessier et al. (2021).

4.3. Hierarchical Clustering on Principal Components (HCPC) clusters

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. The first three principal components (PCs) accounted for 42.2%, 16.6% and 11.5% of the total variability. The variables most highly correlated with PC1 were wheel traffic and soil cover. The most influential variables for PC2 were plowing and plowing depth (Figure 20a).

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 consolidation, utilizing the outcomes of the PCA. The results of the HCPC have separated the 46 farmers into six clusters (Figure 20b and details presented in Appendix J).

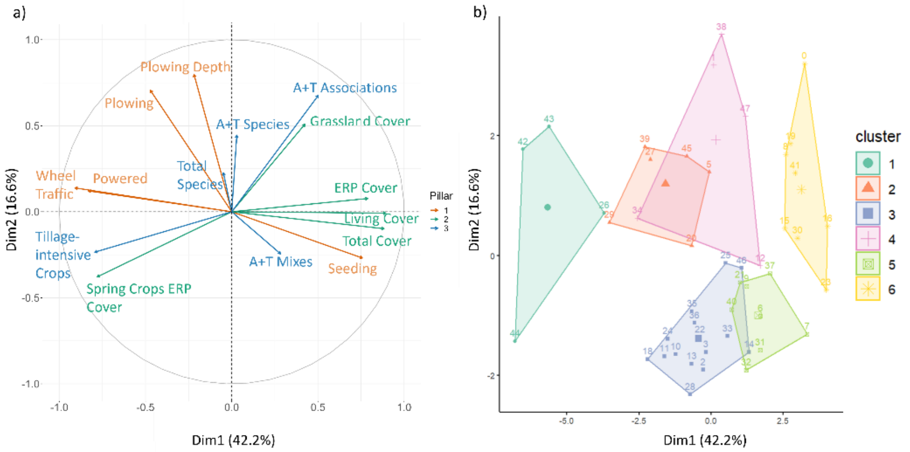


Figure 20 (a) Graph of PCA variables. (b) Visualization of farmers on the first two dimensions of the PCA. Color code representing the Hierarchical Clustering results
Legend: Annual crops (A), Erosion risk period (ERP), Temporary grassland (T).

4.4. Crossover between archetypes and HCPC clusters

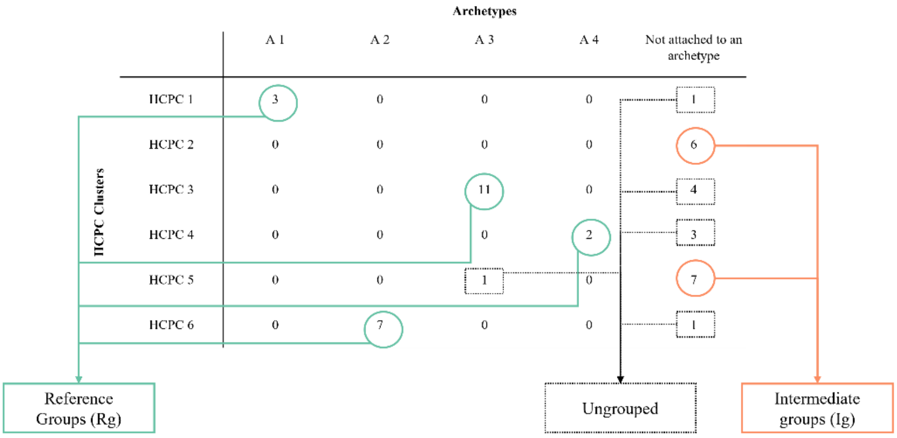
The groups for which the AA and HCPC results align are defined as reference groups (Rg) (Table 9). Second, all HCPC groups that do not match an archetype are defined as intermediate groups (Ig).

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 toward 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 9), were identified by cross-referencing the AA and HCPC results. Ten farmers were not assigned to any group (dashed squares in Table 9).

Table 9 Cross-tabulation of clusters from Hierarchical Clustering on Principle Components ("HCPC") and archetypes from Archetypal Analysis ("A") results
Explanatory notes: 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).



HCPC Clusters	Archetypes				
	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

Following the robustness test (explained in section 0), 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 (see Appendix K for details).

4.5. 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 Figure 21 and Table 10 (see Appendix L for raw values).

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

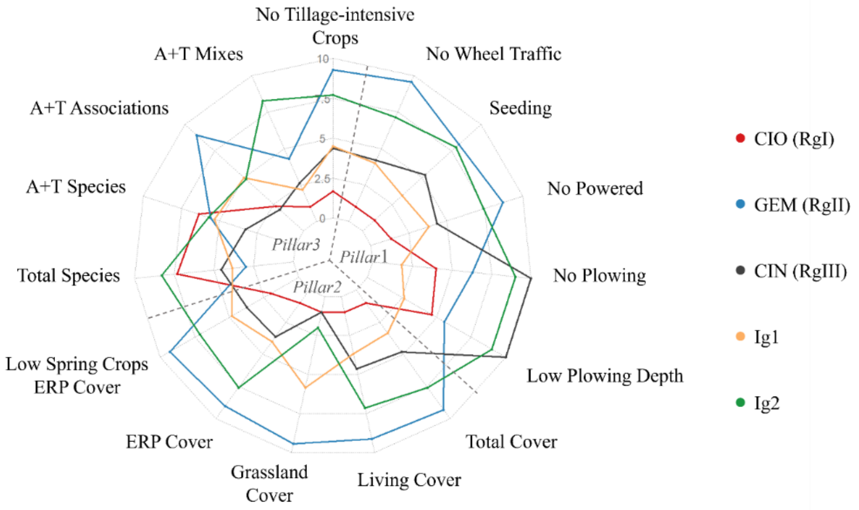


Figure 21 Radar charts showing the average scores of Conservation Agriculture types for the fifteen variables

Legend: Reference groups (RgI, II, and III), Intermediate groups (IgI and II), 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).

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.

Figure 22 shows the geographical distribution of the CA-types and their main features are described below.

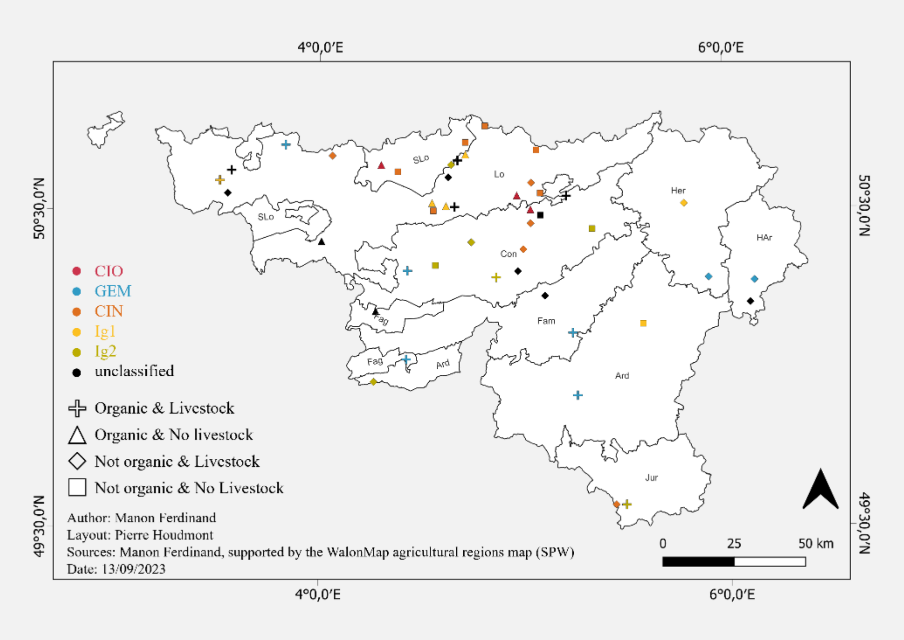


Figure 22 Geographic distribution of Walloon CA-types on the map of agricultural regions

Legend: Sandy Loam (SLo), Loam (Lo), Condroz (Con), Herbagère (Her), Fagne (Fag), Famenne (Fam), Haute Ardenne (HAr), Ardenne (Ar) and Jurassic (Jur).

Table 10 Average scores of each variable for each Conservation Agriculture type. *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 (IgI and II), Erosion risk period (ERP), Annual crops (A), Temporary grassland (T). See Appendix L for raw values.*

	CIO (RgI)	**GEM (RgII)**	**CIN (RgIII)**	**Ig1**	**Ig2**
Number of farmers	3	7	11	6	7
With organic certification	3	5	0	4	2
With the presence of livestock	0	7	5	2	5
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

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. Tillage-intensive crops

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. Tillage-extensive crops

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.

5. Discussion

5.1. 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 8).

To characterize CA practices, the score for each pillar is derived by adding the scores of the five variables (cf. Table 10). 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 sequences, as observed in the CIO type. 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, as seen in CIO and CIN types. Temporary grasslands lower the number of species grown annually but promote species associations, as observed in GEM type. The most optimal species diversification is observed in crop sequences with a high proportion of tillage-extensive crops and do not include grassland, exemplified by the Ig2 CA-type.

5.2. 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 Appendix H). 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 for each pillar. 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).

5.3. 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. In our study, achieving uniform weighting of each pillar was facilitated by transforming each pillar into five variables, which were subsequently standardized. Alternatively, it could have been conceivable to employ a varied number of variables and assign weights in a manner that preserves equilibrium among the pillars.

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.

However, it is noteworthy that over a quarter of the farmers in the sample remained unclassified. To address this, we could have reduced the membership threshold to allocate more farmers to each archetype. However, doing so would have weakened the distinctions between the archetypes, which goes against the fundamental principle of AA. Similarly, to include all the sampled farmers, we could have conducted HCPC without combining it with AA. However, using this method would have resulted in less pronounced group differentiations. This could have caused farmers who were initially situated between distinct groups to not find themselves in the assigned categories. Additionally, it would have been more complex to distinguish between CA-types with particularly distinct practices and those characterized by more intermediate practices.

The methodology used in this study is based on the practices of CA farmers in 2020/2021. It would have been interesting to categorize the diversity of trajectories instead of practices, by tracing the evolution of farmers' practices over time, as demonstrated in the research conducted by Fouillet et al. (2023). Such an approach would be dependent on a meticulous multi-annual data collection process and a comprehensive characterization of each practice under the three pillars of CA. Like numerous studies, our investigation could have delved deeper and yielded richer insights if additional data were available. Enhancing the robustness of scientific inquiry often hinges on the availability of more extensive datasets.

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 (< 2 ha) farms (Statbel 2022).

Equal importance was given to each pillar of CA, avoiding the common shortcut of reducing CA to its first pillar, reduced tillage. Additionally, a diversity of production methods, including organic and non-organic, with or without livestock, were included, without limiting to specific crop types. This choice aligns with the principle that CA can be applied to a variety of crops, including root and tuber crops (Kassam et al. 2018). By choosing to prioritize the equality of the three pillars and the inclusion of various modes of production, we have successfully encompassed a wide range of CA practices. However, some may argue that this diversity exceeds the limits of the CA system, as occasional and superficial plowing may not be tolerated in CA and that CA is limited to continuous no-till. If this approach had been followed, organic farmers growing tillage-intensive crops would have been excluded, ruling out the CIO type. Our choice of inclusion has enabled us to highlight the trade-offs (cf. section 5.2) and visualize the CA system boundary.

Depending on our perspective, we can assert that we have approached or even transgressed it. To represent this boundary on a radar chart (like in Figure 21), we could define, depending on the region studied, a CA boundary can be defined within the graph. This would mean that any CA practice exceeding this boundary would be considered to be outside the CA system.

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.

5.4. 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 the same capacity to improve soil structure or sequester carbon. The impact of this diversity is discussed in greater detail in Chapter 5.

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. Differences in transition factors and changes in practices between CA-types are discussed in Chapter 6.

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

6. Conclusion

The fact that CA brings together a diversity of practices is beyond question. However, both the scientific community and society tend to overlook this diversity when evaluating CA and, consequently, when attributing benefits, such as carbon sequestration, and challenges, such as glyphosate dependence. Categorization serves to simplify and group different CA practices into fewer CA-types to facilitate comprehension of this diversity. Currently, there is no systematic approach for categorizing the diversity of CA practices based on the three pillars implemented by farmers.

Focusing on the CA system in Wallonia, Belgium, we combined an AA and hierarchical clustering to establish such categorization. This methodology successfully identified distinct CA-types, including both extreme and salient practices called “references”, and intermediate CA-types, displaying practices located between these extremes. None of these CA-types maximizes all three pillars of CA simultaneously.

Our study successfully approached or even surpassed the system boundary by treating the three pillars of CA equally and incorporating a diversity of production modes (organic and non-organic, with and without livestock, with and without roots and tubers crops in the crop sequence). This sheds light on the factors that account for the diversity and trade-offs preventing farmers from maximizing all three pillars simultaneously.

This innovative classification method has the potential to be adapted to various geographical contexts and farming systems beyond Wallonia, Belgium. The application of this method could offer valuable insights into comprehending and improving the effectiveness of CA practices globally.

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Chapter 5 Digging deeper: assessing soil quality in a diversity of Conservation Agriculture practices

An article based on this chapter is in preparation, co-authored with Brieuc Hardy (CRA-W).

Chapter 4 enabled us to tame our second elephant in the room, by providing a method for identifying and categorizing the diversity of CA practices on a regional scale. Based on this method, five CA-types were identified in Wallonia: three CA-types with extreme and salient practices, and two intermediate CA-types comprising farmers whose practices fall between these references.

This chapter sets out to tame our third and final elephant in the room: integrating this diversity of practices, which has been categorized, into the assessment of CA. In this case, we study and compare the impact of CA-types on three soil quality indicators: soil structural stability, the soil organic carbon:clay (SOC:Clay) ratio and labile carbon fraction. These indicators were compared on 19 CA plots throughout Wallonia, representing four of the five CA-types.

This study showed that the CA-type called GEM, characterized by temporary grassland in its cropping sequence and occasional inversion tillage, exhibits the highest soil structural stability, SOC and Permanganate oxidizable carbon (POXC) contents, and SOC:Clay ratio. In contrast, the CIN CA-type, characterized by tillage-intensive crops in their crop sequence and non-inversion tillage, yielded the lowest results in terms of these soil quality indicators. Intermediate CA-types present intermediate results between these two CA-types.

Results underscore the need to move beyond simplistic dichotomies when evaluating CA's impact. CA cannot be reduced to a single pillar or tool, i.e. the plow; each pillar encompasses diverse practices with varied impacts.

While many Walloon CA-managed soils exhibit SOC deficits (SOC:Clay ratio less than 1:10), suggesting potential for increased carbon contents, we advocate exploring causal links between practices, pedo-climatic contexts, and soil quality impacts. Unfortunately, constructing a balanced sample for comparing CA-types in Wallonia poses complex challenges.

1. Introduction

Soils play a crucial role, encompassing environmental and social dimensions, in maintaining productivity and preserving ecosystem services, which help support resilience and cope with climate change (Baveye et al. 2020; Weil and Brady 2017). Soil quality is defined as the soil's capacity to perform multiple functions like sustain productivity, maintain environmental quality, and promote plant and animal health, and can be assessed through the analysis of soil chemical, physical, and biological parameters (Doran and Parkin 1994; Bongiorno et al. 2019). However, soil quality is deteriorating and threatened (FAO and ITPS 2015; IPCC 2019). 70% of European soils are degraded (Panagos et al. 2022b). This is due to increased pressure on the land to meet food, fiber and fuel demands, and unsustainable farming practices (Mason et al. 2023).

Conservation Agriculture (CA) has been proposed as an alternative farming system capable of achieving sustainable productivity while limiting soil degradation and improving soil quality (Thierfelder et al. 2017; Chabert and Sarthou 2020). CA is based on three agronomic pillars (or principles) applied simultaneously: (i) minimum mechanical soil disturbance, (ii) maximum soil organic cover, and (iii) maximum crop species diversification.

Reducing mechanical soil disturbance leads to the accumulation of organic matter (OM) at the soil surface, resulting in enhancements across several critical soil attributes. Firstly, OM increases the structural stability of soil aggregates, which in turn mitigates soil erosion, amplifies water infiltration rates, enhances water retention and availability, and reduces overall water loss (Hobbs et al. 2008; Giller et al. 2009; Pisante et al. 2015; Busari et al. 2015; González-Sánchez et al. 2017; FAO 2023b). Secondly, the increased presence of OM in surface horizons may exert a positive effect on soil fertility and productivity of some crops (Pisante et al. 2015; González-Sánchez et al. 2017). Lastly, the optimization of both physical and chemical soil properties through the reduction of tillage enhances resilience to environmental stresses, thereby facilitating adaptations to climate change (Wauters et al. 2010; Powlson et al. 2016; González-Sánchez et al. 2017; Chenu et al. 2019).

The increase of soil organic cover serves as a physical shield against the erosive impact of rainfall, effectively mitigating aggregate disintegration, crusting, and surface runoff, while concurrently enhancing infiltration rates (Hobbs et al. 2008; Busari et al. 2015; González-Sánchez et al. 2017; FAO 2023b). This protective role significantly reduces erosion (Giller et al. 2009; Soane et al. 2012; Pisante et al. 2015; Kassam et al. 2018). Additionally, soil cover increases soil organic carbon (SOC) inputs and storage (Chenu et al. 2019) and promotes soil-dwelling fauna, such as earthworms, which, through their subterranean burrowing activities, further augment water infiltration (González-Sánchez et al. 2017).

Crop species diversification through the integration of plants with varied root structures contributes to the development of an extensive network of root canals, resulting in more efficient resource utilization and heightened agricultural productivity (González-Sánchez et al. 2017; Bahri et al. 2019). Moreover, incorporating plants with deep and strong taproots mitigates soil compaction by penetrating compacted layers, progressively decomposing, and forming root voids and channels (Hamza and Anderson 2005; Jabro et al. 2021). Additionally, species diversification enriches the overall diversity of microbial, fauna, and flora communities, thereby enhancing pest and disease control and facilitating more effective nutrient recycling (Hobbs et al. 2008; Meena and Jha 2018).

1st gap: The CA's impact on soil quality is not well known

Compared to conventional or organic agriculture, CA has been little studied (Chabert and Sarthou 2020; Christel et al. 2021). Furthermore, there is few research addressing the effects of CA practices on soil quality (Chabert and Sarthou 2020). In addition to being understudied, the impact of CA practices on soil quality exhibits variability across different studies, and the origin and processes underlying this variability are still poorly understood (Chenu et al. 2019; Chabert and Sarthou 2020). The extent and significance of CA's impact on soil quality are known to fluctuate according to factors such as soil texture, climatic conditions, and specific CA practices (Lahmar 2010; Page et al. 2020). For instance, reduced tillage may occasionally increase soil compaction, impeding both water infiltration and root growth (Van den Putte et al. 2012; Pisante et al. 2015).

2nd gap: The three pillars of CA are rarely met simultaneously

Scant research has been conducted to assess CA systems that fully integrate all three pillars (Adeux et al. 2022; Bohoussou et al. 2022). Many studies investigating CA's effects on soil properties have primarily focused on comparing no-till and residue retention with conventional tillage and residue export, often overlooking the broader range of CA practices and the consideration of the third pillar, as illustrated in Table 1 of Page et al. (2020). However, the advantages of soil conservation practices on soil quality are larger when the CA system's pillars are associated and implemented together due to interactive and synergistic effects (Chenu et al. 2019; Page et al. 2020; Adeux et al. 2022).

3rd gap: The neglect of diversity of practices

Since each pillar can be implemented through various practices depending on the local context, constraints and farmers' needs, farmers may not fully implement all three pillars, resulting in a diversity of practices within the CA system (Ferdinand and Baret 2024). Accordingly, the impact of CA on soil quality, as well as the benefits associated with the system, depend on the specific CA practices implemented (Scopel et al. 2013; Craheix et al. 2016; Cristofari et al. 2017). The neglect of studies to consider the diversity of agricultural practices when it comes to studying their impacts is not unique to CA (Riera et al. 2023).

Our research goals

These shortcomings highlight the existing gaps in research on the impact of CA-types and related practices on soil quality, considering both the three pillars and the intrinsic diversity within them. In this study, our aim is twofold: to assess the soil quality from contrasted CA-types; and secondly, to identify the practices within the three pillars of CA that exert the most significant influence on soil quality.

For this purpose, we compared CA fields in the Walloon Region, Belgium, according to three soil quality indicators: soil structural stability, SOC:Clay ratio, and labile carbon fraction. Since biological indicators often exhibit higher spatiotemporal variability (Krüger et al. 2018), our focus was exclusively on physical and chemical indicators.

Soil Structural stability by the QuantiSlake Test

Soil structural stability is a reliable indicator of soil quality as it measures the soil's ability to resist disturbing forces (Wu et al. 2024). The QuantiSlake Test (QST), developed by Vanwindekens and Hardy (2023), was used to assess soil structural stability. This test involves the quantitative measurement of the slake test, which dynamically weighs a dried structured soil sample immersed in water (Vanwindekens and Hardy 2023). When immersed in water, soil mass undergoes an initial increase as the water rapidly displaces air in the soil pores. Soil mass then reaches a maximum before gradually decreasing, attributed to the loss of mass due to soil disaggregation. The curves of soil mass evolution over time are then used to calculate indicators, e.g., total relative mass loss, disaggregation speed, or time to meet a particular threshold value (Vanwindekens and Hardy 2023). Not all indicators have been linked to a disaggregation process. Nevertheless, in a comparison with the tests of Le Bissonnais, Vanwindekens and Hardy (2023) associate the beginning of the QST curves mainly to slaking, while the end of the curve is more related to the resistance to clay dispersion and differential swelling. Our analysis focused on the global indicator "Wend", which offers an overview of soil mass evolution by representing the relative soil mass at the end of the experiment.

SOC:Clay ratio

SOC:Clay is a reliable soil physical quality indicator to assess SOC status and carbon storage potential in relation to land use (Prout et al. 2020; Pulley et al. 2023). While soil texture determines potential SOC content, the SOC:Clay ratio is determined by farming practices, independently of clay content (Johannes et al. 2023). This allows for the comparison of soils with different textures (Pulley et al. 2023).

In Wallonia, a proposed agri-environment-climate measure uses the SOC:Clay ratio to enable volunteer farmers to identify degraded soils on their farms (Prout et al. 2020) and to offset costs associated with improving and maintaining SOC levels (SPW 2023c).

Soil structural quality tended to improve with increasing SOC:Clay ratio. In France and Poland, a critical SOC:Clay threshold of 1:10 was identified (Dexter et al. 2008). Below 1:10, there is a significant reduction in soil porosity which increases the risk of structural collapse (Guillaume et al. 2022a). Johannes et al. (2017) have proposed threshold values linking SOC:Clay ratio to an expected structural quality: ≥ 1:8 for a “very good” structural quality, 1:8 to 1:10 for “good” structure, 1:10 to 1:13 for “moderate” structure, and <1:13 for soils where structural degradation is likely. These empirical thresholds have already been validated on various European soils (Johannes et al. 2017; Prout et al. 2020), suggesting that they can be extrapolated to other temperate European regions with similar pedoclimatic conditions and clay mineralogy, such as Wallonia (Vanwindekens and Hardy 2023).

On average, the higher the clay content, the higher the SOC content required to achieve a given structural quality (Johannes et al. 2017). Soils with high clay content are expected to have greater carbon storage potential than sandy soils (Pulley et al. 2023). In Wallonia, for arable soils with low SOC content, clay dispersivity and differential swelling are strong drivers of soil disaggregation under wet conditions (Vanwindekens and Hardy 2023). Grasslands have higher SOC content than croplands, and crop sequences that include temporary grassland have higher SOC contents than those strictly dedicated to crops (van Wesemael et al. 2019). Therefore, while a ratio lower than 1:10 is often observed in cropland soils, a ratio higher than 1:10 is commonly found in grasslands (Prout et al. 2020). Dexter et al. (2008) found that the increase in carbon content associated with clay (referred to as complexed organic carbon) tended to depend on the increase in organic carbon in arable soils and on the increase in clay content in grasslands.

Labile carbon fraction

Permanganate oxidizable carbon (POXC) constitutes a labile sub-pool of SOC, defined as carbon that undergoes oxidation when treated with potassium permanganate ($KMnO_4$) 0.2 M (Huang et al. 2021). Due to its relatively short turnover time, POXC exhibits higher sensitivity to soil management practices than total SOC (Culman et al. 2012).

POXC:SOC ratio serves as a reliable indicator of nutrient cycling, soil structure, microbial pools, activity, and biodiversity, providing insights into soil degradation or improvement (Weil et al. 2003; Bongiorno et al. 2019). In a European study, reduced tillage and high organic matter input increased concentrations of labile carbon fractions in soil compared to conventional tillage and low organic matter addition (Bongiorno et al. 2019). According to Bongiorno et al. (2019), the fraction of POXC in European soils ranges from 1.45% to 4.32% of total SOC.

The practices implemented on the Walloon CA fields were categorized into different CA-types according to the method presented by Ferdinand and Baret (2024) (cf. Chapter 4). Subsequently, the results of the three indicators were compared among the CA-types.

2. Materials and methods

2.1. Study area

The study was conducted in Wallonia, the southern region of Belgium (16 900 km^2), characterized by an oceanic temperate climate. From northwest to southeast, precipitation increases (800 to 1400 mm) along with elevation (180 to 690 m) and a decrease in mean annual temperature (11 to 7.5 °C) (Chartin et al. 2017; SPW ARNE et al. 2018). In the same direction, there is a gradient in soil types, transitioning from deep sandy loam and silty soils to shallow silt loam and stony soils, and a shift from intensive arable agriculture to more extensive cattle breeding (Goidts 2009; Chartin et al. 2017). Agriculture covers 44% of Wallonia’s area (738 927 ha), with 52% as fodder meadows, 28% cereals, and smaller portions for fodder corn, potatoes and sugar beets (Antier et al. 2019; SPW 2023a). Organic farming extends over 12% of Walloon cultivated areas (Apaq-W and Biowallonie 2023).

Wallonia is divided into ten distinct agricultural regions, each characterized by relatively homogeneous soil attributes (such as texture, depth, stoniness, and drainage capacity) as well as specific geographical and climatic features, shaping the agro-economic potential and the type of farming practices within each region (Goidts 2009; Chartin et al. 2017). In Belgium, farming systems and soil quality evolution are commonly studied with reference to agricultural regions (Chartin et al. 2017).

2.2. Farmers and fields selection

Currently, 191 CA farms have been identified in Wallonia, which represents 5.5% of Walloon arable crop farms (Ferdinand and Baret 2024) (cf. Chapter 3). Out of the 191 CA farmers, the agricultural practices of 46 farmers were categorized according to the methodology of Ferdinand and Baret (2024). Only farmers with more than five years of experience in CA were chosen to conduct soil quality measurements. One farmer did not respond to the invitation. As a result, 28 CA farmers were selected.

In each CA farm, one field was selected for sampling based on the following criteria:

- CA practiced for more than five years;
- Be sown by winter cereals: durum or soft wheat (*Triticum durum* or *Triticum aestivum*), spelt (*Triticum spelta*), einkorn wheat (*Triticum monococcum*), rye (*Secale cereale*), triticale (*Triticosecale Wittm. ex A. Camus)*, winter barley (*Hordeum vulgare*), including malting barley sown in winter;
- Have carried out the last tillage operation (e.g., sowing) at least two weeks prior to the measurements;
- Accessible by car;
- Have a maximum slope of 10%;
- Be representative of the SOC content in the farmer's fields. This can be estimated using the predicted SOC map developed by Dvorakova et al. (2023), which was derived from Sentinel-2 images taken between 2016 and 2021. The aim is to avoid selecting fields whose surface SOC levels are significantly lower or higher compared to the farmer's other fields.

2.3. Soil sampling

Soil sampling was conducted from November 2021 to February 2022 in a one-hectare area within the selected field, positioned at least ten meters from the field's edges. The area has a homogeneous cropping history, i.e., the same technical practices have been applied throughout the area over the past five years. Several areas were excluded from sampling, such as headlands, field edges along roads, borders with neighboring fields, areas used for manure, beet or potato storage, and wheel tracks. The soil characteristics in the sample area, mainly texture and drainage, were as uniform as possible. They were checked with the farmer using Google Hybrid imagery and the digital soil map of Wallonia.

In each field, physical analyses were performed on six 100 cm^3 structured soil samples collected with steel Kopecky cylinders at a depth of 2–7 cm.

Chemical analyses were performed on composite samples taken from the four corners of each field. The composite samples consisted of five samples collected with a half-cylinder auger from 0-30 cm depth. The five samples are carefully mixed in a bucket, filling a ± 1L freezer bag.

2.4. Soil analysis

To compare the different CA-types based on soil quality indicators, we selected indicators that are quick to assess, simple to implement, cost-effective, significant and easily comprehensible for scientists and farmers, and responsive to changes in agricultural practices. Furthermore, we conducted additional analyses to characterize soil properties.

Physical analysis

Once collected, the soils in the Kopecky cylinders were transported to the laboratory, removed from the molds, and let air-dry for a minimum of thirty days. The structured soil sample is then introduced, supported by a metallic mesh basket, into distilled water, and soil mass is continuously measured by dynamically weighing the basket's content (Vanwindekens and Hardy 2023). The Wend indicator represents the relative soil mass at the end of the experiment, using a reference time of 900 seconds. Results for other indicators obtained from the QST can be found in Appendix M.

Chemical analysis

Fresh soil samples were dried at 20-25 °C for at least one week and then sieved at 2 mm. Chemical analyses were performed on the < 2 mm soil in the MOCA plateform (Mineral and Organic Chemical Analysis, Earth and Life Institute, UCLouvain).

a) SOC

The total organic carbon and nitrogen content were determined through combustion using a VARIO MAX CN elemental analyzer (Shimadzu). Inorganic carbon content was determined after a reaction with HCl with a calcimeter with an electronic pressure sensor (Sherrod et al. 2002). Following sample dry weight correction, we subtracted inorganic carbon from total carbon to obtain the organic carbon content.

b) POXC

POXC was determined using the method described by Culman et al. (2012), available at the following link: https://lter.kbs.msu.edu/protocols/133 (verified as of October 27, 2023). Briefly, 2.5 g of air-dried soils, passed through a 2 mm sieve, were mixed with 18 mL of deionized water and 2 mL of 0.2 M $KMnO_4$ solution in 50 mL centrifuge tubes. The tubes were shaken at 240 oscillations per minute for 2 minutes on an oscillating shaker. The tubes were then allowed to stand for 10 minutes. Subsequently, 0.5 mL of the supernatant were transferred to another 50 mL centrifuge tube and mixed with 49.5 mL of deionized water. The resulting mixture were homogenized and stored in darkness until the absorbance measurements were taken at 550 nm using a spectrophotometer. A 200 µL aliquot of each sample was loaded onto a plate, alongside a suite of internal standards, including a blank of deionized water, four standard stock solutions (0.05, 0.1, 0.15, and 0.2 mmol L^{-1} $KMnO_4$), a soil standard and a solution standard. Permanganate oxidizable carbon was determined following Weil et al. (2003):

$$POXC\ (mg\ kg^{-1}) = [0.02\ mol\ L^{-1} - (a+b\times Abs)] \times (9000\ mg\ \mathrm{C}\ mol^{-1}) \times (0{,}02\ L\ W\mathrm{t}^{-1})$$

Where:

- 0.02 mol L^{-1} represents the concentration of the initial $KMnO_4$ solution;
- a is the intercept of the standard curve;
- b is the slope of the standard curve;
- Abs denotes the absorbance of the unknown soil sample;
- 9000 mg is the amount of C oxidized by 1 mol of MnO_4 reduced from Mn^{7+} to Mn^{4+};
- 0.02 L is the volume of $KMnO_4$ solution reacted;
- Wt corresponds to the mass of soil (in kg) employed in the reaction (Culman et al. 2012).

c) Soil texture

Granulometry was determined by sedimentation and sieving in accordance with standard NF X 31-107, by the Centre Provincial de l'Agriculture et de la Ruralité (CPAR) in La Hulpe. The measurement revealed clay (< 2 µm), silt (2-50 µm) and sand (50-2000 µm) contents.

d) pH_{H2O} and pH_{KCl}

The pH_{H2O} was measured by the Centre Provincial de l’Agriculture et de la Ruralité (CPAR) in La Hulpe, following the NF EN 13037 standard. This was achieved by mixing soil in deionized water with a 1:5 mass ratio and then measuring pH using a pH meter. The pH_{KCl} was measured using a 1M KCl solution to desorb the exchangeable H^+ ions in the soil exchange complex, allowing for the determination of the soil’s potential acidity.

e) Potential cation exchange capacity and base saturation

The sample's potential cation exchange capacity (CEC) was assessed using the NF X31-130 standard. This method involves desorbing cations by passing 1M ammonium acetate solution naturally buffered at pH 7. Basic cations are then quantified using ICP-AES. Excess reagent is eliminated by rinsing with ethanol. Ammonium is subsequently desorbed using 10% KCl at pH 3, and the released ammonium is determined by spectrophotometry (Spectroquant Test Ammonium, Merck Kit 114752) to determine the potential CEC. Base saturation is calculated by dividing the sum of the base cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) by the CEC.

f) Residual soil humidity

To eliminate the weight of residual water in the measurements, we determined the weight content of matter and water to correct the SOC, POXC, CEC and exchangeable bases measurements, according to the ISO 11465:1993/Cor 1:1994 protocol.

2.5. Data treatment

SOC:Clay ratio

A consensus regarding the definitions of clay and clay minerals remains elusive, largely due to the remarkable variability of clay across geological, textural, and mineralogical terms, as well as its diverse range of applications (Rautureau et al. 2017). In this study, clays were characterized based on size (<2µm) rather than as a mixture of minerals comprising phyllosilicates. Consequently, particle size distribution was employed as a proxy to estimate clay content.

Categorization of CA practices into CA-types

Farmers' CA practices were classified according to their implementation of the three pillars based on the classification method of Ferdinand and Baret (2024). This categorization was carried out based on fifteen variables, five per pillar:

1) Minimum tillage is characterized by: (i) the frequency of tillage operations (named "Wheel Traffic"), (ii) the proportion of seeding operations compared to other tillage operations ("Seeding"), (iii) the frequency of use of powered tools ("Powered"), (iv) the frequency of use of plowing tools ("Plowing") and (v) the plowing depth ("Plowing Depth").
2) Soil organic cover is defined by: (i) the number of days the soil is covered by dead or living mulch ("Total Cover"), (ii) the cover produced by living mulch only (i.e., annual crops, temporary grassland or cover crops) ("Living Cover"), (iii) the cover produced

by temporary grassland (“Grassland Cover”), (iv) the soil cover during the erosion risk period (“ERP Cover”), and (v) the proportion of days of soil covered by spring crops during the ERP (“Spring Crops ERP Cover”).

3) Crop diversification is defined by: (i) the total number of different species grown (i.e., annual crops (A), temporary grassland (T), and cover crops) (“Total Species”), (ii) the number of different short-term income crop species (“A+T Species”), (iii) the proportion of crop species planted in association in A and T (“A+T Associations”), (iv) the mix of varieties in A and T (“A+T Mixes”), and (v) the number of tillage-intensive crops (“Tillage-intensive Crops”). We have defined tillage-intensive crops as spring-sown crops requiring a deeper soil preparation, a thin seedbed and/or can degrade the soil structure due to late harvesting. In Wallonia, these crops include beet, chicory, potatoes, carrots, onions, maize, vegetables such as peas, beans, etc. In contrast, tillage-extensive crops include cereals (other than maize), meslin, rape, flax, etc.

The method yielded five CA-types: three references characterized by extreme and salient practices, named CIO, CIN, and GEM, and two intermediate CA-types, named Ig1 and Ig2, characterized by practices located between the references. Farmers who did not exhibit significant proximity to any specific group remained unclassified.

The reference types are distinguished by three explanatory factors: the presence of temporary grassland in the crop sequence, the proportion of tillage-intensive crops, and the organic certification status. The labels were assigned based on these factors: ‘G’ or ‘C’ indicates a significant presence of temporary grassland or cash crops in the crop sequence, ‘I’ or ‘E’ denotes the dominance of tillage-intensive or tillage-extensive crops, and ‘O,’ ‘N,’ or ‘M’ indicates that farmers in the CA-type are exclusively organic, non-organic, or a mix of organic and non-organic. CIO brings together farmers with a significant proportion of tillage-intensive crops who are organic; CIN regroups farmers with a significant proportion of tillage-intensive crops who are non-organic; and GEM rallies farmers with a significant proportion of temporary grassland and tillage-extensive crops in their crop sequence, whether the farmers are organic or non-organic.

The crop sequence of Ig1 farmers is characterized by a significant proportion of tillage-intensive crops where some farmers also cultivate temporary grassland. Ig2 farmers grown mainly tillage-extensive crops (e.g., winter cereals, rapeseed) without incorporating temporary grassland into their crop sequence. Further details on the characteristics of practices within the pillars for each CA-type of CA are available in Chapter 4).

2.6. Working assumptions

Soil quality is positively correlated with reduced soil disturbance (Tahat et al. 2020), longer soil cover (Koudahe et al. 2022), and the inclusion of temporary grasslands in the crop sequence (Guillaume et al. 2022b). Based on the characteristics of each CA-type according to the three pillars (cf. Table 10 and Figure 21 in Chapter 4), we argue that fields categorized as CIO and CIN are prone to exhibit lower soil quality, characterized by reduced soil structural stability, a diminished SOC:Clay ratio, and decreased levels of labile and total carbon content compared to those categorized as GEM (Figure 23). Meanwhile, intermediate types are expected to demonstrate an intermediate level of soil quality.

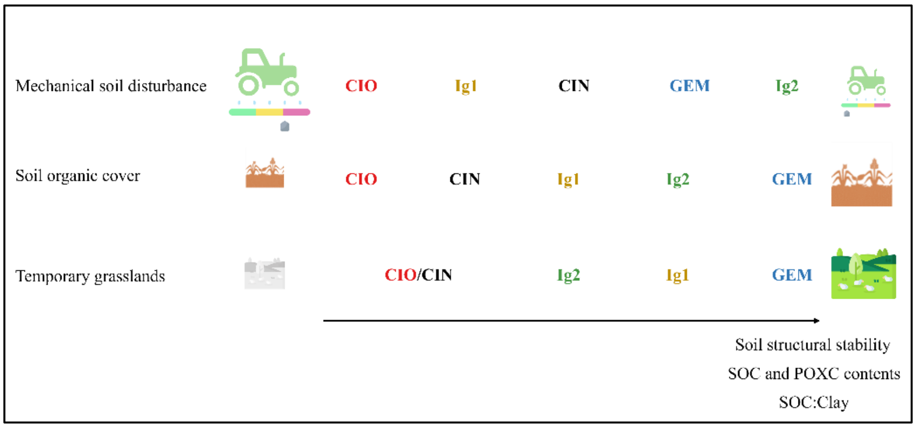


Figure 23 Ranking of CA-types according to mechanical soil disturbance, soil organic cover, and presence of temporary grasslands, in relation to expected soil structural stability, SOC and POXC contents and SOC:Clay ratio

2.7. Data processing

After obtaining the data, a cleaning process was implemented to remove fields and samples with missing information or those where a measurement error was identified. Data analyses were carried out using R-4.3.2 software.

3. Results

3.1. Conservation Agriculture categorization and agricultural regions

Soil sampling was carried out simultaneously with the interviews to achieve categorization. Consequently, farmers' assignment to specific CA-types were established after sampling. This resulted in an unbalanced sample, both between agricultural regions and CA-types. Notably, the CIO type and the regions Haute Ardenne, Ardenne and Famenne were not represented.

Additionally, seven farmers were not classified. Since the objective is to compare the impact of different CA-types practices on soil quality indicators, the analysis excludes fields that have not been classified under any CA-type. Consequently, of the 28 fields sampled, two were excluded from analysis due to incomplete data, and seven were not included in the CA-type comparisons as they were not classified (details of farm characteristics in Appendix N).

Therefore, 19 fields were analyzed to compare CA-types (Table 11). Organizing the sample by CA-type and agricultural region led to limited data within each subgroup. Given the imbalance between CA-types and agricultural regions, as well as the small number of observations in some group (e.g. only two fields in GEM) which reduces the power of statistical tests, we chose to use descriptive statistics to provide an overview of the observed trends. We have deliberately avoided using inferential statistics in this analysis.

Table 11 Distribution of farmers by CA-type and distribution of fields sampled
Explanatory notes: Fields in brackets were not analyzed to compare CA-types. Legend: 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), Intermediate groups (IgI and II), Sandy Loam (SLo), Loam (Lo), Condroz (Con), Fagne (Fag), Herbagère (Her) and Jurassic (Jur)

CA-type	**Farmers categorized**	**Fields sampled and analyzed for CA-type comparison**						
		Lo	SLo	Con	Fag	Her	Jur	Total
CIN	11	6	2	2			(1)	10
GEM	7			(1)	1	1		2
CIO	3							
Ig1	6	2				1		3
Ig2	7		1	2			1	4
Unclassified	12	(4)		(3)				
Total	46	8	3	4	1	2	1	19

3.2. Sample and soil properties

Table 12 displays the main soil and climate properties of the experimental CA farms and sampled fields. Temperatures ranged from 8.5 to 10.9°C and precipitation values ranged from 742.7 to 1061.0 mm. At the field level, clay contents ranged from between 10.6 to 20.8%, soil pH_{H2O} fluctuated between 6.48 and 8.15, pH_{KCl} ranged from 5.09 and 7.59, potential CEC varied between 7.8 and 17.5 $cmol_c$/kg, and base saturation values were between 62.67 and 100%. SOC contents spanned from 0.96% to 2.97%, and POXC varied between 336 and 619 mg/kg.

Table 12 Soil and climate properties of CA farms and sampled fields

Legend: Sandy Loam (SLo), Loam (Lo), Condroz (Con), Herbagère (Her), Fagne (Fag), Jurassic (Jur), Mean annual temperature (Temp.), and precipitation (Rain) for the reference period 1991-2020 according to IRM (2021), cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with a mix of organic and non-organic farmers (GEM), intermediate group (Ig1 and Ig2).

Agricultural region	Temp. (°C)	Rain (mm)	Livestock Yes=1 No=0	**Field code**	CA-type	Organic certified Yes=1 No=0	Clay (<2 µm)	Silt (2-50 µm)	Sand (50-2000 µm)	pH H_2O (-)	pH KCl (-)	pot. CEC ($cmol_c$ kg^{-1})	Base saturation (%)	SOC (%)	C:N (-)	POXC (mg/kg)
SLo	10.5	875	0	**2**	CIN	0	13.2	79.3	7.6	7.55	6.47	10.6	98.99	0.96	8.48	336
Lo	10.8	848	1	**3**	CIN	0	14.7	78.8	6.5	7.27	5.95	10.8	94.34	1.00	8.92	397
Con	9.7	917	1	**10**	CIN	0	16	74.5	9.4	8.14	7.24	11.7	100.00	1.13	9.20	338
Con	10.4	820	1	**11**	CIN	0	20.4	67.4	12.3	8.15	7.32	17.5	92.82	1.62	10.01	499
Lo	10.4	743	0	**13**	CIN	0	12.7	82.2	5.1	7.14	6.38	7.8	100.00	1.20	9.84	393
Lo	10.4	764	1	**22**	CIN	0	17.6	78.3	4.1	7.48	6.62	12.0	100.00	1.03	8.83	368
Lo	10.3	790	0	**28**	CIN	0	18	74.7	7.3	7.57	6.46	12.4	99.20	1.44	10.40	457
SLo	10.7	767	0	**33**	CIN	0	15.2	77.5	7.3	6.78	5.70	9.3	92.67	1.01	9.31	345
Lo	10.8	734	0	**35**	CIN	0	14.6	78.1	7.3	7.32	6.36	9.5	97.20	1.12	9.04	423
Lo	10.4	799	0	**36**	CIN	0	19.3	76.5	4.1	7.91	7.18	11.6	100.00	1.00	8.23	387
Fag	9.6	1002	1	**8**	GEM	1	16.6	74.5	8.9	7.10	5.92	13.9	66.85	1.66	9.10	554
Her	8.5	1061	1	**19**	GEM	0	10.6	69.7	19.7	6.59	5.74	15.1	62.67	2.97	9.17	619
Lo	10.9	843	1	**5**	Ig1	1	11.6	52.4	35.9	8.06	7.59	10.3	100.00	1.23	10.19	400
Her	9.8	1023	1	**20**	Ig1	0	20.8	54.6	24.6	6.48	5.29	15.9	68.76	2.41	9.82	542
Lo	10.4	815	0	**39**	Ig1	1	18.7	74.7	6.6	7.17	6.20	14.7	85.34	1.59	10.30	487
Con	9.8	921	0	**6**	Ig2	0	16.8	78.7	4.5	7.58	6.78	9.4	100.00	1.24	9.31	455
Jur	9.5	1173	1	**21**	Ig2	1	16.8	24.8	58.4	6.62	5.09	10.9	72.30	1.30	8.53	371
SLo	10.5	790	1	**31**	Ig2	0	16.4	70.1	13.5	7.23	6.37	8.4	100.00	1.05	8.85	411
Con	9.8	860	0	**40**	Ig2	0	21.5	67.8	10.7	7.21	6.33	13.3	94.95	2.13	11.40	490

3.3. Soil quality indicators and CA pillars

Pearson correlations were calculated between the soil properties, soil quality indicators and the variables used to categorize CA practices (Table 13). Regarding the first pillar and focusing on indicators, wheel traffic negatively correlates with Wend and SOC:Clay, while plowing depth positively correlates with SOC:Clay. Regarding the second pillar, the soil organic cover ("Total Cover” and “Living Cover”) positively correlates with Wend. The soil cover attributed to temporary grasslands positively correlates with SOC:Clay, and negatively correlates with POXC:SOC. At the third pillar level, the presence of crop associations is positively correlated with Wend, while the presence of tillage-intensive crops in the crop sequence is negatively correlated with Wend.

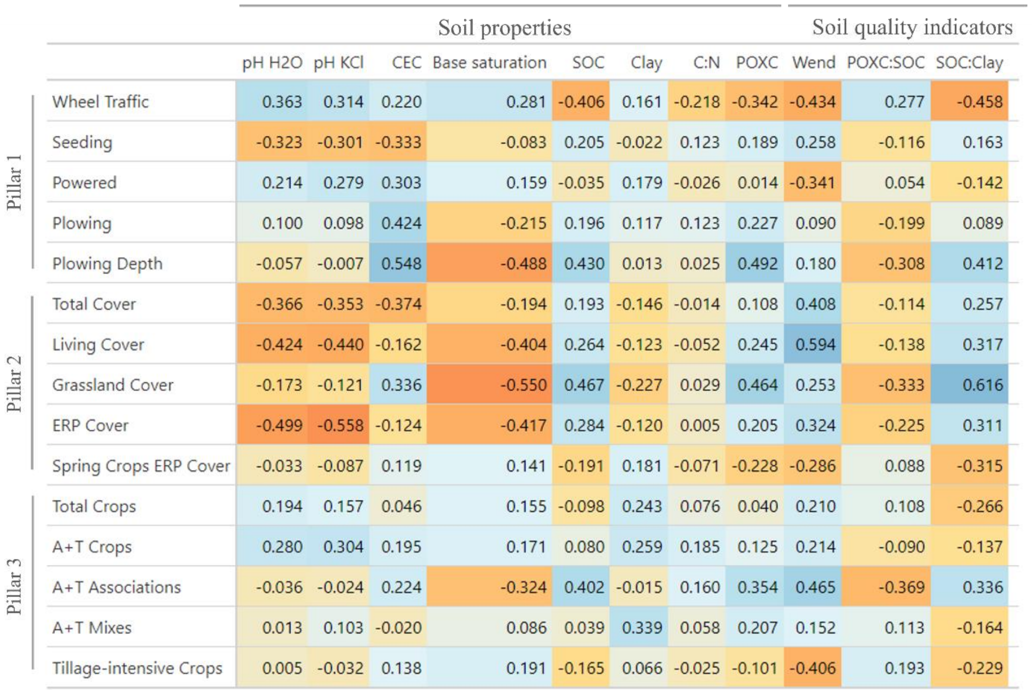
The contents of SOC and POXC are more closely correlated with CA practices, specifically wheel traffic, plowing depth, grassland cover, and crop associations, compared to the POXC:SOC ratio.

Pearson correlation coefficients between soil properties and soil quality indicators are presented in Appendix O.

Table 13 Pearson correlation coefficients between average CA pillar variables calculated to perform categorization, soil properties, and soil quality indicators, inspired by Vanwindekens and Hardy (2023)

Explanatory notes: The color gradient relates to the positive (blues) or to the negative (oranges) relative amplitude of the correlation coefficients. The variables defined to characterize the CA pillars is presented in Chapter 4.

Legend: Annual crops (A), Erosion risk period (ERP), Temporary grassland (T).



		Soil properties								Soil quality indicators		
		pH H2O	pH KCl	CEC	Base saturation	SOC	Clay	C:N	POXC	Wend	POXC:SOC	SOC:Clay
Pillar 1	Wheel Traffic	0.363	0.314	0.220	0.281	-0.406	0.161	-0.218	-0.342	-0.434	0.277	-0.458
	Seeding	-0.323	-0.301	-0.333	-0.083	0.205	-0.022	0.123	0.189	0.258	-0.116	0.163
	Powered	0.214	0.279	0.303	0.159	-0.035	0.179	-0.026	0.014	-0.341	0.054	-0.142
	Plowing	0.100	0.098	0.424	-0.215	0.196	0.117	0.123	0.227	0.090	-0.199	0.089
	Plowing Depth	-0.057	-0.007	0.548	-0.488	0.430	0.013	0.025	0.492	0.180	-0.308	0.412
Pillar 2	Total Cover	-0.366	-0.353	-0.374	-0.194	0.193	-0.146	-0.014	0.108	0.408	-0.114	0.257
	Living Cover	-0.424	-0.440	-0.162	-0.404	0.264	-0.123	-0.052	0.245	0.594	-0.138	0.317
	Grassland Cover	-0.173	-0.121	0.336	-0.550	0.467	-0.227	0.029	0.464	0.253	-0.333	0.616
	ERP Cover	-0.499	-0.558	-0.124	-0.417	0.284	-0.120	0.005	0.205	0.324	-0.225	0.311
	Spring Crops ERP Cover	-0.033	-0.087	0.119	0.141	-0.191	0.181	-0.071	-0.228	-0.286	0.088	-0.315
Pillar 3	Total Crops	0.194	0.157	0.046	0.155	-0.098	0.243	0.076	0.040	0.210	0.108	-0.266
	A+T Crops	0.280	0.304	0.195	0.171	0.080	0.259	0.185	0.125	0.214	-0.090	-0.137
	A+T Associations	-0.036	-0.024	0.224	-0.324	0.402	-0.015	0.160	0.354	0.465	-0.369	0.336
	A+T Mixes	0.013	0.103	-0.020	0.086	0.039	0.339	0.058	0.207	0.152	0.113	-0.164
	Tillage-intensive Crops	0.005	-0.032	0.138	0.191	-0.165	0.066	-0.025	-0.101	-0.406	0.193	-0.229

3.4. Soil quality indicators and CA-types

Mean values of soil indicators were calculated for each CA-type (Table 14). The raw values for each sample are available in Appendix N.

The mean Wend values increased as follows: CIN << Ig1 < Ig2 ≈ GEM. The percentages of POXC:SOC increased in the sequence GEM < Ig1 < Ig2 < CIN. The SOC:Clay ratios rose in the order CIN ≈ Ig2 < Ig1 << GEM. Wend and SOC:Clay have the highest averages in GEM fields, while CIN fields exhibit the lowest averages. Conversely, POXC:SOC shows the highest averages in CIN fields and the lowest averages in GEM fields.

Table 14 Descriptive statistics of soil quality indicators per CA-types (mean ± standard deviation)

Legend: cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with a mix of organic and non-organic farmers (GEM), intermediate groups (Ig1 and Ig2).

Indicator (unit)	**CIN**	**Ig1**	**Ig2**	**GEM**	**All CA fields**
Number of fields	*10*	*3*	*4*	*2*	*19*
Number of samples	*59*	*16*	*21*	*12*	*140*
Wend (-)	0.48 ±0.33	0.72 ±0.31	0.88 ±0.16	0.90 ±0.05	0.680 ±0.321
Number of samples	*40*	*12*	*16*	*8*	*100*
POXC:SOC (%)	3.48 ±0.43	2.88 ±0.50	3.21 ±0.71	2.71 ±0.67	3.26 ±0.57
SOC:Clay (-)	0.07 ±0.02	0.10 ±0.02	0.08 ±0.02	0.19 ±0.11	0.09 ±0.05

The following sections analyze each soil quality indicator separately.

3.4.1. Soil structural stability

The QST method of Vanwindekens and Hardy (2023) was used to analyze the structural stability of the samples (Figure 24). Appendix P displays QST curves for different fields, according to their respective CA-type.

CIN samples exhibit the lowest Wend values, which represents the fraction of the sample that has not undergone disaggregation.

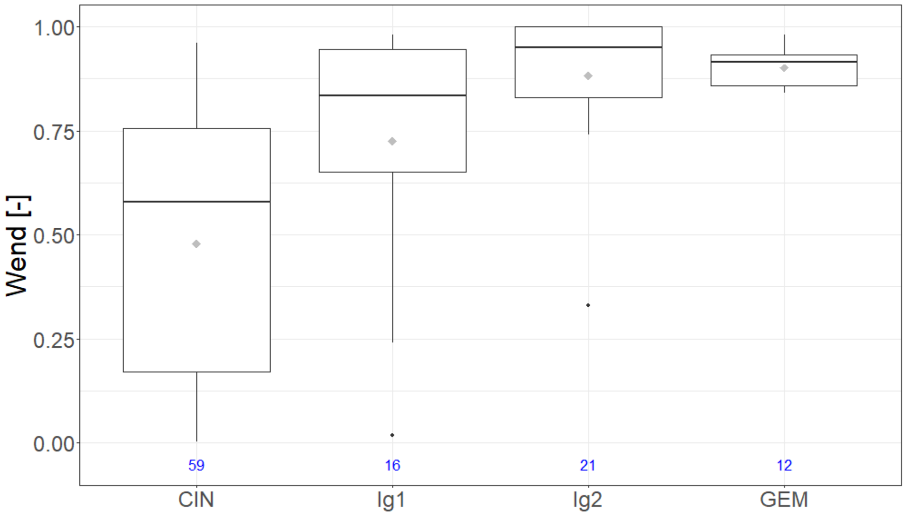


Figure 24 Box plots of the Wend indicator in the QuantiSlake Test for the four CA-types

Explanatory notes: The boxes represent the interquartile range (IQR) between the 25th and the 75th percentiles. The thin lines represent the minimum and the maximum values within 1.5 times the IQR from the lower and upper quartiles. Points beyond these lines are the outliers, represented by open dots. The thick line inside the box is the median. The grey diamond is the average. The figures in blue represent the number of samples. Legend: cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with a mix of organic and non-organic farmers (GEM), intermediate groups (Ig1 and Ig2).

3.4.2. POXC:SOC ratio

To facilitate the interpretation of the POXC:SOC ratio, the SOC and POXC contents were also visualized (Figure 25). Contents of SOC and POXC increase in the order CIN ≈ Ig2 < Ig1 < GEM. Conversely, the POXC:SOC ratio increases in the order GEM ≈ Ig1 < Ig2 < CIN.

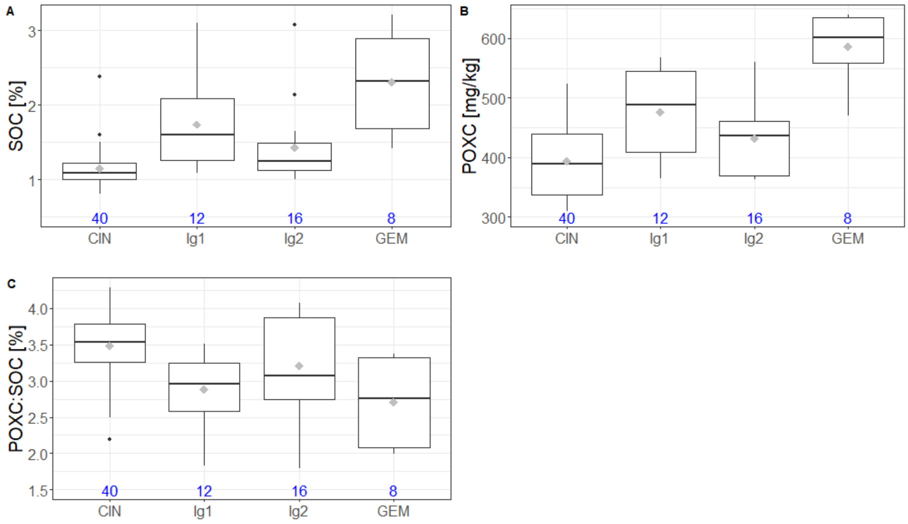


Figure 25 Box fields of the (A) SOC contents, (B) C:N ratios, (C) POXC contents and (D) POXC:SOC ratios across the four CA-types

Explanatory notes: The boxes represent the interquartile range (IQR) between the 25th and the 75th percentiles. The thin lines represent the minimum and the maximum values within 1.5 times the IQR from the lower and upper quartiles. Points beyond these lines are the outliers, represented by open dots. The thick line inside the box is the median. The grey diamond is the average. The figures in blue represent the number of samples. Legend: cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with a mix of organic and non-organic farmers (GEM), intermediate groups (Ig1 and Ig2).

When comparing POXC levels with SOC levels, notable variations emerge in the relationship between POXC and SOC, particularly between the GEM and CIN types (Figure 26). Initially, POXC levels rise rapidly in conjunction with SOC levels, plateauing at approximately 0.6 g/kg. This plateau is notably pronounced in Ig1 and GEM fields.

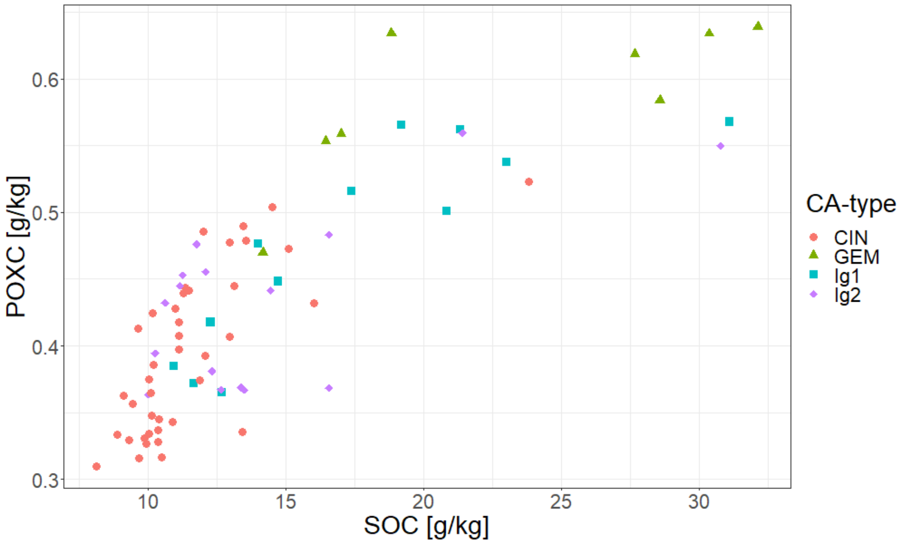


Figure 26 Permanganate oxidizable carbon (POXC) as a function of soil organic content (SOC), according to the CA-types

3.4.3. SOC:Clay ratio

The classification of Johannes et al. (2017) was used to relate SOC:Clay ratios to an expected structural quality. The proportions of samples above and below the three SOC:Clay thresholds differed between CA-types (Table 15 and Figure 27). A significant proportion of CIN samples had SOC:Clay <1:13 (i.e., depleted in SOC for their clay content) and a significant proportion of GEM samples had SOC:Clay ≥ 1/8 (i.e., enriched in SOC for their clay content).

Table 15 Observed frequencies of the number of samples categorized by CA-type based on their SOC:Clay ratio according to the classification of Johannes et al. (2017)

Legend: cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with a mix of organic and non-organic farmers (GEM), intermediate groups (Ig1 and Ig2).

SOC(g/kg):Clay(g/kg)	Expected structural quality	CIN	Ig1	Ig2	GEM	Total
Number of fields		10	3	4	2	19
Number of samples		40	12	16	8	76
≥ 1:8	Very Good	0	3	1	4	8
1:10 ≤ SOC:Clay < 1:8	Good	5	2	0	2	9
1:13 ≤ SOC:Clay < 1:10	Moderate	10	6	7	2	25
< 1:13	Bad	25	1	8	0	34

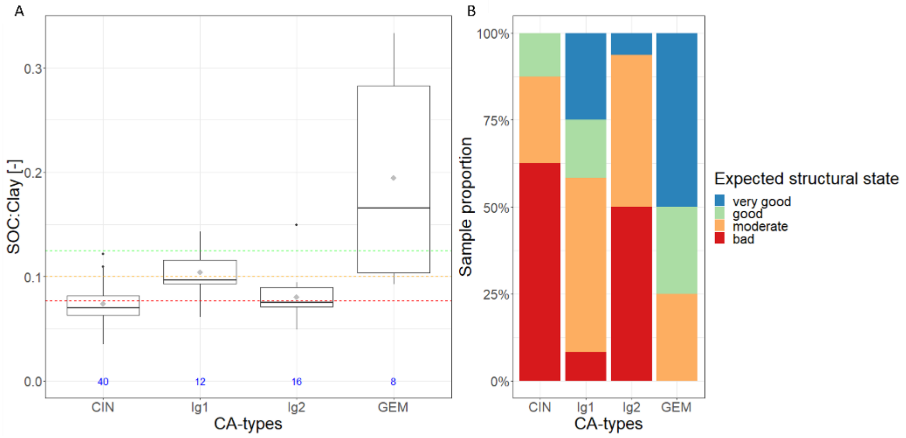


Figure 27 (A) Box fields of SOC:Clay ratio for each CA-type. Lines are SOC:Clay thresholds: Green = 1:8, orange = 1:10, red = 1:13. (B) Proportions of samples categorized by CA-type according to expected soil quality by SOC:Clay ratio, as defined by Johannes et al. (2017)

Explanatory notes: The boxes represent the interquartile range (IQR) between the 25th and the 75th percentiles. The thin lines represent the minimum and the maximum values within 1.5 times the IQR from the lower and upper quartiles. Points beyond these lines are the outliers, represented by open dots. The thick line inside the box is the median. The grey diamond is the average. The figures in blue represent the number of samples. Legend: cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with organic and non-organic farmers (GEM), intermediate groups (Ig1 and Ig2).

4. Discussion

4.1. Soil structural stability in Conservation Agriculture beyond tillage

Our QST values can be compared to those obtained in the study by Vanwindekens and Hardy (2023), which was based on 35 fields in Belgium's silt loam region. However, this comparison must be made cautiously as their study focused on arable soils (without temporary grassland) and a specific agricultural region in northern Wallonia. Not all QST indicators appear relevant in our context of comparing CA-types. Indeed, many CA soil samples show high stability when submerged in water, resulting in a gentle slope (as shown in Appendix P). Therefore, global indicators calculated based on the whole QST curve, such as Wend, are more suitable than local indicators calculated at a specific point in time. This is confirmed by the high correlation between Wend and various CA practices (Table 13).

The medians of the Wend indicator derived from the samples analyzed by Vanwindekens and Hardy (2023) were approximately 0.4 for plowed fields and 0.75 for reduced tillage fields. Our CA fields exhibit a Wend's median of 0.81 (Table 14), placing them within the range of values observed for reduced tillage practices in the study conducted by Vanwindekens and Hardy (2023). The observation was not surprising since the sampled fields are managed under a CA-type, which involves reduced soil tillage compared to conventional practices.

However, we observed that the use or non-use of a plow does not fully explain the differences among the CA-types. Among the CA-types, CIN is the only type where all farmers consistently implement non-inversion tillage practices. Despite this, these fields exhibit the highest degree of soil disaggregation, represented by the lowest value of the Wend indicator (Table 14). In relation to our working hypotheses, the correlation coefficients between the Wend indicator and CA practices (Table 13) show that, in addition to reduced tillage, soil cover and crop associations are positively correlated with improved structural stability. Furthermore, the inclusion of tillage-intensive crops (predominant in the CIN type and less in the GEM type) is negatively correlated with the Wend indicator. These results are in line with previous studies showing that the benefits of soil conservation practices on soil quality are larger when the pillars of CA are implemented together (Chenu et al. 2019; Page et al. 2020; Adeux et al. 2022).

4.2. Soil quality variations in Conservation Agriculture driven by temporary grassland

The observed levels of POXC and the POXC:SOC ratios align with reported values in Europe (Bongiorno et al. 2019), despite the absence of specific references for Wallonia. Additionally, the trend toward a plateau in POXC levels beyond a certain SOC threshold (Figure 26) has been documented (Jensen et al. 2019). Beyond this plateau, similar to observations made in grass pastures, the POXC:SOC ratio diminishes (Awale et al. 2017).

Our study reveals a positive linear correlation between SOC and POXC levels and the incorporation of temporary grassland in the crop sequence (Table 13). The GEM type, characterized by a significant proportion of its cropping sequence under temporary grassland, exhibits higher levels of SOC and POXC than other CA-types but a lower POXC:SOC percentage. This outcome aligns with the inverse relationship between the POXC:SOC percentage and stable SOC levels (van Wesemael et al. 2019).

These findings are elucidated by the higher carbon input from temporary grasslands from both above and below ground biomass. This leads to an increase in SOC contents as the formation of SOC surpasses its decomposition, given the positive correlation between SOC formation and labile carbon input rates (Bradford et al. 2008). The labile SOC fraction is pivotal in sustaining soil organic matter (SOM) and gradually contributes to stable SOC stocks (van Wesemael et al. 2019). The enhanced biomass and microbial activity under grassland conditions also foster a more rapid transformation of POXC pools into a more stabilized SOC form (Awale et al. 2017). Conversely, CIN fields, characterized by a cropping sequence devoid of temporary grassland and dominated by tillage-intensive crops, exhibit lower carbon input. This reduction in carbon input leads to a decrease in SOC contents as SOC decomposition surpasses its formation.

Regarding the SOC:Clay indicator, our results indicate a positive correlation with the inclusion of temporary grassland in the cropping sequence and a negative correlation with wheel machinery traffic on the field. Consistent with previous investigations by Dexter et al. (2008), Johannes et al. (2017), and Prout et al. (2020), the GEM CA-type, characterized by the highest proportion of temporary grassland in its cropping sequence, exhibits the more significant proportion of samples exceeding the 1:10 SOC:Clay ratio (Figure 27). In contrast, the CIN CA-type, without grassland and with a notable presence of tillage-intensive crops, shows the highest proportion of samples falling below the 1:10 threshold. This suggests that a significant portion of SOC in GEM fields exists in the form of particulate organic carbon, meaning it is not stabilized by organo-mineral associations. Similar observations have been documented in long-term permanent pasture fields (Pulley et al. 2023). Furthermore, our results show that no sample from a GEM field falls below the 1:13 threshold, indicating its relevance as a critical point for evaluating soil degradation in Wallonia. Additionally, most arable soils managed under CA in Wallonia fall below the saturation line of 1:10, indicating their potential to sequester more organic carbon in complexed forms (Dexter et al. 2008).

Our findings are in line with recent studies indicating that the increase in SOC contents and carbon sequestration is primarily due to the other two pillars of CA – soil organic cover and crop species diversification – achieved by increasing primary production through rotations and cover crops, increasing the biomass returned to the soil by crop residues, and improving grassland management (Chenu et al. 2019; Blanco-Canqui 2024).

4.3. When digging into the diversity of practices hits a rocky road

This study compares the impact of CA practices on three soil quality indicators, considering the three pillars of CA and their diversity of implementation. To achieve this, we conducted an exploratory study involving on-farm observations. Experiments conducted in controlled environments in research stations enable the decoupling of factors by isolating agricultural practices and controlling various parameters studied to discern the individual effects of these practices. However, such experiments often inadequately represent on-farm field processes (Dupla et al. 2021). Extrapolating the results of such studies to cropping systems is, therefore, not always straightforward and must be approached with caution. In contrast, on-farm observations offer a more realistic depiction of CA practices and their impacts. Quantitative analysis of the three pillars of CA for different cropping systems recognizes that these practices evolve based on farmer’s experiences and needs (Dupla et al. 2021).

Our study design also has several limitations. It allowed us to analyze only 19 agricultural fields, which were unevenly distributed among CA-types and agricultural regions. Although the study encompassed both arable (northern Wallonia) and livestock (southern Wallonia) regions, the design did not permit the isolation of confounding factors (such as pedo-climatic factors) from agricultural practices, nor did it allow for inferential statistics to extend the results from the sample to the entire population of CA practitioners in Wallonia. To achieve this, a balanced sampling protocol with a sufficiently high number of fields per CA-type and agricultural region would have been necessary, requiring sample size calculation and classification of CA-types prior to field sampling, thereby extending the duration of the experiment. Nevertheless, we doubt that all Walloon CA-types are present in each agricultural region; for instance, the GEM type appears more prevalent in southern Wallonia, while the CIN type predominantly occupies the northern part. In some respects, we are faced with a circularity as some practices are only present in certain soil types, and those soil types constrain the practices that can be implemented.

Ideally, additional variables, including farmers’ experience in CA, as well as other agricultural practices beyond the scope of the three pillars, such as fertilization and pesticide use, should have been standardized.

All sampled fields had been under CA for at least five years. However, the historical land use and practices before this period could influence the results, and the design used does not allow for the separation of the benefits derived from CA practices from the initial soil conditions. For instance, the sampled GEM fields might have been under permanent grasslands before, a land use that could enhance soil properties such as carbon content.

Even with a sufficient number of fields per CA-type, other challenges could have disrupted the interpretation of results, such as inter-parcel variability. Additionally, a field-based setup invariably introduces increased mobility, resulting in an extended field phase, leading to a broader date range for sample collection and, consequently, diverse sampling conditions. Lastly, many of the processes connecting agricultural practices, such as CA pillars, to soil health effects are still poorly understood (Chenu et al. 2019).

4.4. Multifaceted influences on SOC dynamics in Conservation Agriculture: the confounding drivers

The positive correlation between SOC content and plowing depth (Table 13), which contradicts the prevailing scientific literature, may be explained by the presence of a confounding factor: temporary grassland. Plowing is often used to destroy temporary grassland within cropping sequences that include it. The correlation observed between plowing depth and SOC content in our study is likely due to the mechanical destruction of temporary grassland by occasional plowing in GEM CA-type. Additionally, organic certification may explain the positive correlation between plowing and SOC content. Organic farmers tend to perform more occasional plowing but also use organic fertilizers instead of mineral fertilizers. Organic fertilizers (manures, composts…) increase carbon inputs and improve SOC contents and stability (Chenu et al. 2019).

While several studies have already demonstrated that land use is the most influential environmental parameter on SOC dynamics, land-use history, topography, climate, and soil type can also explain the variability in CA-types (Chartin et al. 2017; Prout et al. 2020).

Regarding land use history, it would have been valuable to investigate the land use patterns over the past ten to twenty years leading up to the sampling. Indeed, some fields may have been in a permanent pasture two decades ago, and this prior land use could have had a substantial impact on organic carbon stocks (Prout et al. 2020).

Similarly, further investigation could be conducted into the effects of topography, soil type, and climate. A positive gradient of SOC stocks – mainly correlated with changes in elevation, precipitation, temperature and clay and fine silt content – exists from the northwest to the center of Wallonia, with a slight decrease in the Ardennes and locally in Jurassic agricultural regions (Chartin et al. 2017). GEM farms are located in agricultural regions with higher rainfall and lower temperatures (Table 12), which are more favorable for maintaining higher SOC levels (i.e., higher C-input rates and lower mineralization rates) (Chartin et al. 2017). In addition, GEM farms are located in regions with higher clay and fine silt contents compared to regions further north in Wallonia (Chartin et al. 2017). The fine carbon fraction (< 20 µm), also known as stable, can be associated with clay and fine silt, which can explain the higher levels of stable carbon within the GEM type (van Wesemael et al. 2019). In contrast, farms classified as CIN type and situated in the Sablo-limoneuse, Limoneuse, and Condroz agricultural regions, which have soils with lower clay and fine silt content, higher temperatures, and lower precipitation, exhibit a lower storage carbon capacity (van Wesemael et al. 2019).

Finally, it is essential to emphasize that our study focused solely on agricultural practices related to the three pillars of CA. It would be worthwhile to consider other farming practices that may affect SOC dynamics, such as fertilization, the amount of carbon input produced and remaining on the field, phytosanitary treatments, grazing management, or the specific type of crops implemented.

5. Conclusion and perspectives

Concluding the sustainability of CA can be challenging when the approach's intrinsic diversity is overlooked. Our study revealed significant variations in three soil quality indicators among different Walloon farms that practice CA. The categorization of CA practices revealed that the GEM CA-type had the highest structural stability, SOC and POXC contents, and SOC:Clay ratio. This CA-type is characterized by a high proportion of temporary grassland and tillage-extensive crops in their cropping sequence, and occasional inversion tillage. In contrast, the CIN CA-type, characterized by non-inversion tillage and tillage-intensive crops in their cropping sequence, yielded the lowest results in terms of these soil quality indicators.

The integration of temporary grassland in the crop sequence is the practice identified as having the greatest impact on the studied soil quality indicators. This practice increases soil organic cover and reduces tillage over multiple consecutive years, thereby mitigating soil erosion. Additionally, it promotes above and below ground biomass, and stimulates microbial activity, consequently enhancing SOC levels.

These results emphasize the importance of considering more than just the simple choice between plowing and direct seeding when evaluating the impact of CA on soil quality. CA cannot be reduced to only one of its three pillars, nor can it be reduced to the exclusive use of a single tool. Each of the three pillars of CA encompasses a variety of practices, and their combination generates diverse impacts. Ignoring this diversity and its consequences undermines our understanding of the potential environmental benefits of CA.

In addition to CA practices, other factors such as land-use history, topography, climate, and soil type can influence soil quality. In Wallonia, farms classified as GEM, with the best-preserved soils, are in areas more conducive to soil conservation. Therefore, it is challenging to establish a direct correlation between certain practices and factors and their impact on a soil quality indicator. To elucidate these complex interactions, a potentially fruitful avenue for investigation involves a comparative analysis with control plots situated in identical local conditions.

Although many Walloon arable soils managed under CA have substantial SOC deficits (SOC:Clay ratio less than 1:10), suggesting the possibility of further increasing carbon contents, we recommend an in-depth exploration of the causal links between agricultural practices, pedo-climatic contexts, and their impacts on soil quality. Unfortunately, building a balanced sample to compare different CA-types in Wallonia is proving complex.

Acknowledgment

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Chapter 6 Transition in Conservation Agriculture: integrating the diversity of practices to explore the before and the after

Chapter 4 tamed the second elephant in the room by classifying CA practices implemented by farmers in Wallonia into five CA-types. Like Chapter 5, this chapter sets out to tame the third elephant in the room: integrating the diversity of CA practices, which has been categorized, into the assessment of CA.

This chapter aims to explore the drivers of change that led farmers to implement a certain type of CA, as well as how their plans to modify their CA practices in the coming years, specifically in Wallonia, southern Belgium. This chapter distinguishes itself from previous ones by relying on discourse analysis from farmers who practice CA and a qualitative data analysis methodology, rather than quantitative data.

To achieve this, a theoretical framework is provided in section 2, serving as the basis for analyzing farmers' discourse. The NVivo software tool is then employed to implement this analysis (section 3). Two outcomes emerge from this process, which are presented in section 4 and discussed in section 5. Firstly, there exists a diversity of drivers of change, seemingly unrelated to the CA-types. These drivers can be divided into two main processes of change: those related to implementing simplified cultivation techniques and those associated with adopting CA. Secondly, farmers belonging to a CA-type do not necessarily share the same desires or plans for modifying their CA practices. While some farmers aim to align more closely with CA pillars, others choose to deviate from these pillars, primarily to enhance farm profitability.

This methodological approach offers a complementary perspective, enriching the understanding of transition dynamics within CA practices in Wallonia.

1. Introduction

Conservation Agriculture (CA) emerges as an alternative due to its potential to maintain and improve soil quality and fertility while increasing production efficiency (FAO 2023a). CA is based on three agronomic pillars (or principles): (i) minimum mechanical soil disturbance, (ii) maximum soil organic cover, and (iii) maximum crop species diversification. In 2019, the worldwide CA cropland covered approximately 205.4 million hectares, accounting for roughly 14.7% of the total global cropland (Kassam 2022).

The three pillars of CA offer great flexibility of application, resulting in a diversity of practices observed both on a global scale (between countries) and within local regions (Lahmar 2010; Scopel et al. 2013; Craheix et al. 2016; Brown et al. 2017; Derrouch et al. 2020; Bouwman et al. 2021). Farmers shape each CA practice to meet their specific needs and objectives and this multiplicity of practices results in various outcomes.

The diversity of CA practices implies a corresponding diversity in transition processes to CA. A transition is the change from one state to another, e.g. from conventional agriculture to CA, and is composed of a series of processes of change, i.e. a set of events that occur in succession over a period of time and lead to one or more changes in practices, e.g. the reduction of tillage (Chantre and Cardona 2014).

The implementation of various soil conservation practices by farmers is influenced by a diversity of incentives and constraints (Rodríguez-Entrena and Arriaza 2013). These incentives and constraints can be referred to as “drivers of change”, i.e. factors that farmers themselves cite as triggering their decision to change their practices, such as soil tillage, soil cover, or crop diversification (Mawois et al. 2019). These drivers can be (i) external to the farm and related to the social, cultural, or economic environment, such as interactions with stakeholders (firms, input seller, farmers networks), the structuring of markets and supply chains, or changes in the policy context, or (ii) internal to the farm and related to specific farm characteristics, changes in the famers’ organizational choices or values, and farmers’ knowledge and motivations (Rodríguez-Entrena and Arriaza 2013; Prost et al. 2017; Mawois et al. 2019). Given the dynamic nature of external and internal drivers of change over time, farmers’ strategies and practices remain in a continuous state of evolution and adaptation (Vanwindekens et al. 2013).

Understanding these drivers of change can guide policy by designing levers of action to facilitate the implementation of a given innovative practice or combination of innovative practices on other farms and to design development scenarios for these practices (Mawois et al. 2019; Fouillet et al. 2023).

Few studies focus on the analysis of the transition processes toward CA (Serebrennikov et al. 2020). Among these studies, most are concentrated in Africa and Asia, with fewer focusing on Europe. Since each region presents a unique set of circumstances, there is no universally applicable transition process and research must be done at the local scale (Knowler and Bradshaw 2007; Lahmar 2010; Rodríguez-Entrena and Arriaza 2013; Knowler 2015; Varia et al. 2017). Most studies exclusively concentrate on the barriers and drivers influencing farmers' adoption or non-adoption of practices (Knowler 2015). Furthermore, these studies often take place before the completion of the transition process (Wauters and Mathijs 2014). Additionally, the transition to CA practices is frequently summarized by the binary distinction of no-till and tillage adoption. The holistic consideration of the three pillars, encompassing their complexity and diversity, is notably underrepresented in these studies.

The aim of this chapter is to explore the various drivers of change that led farmers to implement a certain type of CA, as well as how farmers plan to change their CA practices in the coming years, specifically in Wallonia, southern Belgium. We wanted to investigate why farmers, with well-established CA practices, decide to switch to a particular CA-type, and how they envision the future development of their practices, at the regional level and by integrating the diversity of existing practices within the three pillars of CA.

To achieve these two goals, we adopted an approach focused on the co-production of knowledge with CA farmers by semi-structured interviews. To grasp the comprehension of the diversity of practices, typologies were used to categorize and study the CA practices as CA-types (refer to Chapter 4). We identified three CA-types with extreme and salient practices, termed references, and two intermediate CA-types, where their practices intersect with those of the references. Both objectives are met through the prism of CA-types.

The limitation of this chapter is to study change processes through interviews that focus specifically on the three pillars of CA, in order to stay within the scope of the thesis. To do so, we cannot pretend to document all stages of change processes or understand all dimensions of CA adoption, particularly those that are not directly related to the three pillars and farmer characteristics.

2. Theoretical framework: the transition in CA

The aim of this section is to construct a theoretical framework for the analysis of the drivers of change in the transition to and within CA, based on previous European studies. It is not meant to be a literature review.

2.1. Literature search process

The literature search was conducted the 20th of November 2023 on Scopus using the following search: Title (transition* OR pathway* OR trajectory* OR adopt* AND "conservation agriculture"). The search was restricted to peer-reviewed articles published in English (exclusion of preprint and conference papers), resulting in 118 distinct articles, representing 9% of CA research. Subsequent screening of titles and abstracts was performed to select articles that specifically examined regions in Europe, those that did not specify a region, or those with a global scope. This refined the selection to 23 papers. Notably, a significant portion of the excluded papers predominantly focused on Africa (53%) and Asia (18%).

Most European and global papers focus on specific case studies such as glyphosate, wheat, weeds, soil porosity and nitrogen fertilization, which fall outside the scope of our research theme and were therefore excluded. We also excluded review papers that discuss the benefits attributed to CA, rather than the reasons why farmers choose to transition to CA. Only ten articles align with our research theme. A comprehensive analysis of the introductions of these ten articles was conducted to extract their content and compile a list of referenced works. Furthermore, we used the ResearchRabbit application (https://www.researchrabbit.ai/), a tool that begins the search with one or more core articles and then identifies additional relevant papers based on the specified topic of interest derived from the selected core articles, thereby refining the initial list. In total, thirteen articles were utilized to build this theoretical framework (Table 16).

Table 16 Sources analyzed to formulate the theoretical framework

N°	Title	First author	Year	Study area
1	Farmers' adoption of conservation agriculture: A review and synthesis of recent research	Knowler	2007	World
2	Adoption of conservation agriculture in Europe. Lessons of the KASSA project	Lahmar	2010	Europe
3	Socio-economic factors influencing farmers' adoption of soil conservation practices in Europe	Prager	2010	Europe

4	Adoption of conservation agriculture in olive groves: Evidences from southern Spain	Rodríguez-Entrena	2013	Spain
5	The adoption of farm level soil conservation practices in developed countries: a meta-analytic review	Wauters	2014	Developed countries
6	What do farmers mean when they say they practice conservation agriculture? A comprehensive case study from southern Spain	Carmona	2015	Spain
7	Farmer adoption of conservation agriculture: A review and update	Knowler	2015	World
8	Organic farmers' motivations and challenges for adopting conservation agriculture in Europe	Casagrande	2016	Europe
9	The transition to conservation agriculture: an insularisation process toward sustainability	Vankeerberghen	2016	Belgium
10	Supporting transition toward conservation agriculture: a framework to analyse the learning processes of farmers	Cristofari	2017	France
11	System dynamics model to design effective policy strategies aiming at fostering the adoption of conservation agriculture practices in Sicily	Varia	2017	Italy
12	Adoption of non-inversion tillage across Europe: Use of a behavioural approach in understanding decision making of farmers	Bijttebier	2018	Europe
13	Factors Influencing Adoption of Sustainable Farming Practices in Europe: A Systemic Review of Empirical Literature	Serebrennikov	2020	Europe

2.2. Drivers of change for the transition to CA

An analytical framework was developed through the literature research to categorize the drivers of change prompting farmers to implement CA and identify those already acknowledged in existing literature. Categorizing these drivers of change can help identify potential levers of action to promote desired change.

The authors employ a variety of terms to categorize drivers of change, including economic (or financial), management (or organizational), often combining economic and management, environmental, social, socio-structural, socio-demographic, social capital, institutional, spatial, biophysical, farmers and farms household, and external (or exogenous) drivers. Each author utilizes their unique categories, and none provide explicit definitions for these categories.

Based on the literature, we propose our categories of drivers of change and their definitions (Table 17). Although in the literature, "organizational" and "financial" categories are often not distinguished (e.g. Knowler and Bradshaw, 2007), we have chosen to differentiate these categories. The same drivers, for example, "reduction of labor," can be motivated by financial reasons (the farmer can no longer afford to employ as many people) or organizational reasons (such as a full-time worker, like a retired father, leaving the farm, requiring the same workload with fewer workforce).

Table 17 Categories of drivers of change for the implementation of innovative agricultural practices

Explanatory notes: this table was developed in collaboration with colleagues from the Sytra team.

Type	**Linked to**
Technical	The practical implementation of the innovation.
Financial	The costs, investments, market price, or gains, related to the implementation of the innovation and the financial impacts of the innovation.
Organizational	The organization of tasks or operations.
Institutional	The political contexts and the regulatory and legal frameworks faced by farmers.
Biophysical conditions	Biophysical environmental factors, such as soil, climate, and topography.
Knowledge-related	Knowledge, awareness and experience regarding the innovation and its implementation.
Relationship with actors	The interactions between actors of a value chain, and the balance of power between the parties.
Cultural and social	Attitudes, beliefs, norms, and values.
Market-related	External market conditions.

The transition to CA is influenced by a multitude of drivers. Knowler and Bradshaw (2007) conducted a global assessment, encompassing tropical and temperate regions, along with both developing and developed countries. Among the 31 technology analyses drawn from 23 studies on CA adoption that form the basis of this literature review, 21 focus on the adoption of reduced tillage (refer to Table 3 in the Knowler and Bradshaw's (2007) paper) and three examine the adoption of intercropping and mulch, individually or in combination with the adoption of reduced tillage. Notably, no analysis addresses the adoption of crop species diversification, while five focus on the adoption of so-called “erosion control” practices. In addition, three studies look at the addition of organic inputs, the use of compost and input reductions. Despite the review primarily concentrating on no-till adoption and omitting the third pillar, a total of 170 drivers were identified as significantly influencing farmers’ CA adoption. Their research underscores the absence of universal factors that can uniformly explain CA adoption (Knowler and Bradshaw 2007). Furthermore, the observed results often exhibit contradictions across studies, meaning that certain factors demonstrate positive, negative, or null correlations depending on the study (Knowler and Bradshaw 2007).

The adoption of soil conservation practices adheres to the principle of cost-benefit analysis. Environmental considerations may not be the primary determining drivers in the initial stages of adoption; rather, socio-economic drivers, including cost reduction and escalating fuel prices, are propelling the shift of European farmers toward CA (Lahmar 2010). Additionally, knowledge is recognized as a critical factor throughout the evolutionary process of transition (Prager and Posthumus 2010). The costs and benefits determining the transition are not always easily quantifiable and are influenced by external factors as well as specific and personal characteristics of the farmers.

We characterized drivers of change for the transition as incentives and constraints that motivated farmers to transition to CA. These factors may function as either constraints or incentives depending on the context. Existing literature focuses on the factors that initiated soil conservation practices, yet there is a notable gap in addressing transition factors guiding the implementation of other practices and shaping the specific CA-types. Table 18 provides a list of the transition factors identified in the thirteen studies and categorized in the nine categories of Table 17.

Financial drivers encompass reduction of production costs, financial security of the operation, investment capacity, as well as the potential increase in yields. Regarding technical drivers, they are linked to tool availability and access, or pest management. Organizational drivers cover farm management (e.g., reducing working hours), farm characteristics (such as land area and ownership), as well as farmer attributes (e.g., complementary activities). Biophysical factors, such as climate, soil, and topography, also exert influence on the adoption of CA practices.

At the institutional level, policies, subsidies, or sanctions can play a crucial role in CA adoption. Knowledge, whether related to the benefits of CA or associated techniques, also plays an essential role in the implementation of conservation practices by farmers. Stakeholders also influence this transition, whether through knowledge-sharing or cost mutualization. Market access and market prices are also key elements that shape CA adoption. Finally, individual characteristics of the farmer, such as age, experience, gender, beliefs, etc., as well as values, represent cultural and social factors that exert a significant influence on the adoption of CA practices.

Table 18 Conservation Agriculture adoption factors organized by category

Author's legend: [1] Knowler and Bradshaw (2007), [2] Lahmar (2010), [3] Prager and Posthumus (2010), [4] Rodríguez-Entrena and Arriaza (2013), [5] Wauters and Mathijs (2014), [6] Carmona et al. (2015), [7] Knowler (2015), [8] Casagrande et al. (2016), [9] Vankeerberghen and Stassart (2016), [10] Cristofari et al. (2017), [11] Varia et al. (2017), [12] Bijttebier et al. (2018), [13] Serebrennikov et al. (2020).

Category	**Sub-category**	**Adoption factors**	**Authors**
Financial	Costs of production	Save on machinery, fuel, and labour	[1], [2], [5], [8], [9], [11]
	Financial security	Profitable farms; Insurance scheme	[1], [4], [7], [11], [13]
	Investments capacity	Capitals; Access to credit; Attractive interest rate	[1], [3], [5], [7]
	Yield	Improving yields	[1], [3], [8], [11]
Technical	Tool's availability and accessibility	Availability and accessibility of equipment and technology to implement CA practices	[1], [2], [3], [4], [5], [6]
	Pest management	Limiting weeds, pests, and diseases	[8]
Organizational	Farm management	Time devoted to the farm; Labor requirement and arrangements (e.g., hours of family labor); The flexibility of the farming system to adapt to an innovation; Improved timeliness of operations	[1], [2], [3], [4], [5], [9], [11]
	Farm characteristics	Large area or extension of the acreage; Land ownership	[1], [2], [3], [4], [5], [6], [7], [8], [9], [11], [12], [13]
	Farmer characteristics	Complementary activity and time requirements for other (agricultural) activities	[1]
Biophysical conditions	Climate, soil, and topography characteristics	Slope; Difficult-to-work soil; Soil texture (clay content); Soil erosion; Soil fertility; Rainfall; Temperature; Frost-days	[1], [2], [3], [4], [5], [7], [8], [9], [11]
Institutional	Policies	Inclusion of soil quality management on the European political agenda; FAO's recognition of CA; Issues of sustainable development associated with	[2], [3], [5], [7], [8], [9], [11], [13]

		the evolution of the Common Agricultural Policy (CAP); Policies for training; Support for farmers' initiatives; Incentives programs	
	Subsidies	Government financial incentives and subsidies; Cost compensation	[2], [3], [7], [11], [13]
	Penalties	Fines and penalties	[13]
Knowledge-related	Awareness or perception of environmental benefits of CA	Farmer’s overall environmental concern; Awareness or perception about soil erosion, soil degradation, soil quality, etc.; Perception of soil as ‘living’	[1], [3], [5], [7], [9]
	Knowledge regarding CA techniques	Availability of information; Awareness of conservation technologies; Research carried out; Readings; Education; Trainings	[1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [13]
Relationship with actors	Knowledge sharing	Ease of obtaining information about CA techniques by a neighbor acquaintance, or technical consultants; Interactions and networks; Collaboration; Co-production; Sharing of knowledge, experience, and results; Proximity to other CA farmers and pioneers; Farmer organizations	[1], [2],[4], [5], [7], [8], [11], [13]
	Costs pooling	Costs sharing through farmers’ cooperatives like machinery cooperatives; Collective investments	[2] [5], [6], [11]
Market-Related	Access	Access to the market and the possibility of promoting a new crop to diversify the rotation	[2], [3]
	Price	Input and output prices; Price variability	[1], [5], [7], [13]
Cultural and social	Farmer characteristics	Age; Education; Experience; Gender; Risk acceptance; Entrepreneurial skills; Trust in information and in authorities; Attitude toward change; Belief	[1], [3], [4], [5], [7], [8], [9], [11], [13]
	Social values	Preference for environmental protection; Fuel savings to reduce ecological footprints; The guarantee that the farming activity is continued	[2], [3], [4], [9], [13]

2.3. Farmers' process of change toward CA

As a reminder, the transition to CA involves the shift from one state of an agricultural system to a state of a type of CA. This transition is composed of a set of processes of change, i.e. a series of events that occur in succession over a period of time and lead to one or more changes in practices (Chantre and Cardona 2014).

This section aims to provide an overview of the processes of change identified in the transition to CA practices, based on the reviewed literature. The reviewed information has been organized into two stages that lead to the transition to CA. These stages correspond to two main processes of change: (i) the initiation to CA by challenging conventional tillage, and (ii) the diversification into various CA-types.

2.3.1. Initiation to CA by questioning conventional tillage

Prager and Posthumus (2010) suggest viewing the adoption of CA through three possible entry points. The first involves a voluntary adoption driven by personal motivations, the recognition of issues, or peer pressure. The second entry point entails an individual choosing to participate in an agro-environmental soil conservation program to receive compensation exceeding potential costs. Lastly, the third entry point exemplifies a scenario where an individual is compelled to comply with legislation to avoid consequences such as fines, loss of income, or detrimental effects on reputation.

Most studies focus on the transition from conventional agriculture to CA and summarize this transition by challenging traditional tillage and implementing reduced or no-till practices (e.g. Knowler and Bradshaw (2007); Vankeerberghen and Stassart (2016); Varia et al. (2017)). This initial stage of transitioning from conventional agriculture to CA has been the most extensively studied (e.g., Knowler and Bradshaw (2007), Lahmar (2010), Prager and Posthumus (2010), Cristofari et al. (2017) and Varia et al. (2017)). In instances such as observed in Spain, the transition from plow-based systems to CA may start with a reduction in soil tillage – a more easily implemented and consequently more widespread practice (Lahmar 2010).

Farmers implement a wide range of soil tillage reduction techniques, often by making home-made adaptations on existing equipment (Vankeerberghen and Stassart 2016).

Following this initial reduction in tillage, the adoption of no-till practices may ensue, combined with the implementation of the second pillar, which involves retaining a minimum of 30% of crop residues on the soil surface (Lahmar 2010). Farmers can also make further progress by adopting direct seeding – a more radical change in practice (Vankeerberghen and Stassart

2016). Throughout this process, Knowler and Bradshaw (2007) stress the need of chemical inputs as a substitute for conventional tillage.

2.3.2. Diversification into various CA-types

Once the questioning and reduction of tillage initiate, farmers transition to CA through a continuous process (Lahmar 2010) that goes beyond mere implementations of new practices but entails a comprehensive system overhaul accompanied by a shift in perception (Cristofari et al. 2017).

Vankeerberghen and Stassart (2016) conducted an in-depth exploration of the change in perception associated with CA. The shift in farmers' perception is attributed to viewing soil not merely as a "substrate" but as a "living" entity. This transformative shift, evolving over several years to decades, is linked to experience, experimentation, and the acquisition of new knowledge. Farmers practicing CA adopt an ecosystem-based approach to soil, emphasizing sustainable care for ecosystem services.

This new perception leads to a complete reorganization of the production system, moving from traditional mechanical and chemical management to an emphasis on soil fauna, residues, cover crops, and organic matter. For farmers embracing this ecosystem-based view, CA involves reduced tillage, diversified cover crops, and additional practices like new fertilization and pest control approaches.

2.3.3. From organic farming to organic CA

In Europe, it is not solely conventional farmers who choose to adopt CA. The study conducted by Casagrande et al. (2016) illustrates that some European organic farmers decide to embrace CA pillars primarily to preserve soil fertility. These farmers implement at least two of these practices: green manure, no-tillage and reduced tillage (cf. section 2.1 of Chapter 3).

Through a clustering on principal component analysis based on the ranking of motivations and problems carried out, Casagrande et al. (2016) identified three groups among European organic CA farmers that shared the same type of drivers for adoption CA. The identified groups include: (i) "soil conservationists" characterized by a strong motivation for soil preservation and minimizing environmental impacts, (ii) "agro-technically challenged farmers", primarily expressing agronomic problems and challenges rather than motivations, and (iii) "indifferent farmers", who either did not perceive specific problems in applying conservation practices or found the listed problems in the questionnaire to be inadequate.

The systemic rethinking is also evident in the transition to organic farming and particularly when organic farmers choose to implement soil conservation practices (Casagrande et al., 2016). The limited access to chemical inputs for organic farmers further motivates them to adopt integrated pest management strategies, where cover cropping, mulching, and extended crop rotations can play a significant role (Casagrande et al. 2016).

2.3.4. The never-ending story

The CA-type practiced by farmers is never frozen. Innovation adoption is inherently a dynamic process (Wauters and Mathijs 2014), necessitating continuous adjustment and permanent knowledge generation, upgrading, and sharing among stakeholders (Lahmar 2010). Some farmers do not intend, in the long term, to fully and completely practice the three pillars of CA (Varia et al. 2017). Others abandon conservation practices and revert to their traditional methods, usually due to changes in the initial incentives (Lahmar 2010; Varia et al. 2017).

In addition, the study by Bijttebier et al (2018) showed that, in arable farming in Belgium, a substantial share of plowing farmers indicated that they wanted to apply non-inversion tillage in the near future, while a proportion of farmers practicing no-till indicated that they would not be pursuing the practice.

According to the study of Vankeerberghen and Stassart (2016), CA represents a niche that emerges from the conventional regime and gradually distances itself, potentially detaching completely (an island) or remaining connected to the initial mainland by multiple links (a peninsula). A complete change in perception and the resulting reconfigurations of practices, leads to the island's detachment from the mainland, which increases the irreversibility of the transition (Vankeerberghen and Stassart 2016). However, this principle of insularization has not gained momentum.

In this literature search, we did not find any analyses of the processes of change in farmers' CA practices at the pillar level and based on the diversity of CA-types.

3. Material and methods

3.1. Study area

Our study area focuses on arable land in Wallonia, Southern Belgium. The agricultural area comprises 738,927 hectares (SPW 2023a), accounting for 40% of the Walloon Region (Antier et al. 2019). One out of every eight Walloon agricultural hectares is dedicated to organic farming, primarily in the form of grasslands (Apaq-W and Biowallonie 2023).

Wallonia comprises ten distinct agricultural regions that are characterized by their soil, geographic, and climatic features: Sandy Loam, Loam, Condroz, Campine Hennuyère, Herbagère, Fagne, Famenne, Haute Ardenne, Ardenne, and Jurassic Regions (Goidts 2009). In Belgium, these agricultural regions are commonly used as a reference for the study of agricultural systems (Chartin et al. 2017).

CA began to take root in Wallonia during the 1980s when a handful of pioneers initiated a shift away from traditional plowing practices (Vankeerberghen and Stassart 2016). This marked the inception of a cognitive transformation in how soil was perceived, eventually culminating in the integration of the other two key pillars (Vankeerberghen and Stassart 2016). Presently, there are 191 CA farmers in the Walloon region (cf. Chapter 4).

3.2. Sampling

Since the objective was to gather a variety of experiences from Walloon farmers practicing CA, a purposive sampling approach was employed. This means that farmers were deliberately selected to maximize the inclusivity of the sample. 48 CA farmers were interviewed, and their selection was based on two main criteria.

First, the selection of farmers had to cover a diversity of parameters. This encompassed the pedo-climatic context, involving farmers from various agricultural regions. Certification was also considered, with a mix of both organic and non-certified CA farmers included in the selection. Furthermore, the chosen farmers were involved in different production systems, encompassing those engaged in arable farming both with and without livestock (excluding permanent crops).

Secondly, farmers had to possess sufficient experience in CA. Since the transition from one phase to another took several years (Chantre and Cardona 2014), we specifically chose farmers with at least five years of experience to ensure that their CA adoption process was sufficiently advanced, and they had gained a substantial perspective on their transition. This also ensured that their practices were well established for categorization. This sample was therefore not representative of beginning CA farmers. However, due to the limited number of CA farmers in the Famenne, Ardenne, and Haute Ardenne regions, we had to relax this criterion to include at least two farmers per region. As a result, five farmers in the sample had less than five years of experience in CA or organic CA.

3.3. Semi-directed interviews

We designed a qualitative study based on semi-directed interviews. This approach has been mobilized to study and compare drivers of change for the transition to CA and future changes in practices within the different

CA-types. The interviews were carried out from November 2020 to March 2021.

The questionnaire, conducted in French and formulated as open-ended questions (cf. Appendix A), started with a range of questions aimed at outlining farmers' profiles (career path, arable area, livestock, organic certification). Secondly, farmers were asked to define CA and to explain their drivers of changes behind their transition to CA practices. Thirdly, the farmers described one of their CA crop sequences they practice most often or on the largest land area, forming the basis for classifying their practices into a CA-type (cf. Chapter 4 and the following section 3.4.). Lastly, farmers detailed the changes in practices they wish to implement or intend to implement. The questionnaire took about two hours to be answered.

3.4. Categorization into CA-types

The CA practices of these farmers were categorized using a classification method based on the intersection of hierarchical classification and archetypal analysis (see the Chapter 4 or Ferdinand and Baret (2024) for details). This categorization was carried out based on fifteen variables, five per pillar:

1) The first pillar (minimum tillage) is defined by: (i) the frequency of tillage operations (named "Wheel Traffic"), (ii) the proportion of seeding operations compared to other tillage operations ("Seeding"), (iii) the frequency of use of powered tools ("Powered"), (iv) the frequency of use of plowing tools ("Plowing") and (v) the plowing depth ("Plowing Depth").
2) The second pillar (maximum soil cover) is defined by: (i) the number of days the soil is covered by dead or living mulch ("Total Cover"), (ii) the cover produced by living mulch only (i.e., annual crops, temporary grassland or cover crops) ("Living Cover"), (iii) the cover produced by temporary grassland ("Grassland Cover"), (iv) the soil cover during the erosion risk period ("ERP Cover"), and (v) the proportion of days of soil covered by spring crops during the ERP ("Spring Crops ERP Cover").
3) The third pillar (maximum crop diversification) is defined by: (i) the total number of different species grown (i.e., annual crops, temporary grassland, and cover crops) ("Total Species"), (ii) the number of different short-term income crops (i.e., annual crops (A) and temporary grassland (T)) ("A+T Species"), (iii) the crop associations[14] in A and T ("A+T Associations"), (iv) the mix of

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[14] Two or more crop species planted in the same plot simultaneously.

varieties in A and T (“A+T Mixes”), and (v) the number of tillage-intensive crops[15] (“Tillage-intensive Crops”).

This classification identified five distinct CA-types in Wallonia: three types called “reference”, bringing together farmers with extreme and salient practices, and two “intermediate” types, where farmers practice a form of CA straddling several reference types.

The reference CA-types are labeled based on three explanatory factors: the presence or absence of temporary grassland in the crop sequence (indicated by “G” for grassland or “C” for cash crops), the proportion of tillage-intensive crops (denoted by “I” for tillage-intensive crops or “E” for tillage-extensive crops), and organic certification status (“O” for organic certification, “N” for non-organic, and “M” for a mix of farmers with and without organic certification). The designated reference CA-types are named CIO, GEM, and CIN: CIO represents organic farmers with a significant proportion of cash tillage-intensive crops; CIN designates non-organic farmers with a substantial proportion of cash tillage-intensive crops, and GEM characterizes farmers, whether organic or non-organic, with tillage-extensive crops and temporary grassland in their crop sequence. Ig1 and Ig2 are not labeled, as they lack well-defined characteristics, residing as intermediate types between the reference categories. Ig1 typically features a high frequency and depth of plowing, a significant proportion of tillage-intensive crops and, for some farmers, temporary grassland in their crop sequence. Ig2 is characterized by a substantial proportion of tillage-extensive crops and the absence of grassland. Further details on the characteristics of practices within the pillars for each CA-type are available in Table 10 of Chapter 4.

3.5. Data analysis

During data preparation, we excluded all farmers who were not classified into a CA-type. The interviews were audio-recorded and integrally transcribed. The content of the resulting scripts was then analyzed using the NVivo qualitative analysis software. This software allowed all the information gathered during the interviews to be organized and grouped by theme. In practice, the selected themes are represented in the form of “nodes”, each denoting a specific highlighted theme. The tool helped to count the number of occurrences of specific concepts in each node. Three major nodes were created.

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[15] We have defined tillage-intensive crops as spring-sown crops requiring a deeper soil preparation, a thin seedbed and/or can degrade the soil structure due to late harvesting. In Wallonia, these crops include beet, chicory, potatoes, carrots, onions, maize, vegetables such as peas, beans, etc. In contrast, tillage-extensive crops include cereals (other than maize), meslin, rape, flax, etc.

The first node focused on the drivers of change for the transition to CA. These drivers were categorized into sub-nodes aligned with predefined categories from the theoretical framework (Table 17), while also enriched with interview-derived insights in an iterative process. Once classified, these drivers were analyzed based on the two main processes of change (cf. section 2.3.): (i) the initiation of CA by challenging the conventional soil tillage, and (ii) the diversification of practices toward a specific CA-type. Regarding the initiation phase characterized by the questioning of conventional tillage, a spectrum of practices and techniques emerged, influenced by the varied starting states of agricultural systems (e.g., conventional or organic). The term “simplified cultivation techniques” (SCT) was used to describe the reduction of soil tillage. SCT includes a diverse array of cultivation methods such as loosening and subsoiling operations, pseudo-plowing, shallow tillage, and strip tillage.

To analyze the evolution of the CA practices (the 2nd aim of the chapter), we created two nodes, one addressing the level of change in practices within the pillars of CA (inspired by the fifteen typology variables described in section 3.4.), and the other relating to the status of practice evolution (stable, change to come, desired change but challenging).

Simultaneously, each farmer interview, transcribed into a file, was assigned to a CA-type (cf. section 3.4.). This categorization enabled discourse analysis based on whether a farmer belonged to a specific CA-type, facilitated by the matrix query tool in the NVivo software.

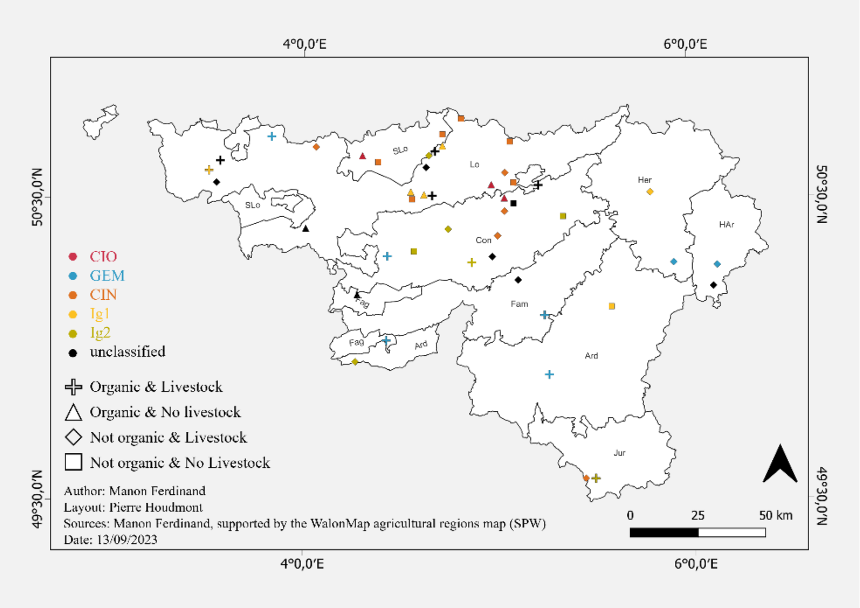
4. Results

4.1. Sample characteristics

Among the 48 surveyed farmers, the practices of 34 farmers have been categorized into five CA-types: three farmers in CIO, seven in GEM, eleven in CIN, six in Ig1 and seven in Ig2 (cf. section 3.4.). The analysis focuses on these 34 farmers, 71% of whom are located in the agricultural regions of northern Wallonia: Sandy-loam (SLo), Loam (Lo), or Condroz (Con) (Figure 28).

41% of these farmers are under organic certification and 56% own livestock (Table 19). The average agricultural areas vary from 119 hectares for GEM farmers to 208 hectares for Ig1 farmers. The average age of farmers remains relatively constant across groups, ranging between 45 and 50 years. Farmers generally took over farm management in the 1990s and 2000s. The initiation of CA practices began on average in 2002 for CIO and CIN farmers, 2003 for GEM and Ig2 farmers, and 2009 for Ig1 farmers. For organic farmers, on average, the conversion to organic agriculture started in 2011 for Ig1, 2012 for CIO, 2013 for GEM, and 2017 for Ig2. On average, the initiation of Organic Conservation Agriculture

(OCA) practices started in 2013 for CIO, 2016 for Ig1, 2017 for Ig2, and 2018 for GEM farmers (see Appendix Q for details on farmers' characteristics).



Author: Manon Ferdinand
Layout: Pierre Houdmont
Sources: Manon Ferdinand, supported by the WalonMap agricultural regions map (SPW)
Date: 13/09/2023

Figure 28 Geographic distribution of Walloon CA-types on the map of agricultural regions

Legend: Sandy Loam (SLo), Loam (Lo), Condroz (Con), Herbagère (Her), Fagne (Fag), Famenne (Fam), Haute Ardenne (HAr), Ardenne (Ar) and Jurassic (Jur).

Table 19 Characteristics of surveyed farmers categorized into CA-types (mean ± standard deviation)

Legend: Intermediate groups (IgI and II), cash tillage-intensive crops organic farmers (CIO), cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with organic and non-organic farmers (GEM), Utilized agricultural area (UAA), Organic Farming (OF), Organic CA (OCA).

	CIO	**GEM**	**CIN**	**Ig1**	**Ig2**
Number of farmers	3	7	11	6	7
Organic certified	3	5	0	4	2
With livestock	0	7	5	2	5
UAA (ha)	178 ±107	119 ±52	204 ±170	208 ±185	156 ±67
Age (years)	Na	50 ±9	48 ±10	45 ±17	50 ±11
Farm takeover (year)	2014 ±3	1996 ±10	1993 ±9	2001 ±13	1992 ±10
Start of CA (year)	2002 ±3	2003 ±12	2002 ±6	2009 ±10	2003 ±12
Conversion to OF (year)	2012 ±4	2013 ±7	Na	2011 ±8	2017 ±3
Start of OCA (year)	2013 ±5	2018 ±2	Na	2016 ±3	2017

4.2. Drivers of change in transition toward CA

During the farmer surveys, a wide variety of drivers of change that prompted farmers to implement CA practices were identified (Table 20). The categories are presented in order of citation frequency among farmers. The three categories of drivers most often mentioned by farmers are (i) technical, (ii) biophysical conditions, and (iii) cultural and social. It is important to emphasize that it is not always straightforward to attribute a transition factor to a single category, as many factors are closely related to several of them.

Table 20 Drivers of change in transition toward CA, listed based on the number of farmers mentioning them.

Legend: Intermediate groups (IgI and II), cash tillage-intensive crops organic farmers (CIO), cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with organic and non-organic farmers (GEM).

Drivers of change	**CIO**	**GEM**	**CIN**	**Ig1**	**Ig2**	**Total**
Number of farmers	3	7	11	6	7	34
Technical						
Availability of suitable tools	2	5	3	3	5	18
Weed management	0	2	0	0	2	4
Crop regrowth management	1	0	1	1	0	3
Wild boar damage management	0	0	1	1	1	3

Biophysical conditions						
Soil	2	5	7	2	2	18
Climate	0	0	2	0	1	3
Topography	0	0	1	0	0	1
Cultural and social						
Values	3	3	3	2	2	13
Risk acceptance	3	1	3	0	3	10
Beliefs	0	0	3	1	0	4
Knowledge-related						
Technical knowledge	1	2	5	1	3	12
Benefit knowledge	1	1	4	2	2	10
Relationship with actors						
Sharing knowledge	0	2	3	1	2	8
Sharing tools	0	1	4	0	1	6
Interactions breeders - growers	0	0	1	1	1	3
Influence of the owners	0	0	0	2	0	2
Relations with businesses	1	0	1	0	0	2
Organizational						
Reduction of working hours	0	3	2	2	1	8
Market-related						
Market price	2	2	2	1	1	8
Financial						
Reduction of production costs	1	3	1	1	0	6
Profitable farm	0	0	0	0	1	1
Institutional, regulations						
Ecological Focus Areas (EFA)	0	0	1	2	0	3
Organic certification	1	1	0	0	0	2
Intermediate nitrate-trap crops, green manure	0	0	1	0	1	2

As explained in section 3.5, the drivers of change mentioned by farmers for the transition to CA were divided into two processes of change: (i) initiation of CA through the implementation of simplified cultivation techniques (SCT), or (ii) diversification of practices toward a specific CA-type. The French version of verbatim is provided in Appendix R.

4.2.1. Drivers of transition to simplified cultivation techniques

The sampling criteria implied that all farmers in the sample implemented SCT. This section presents the drivers cited by farmers for questioning conventional tillage and choosing for SCT as the first step in implementing CA.

Technical

In their discourse, farmers emphasized the necessity of suitable tools to minimize or eliminate plowing. At this stage of the transition process, the interviews showed that farmers are beginning to question conventional tillage by adapting the tools they already own.

Three farmers also cited wild boar damage as a driver for abandoning the plow, since plowing buries corn cobs in the soil and wild boars turn over the soil in search of these cobs.

Farmers with a high proportion of tillage-intensive crops (within the CIN, CIO and Ig1 types) were also motivated to reduce plowing to limit potato regrowth.

Biophysical conditions

Farmers cited several biophysical factors that led them to reevaluate their tillage practices, particularly the use of plow, with soil type, climate, and topography being significant drivers. Shallow, rocky, eroded, compacted, or clayey soils serve as constraints that prompt farmers to minimize plowing. Slopes and soils susceptible to drought also contribute as motivating factors. Regional variations in incentives were observed: compacted soils are frequently mentioned in the Loam region, erosion in the Sandy Loam region, and shallow soils with the presence of rocks are predominantly highlighted by Condroz farmers.

Cultural and social

The interviews highlighted that farmers who challenge conventional tillage practices and implement SCT must overcome a fear of risk and/or have a better risk acceptance.

[1] "The farmer is afraid of failing. He's afraid of doing less (yield) than the neighbor. I'm not." (31)

[2] "Routine... Well, I won't hide it, there are days when my stomach hurts (from stress). Because when you do things where you don't know the outcome, there are days when it's not easy. But so far, that (the risk) appeals to me more than not changing (my practices)." (36)

Additionally, some farmers stated that they take risks to prevent future generations from having to bear them.

[3] "I'm also doing it because I'm at the end of my career, and while I'm at it, since my children are interested in (taking over) the farm, I might as well take the risk of converting (to organic no-till) rather than them." (37)

Additionally, farmers are motivated by personal convictions that encourage them to reevaluate certain practices of the conventional system. We observed that the negative perception of plowing, whether due to its less satisfactory yields or the physical discomfort it can cause, such as the vibrations felt in the tractor, facilitates questioning this practice and promotes the adoption of SCT.

Knowledge-related

Farmers reported that awareness of the benefits of reduced tillage was a key driver. These encompass benefits related to enhanced soil structure, an awareness of soil erosion issues, along with advantages linked to improved water retention and increased organic matter content.

Moreover, insights obtained from interviews with farmers underscored the critical role of familiarity with reduced tillage methods in their transition process. This includes understanding of techniques such as SCT or no-till, as well as proficiency in the use of relevant tools.

Relationship with actors

Knowledge alone isn't sufficient; it needs to reach those interested. Farmers mentioned several forms of knowledge sharing, whether through interaction with other farmers, farm visits, training sessions, conferences highlighting the benefits of SCT and demonstrating implementation techniques. This transfer was also been achieved through videos or reading material, such as books or agricultural magazines, particularly those specifically devoted to SCT. In addition, the adoption of SCT was sometimes in response to requests from landowners, who wanted farm managers to cease plowing.

> *[4] « So, the owner said, « *farmer's first name*, this is the goal. Organic, no-till farming, I want to achieve this, okay? » I said, « Wow, to achieve that, we'll need resources, and it has to come from all sides. » She said, « It takes what it takes. ». » (5)*

Organizational

Several farmers have implemented SCT to reduce working hours. This incentive may stem from a desire to simplify work operations or a decrease in the available workforce due to retirement or illness of the older generation or a worker. Farmers noted that the retirement of a farm staff member provided an opportunity to re-evaluate practices due to the reduced workforce and implement new practices without the constraints imposed by their retired predecessors.

Financial

Farmers discussed a range of financial incentives influencing the adoption of SCT. The cost-saving cited benefits associated with SCT are manifold: reduced fuel expenses and tillage operations, leading to decreased labor requirements.

Additionally, one farmer emphasized that a sound financial position is essential to accept the potential for setbacks or low yields for a few years.

> *[5] « You have to tighten your belt for 2-3 years, financially, you know. » (37)*

Institutional

A farmer cited incentives such as subsidies for green manures left unturned before January 1st as a reason to cease spring plowing, as he deems it inappropriate to plow after January for spring crops.

4.2.2. Drivers of transition to CA-types

The objective here is to highlight the drivers that motivated farmers to implement new practices, complementary to SCT, to shape their CA-type.

Technical

After implementing the initial SCT, often by adapting existing tools, many farmers purchased new machinery, such as specialized tools or direct seeding drills. Additionally, crop association can be achieved through the purchase of specific seeders, enabling the sowing of different seeds (e.g., cereals and legumes). For some farmers, access to this specific equipment has been facilitated through machinery sharing with other stakeholders (see “Relationship with stakeholders” category below). Finally, some farmers have been able to reduce weeding by owning a seed sorter.

> *[6] « We still need tractors. We still need equipment, and maybe even more than before. But we have to work in harmony with nature. So, it’s really about buying or inventing equipment that is tailored to the goals we want to set. » (37)*

Weeds management has been cited as an incentive by GEM and Ig2 farmers. For GEM farmers (organic certified), the competitive combination of cereals and legumes has reduced weed presence, leading to a decrease in mechanical weed control. Temporary pastures were also highlighted for the same advantage of reducing weed stock and mechanical weed control. Ig2 farmers identified lengthening crop rotations to decrease winter cereals frequency and associated weed problems as tools for weed management.

Some GEM and Ig2 farmers highlighted the specific case of black grass as a constraint encouraging adoption. One GEM farmer mentioned using white clover as a permanent cover to address the issue of resistant black grass, as clover outcompetes black grass. An Ig2 farmer switched to direct seeding to minimize soil disturbance and prevent black grass seeds from germinating.

Cultural and social

Environmental and social values drive farmers to embrace additional pillars of CA or additional practices. Environmental values include enhancing nitrogen cycles, increasing organic matter levels, improving water retention, and fostering a more “living” soil. On the social front, stronger interaction with consumers through on-farm stores leads to reduced pesticide use (mentioned by an Ig2 farmer). A CIN farmer expressed a desire to promote local supply chains, influencing crop choices. Additionally, another Ig2 farmer shared a commitment to leave a better land for the next generation. A CIN farmer also emphasized the link to promote between no-till, selected crops, and livestock.

[7] « [...] here, I want to keep cattle because there really needs to be a connection with the soil and what it produces. In this region, forage has its place. And to capitalize on it, a ruminant is needed. » (10)

Knowledge-related

Farmers emphasized the importance of utilizing past experience and new knowledge to reevaluate farming practices. Specifically, they highlighted the value of low-volume techniques, sheep grazing, agroforestry, and agroecology. Regarding the benefits of CA, they mention improvements in soil quality and life, soil fauna, and the reduction of inputs, especially pesticides, to preserve soil life.

[8] « Well, that it is an evolution, it's quite a profound reflection. Agroforestry is a deep reflection. From one day to the next, you start with reduced tillage and all that. You don't see the importance of it. Yet, it's very important. It's the advent of a system. And you begin to master it well and understand that all these little sources of benefits for the land come together to create something fantastic in the end. » (31)

Relationship with actors

In addition to the channels previously mentioned by farmers to facilitate knowledge sharing among stakeholders and influence the adoption of SCT, they also emphasized the role of social media platforms (e.g., Facebook), and associated discussion groups (e.g., WhatsApp groups), in the implementation of CA practices. These platforms allow farmers to share their experiences, whether positive or negative, contributing to collective learning and the enhancement of agricultural practices. In addition, training sessions, conferences, farm visits, and readings also contribute to furthering reflections beyond SCT. YouTube serves as a valuable tool for virtual farm visits and accessing distant conferences.

Interviews with farmers also highlighted the role played by agricultural machinery cooperatives (CUMA in French) or farmers' institutes, as well as equipment rental, typically through the nonprofit organization Regenacterre, in tool sharing.

Interactions between livestock farmers and crop growers were also identified as influencing the adoption of one CA-type over another. A CIN farmer ceased straw-manure exchanges for several reasons: i) to leave straw on the field for better soil coverage, ii) because the exchange is time-consuming, involving fetching manure, composting it ideally to limit weed issues, and spreading it, and iii) because livestock farmers pick up bales when it rains, potentially causing ruts in the fields. Another farmer, Ig1, collaborates with a livestock farmer for sheep grazing on cover crops. The "Collège des producteurs" facilitates connections between livestock and crop farmers for this purpose. Grazing helps destroy cover crops, reducing soil tillage and herbicide use while maximizing cover crop value.

Like the adoption of SCT, landowners have motivated crop managers to further embrace CA practices, often to reduce the ecological footprint of the farm to obtain carbon certifications.

Relationships with businesses were also mentioned as affecting the choice of CA practices. Companies may impose constraints, encouraging farmers to adopt one form of CA over another. For instance, a CIO farmer collaborates with an industry pushing for tillage-intensive crop production, as the factory only guarantees a spot if the farmer commits to producing the requested vegetables every year. Additionally, farmers may have conflicting requirements with industries, prompting them to change crops and terminate contracts. For example, a CIN farmer grew tired of poorly executed potato harvests, leading him to end contracts and potato cultivation. Some CIN farmers also opted for flax and rapeseed crops to meet industry demands in proximity.

Organizational

During the interviews, some farmers expressed that a supplementary and time-consuming activity was an incentive for decreasing tillage operations and cultivating more easy-to-handle crops, i.e., tillage-extensive crops.

[9] « So, actually, since I started working outside, I have significantly reduced certain activities: I stopped growing sugar beets and potatoes. In 2011, I quit sugar beets when Europe reformed the sugar sector. And when the selling price dropped from 45 EUR per ton to 25. At that point, I considered that it was no longer interesting. And potatoes, I

stopped when I transitioned to organic farming because it didn't make sense to produce organic potatoes and have to sell them conventionally. You can't make it profitable. And now, I've stopped because I don't have the time. I needed to simplify. » (0)

Market-related

The differences among various CA-types become more apparent when considering market-related factors. This is because CA-types are categorized based on organic certification and crop sequences, and farmers' crop choices are strongly influenced by market access and prices.

According to GEM farmers:

1) The end of the sugar production quota system in Europe and the resulting price drop led these farmers to stop growing sugar beets;
2) When cereal prices were very low, while livestock feed was expensive, this encouraged these farmers to prioritize the establishment of grassland;
3) In the case of cereals, farmers turned to crops and varieties that align with their desired practices while ensuring satisfactory remuneration. For example, they opt for old varieties capable of mycorrhizal association, even if it results in lower yields, as this sector offers greater added value.

CIN farmers also emphasized that the low prices of winter barley prompted them to substitute it with wheat. This substitution led to an increase in the share of wheat in their crop sequence, resulting in a reduction of diversity.

CIO farmers were motivated to transition to organic practices by the organic market, offering better income. Additionally, the high demand for organic carrots also encouraged the production of this crop, involving more intensive tillage.

Regarding Ig1 farmers, some adjust the length of the alfalfa forage break based on market demand.

Lastly, Ig2 farmers modified their crop rotation to optimize costs. This includes discontinuing sugar beet cultivation due to high costs associated with pesticides and fertilizers, as well as introducing rapeseed, which is less expensive in terms of inputs and allows for a reduction in weed control costs.

Institutional

Various legal obligations have influenced the agricultural practices of farmers across different CA-types. One CIN farmer and two Ig1 farmers were encouraged to diversify their cover crops in response to legal obligations regarding Ecological Focus Areas (EFA).

The organic certification, which prohibits nitrogen application at certain times, prompted a GEM farmer to incorporate white clover into his crop sequence. A CIO farmer mentioned that organic certification requires him not to cultivate the same crop (wheat, in this case) simultaneously on his conventional and organic fields. To comply with these constraints, he was encouraged to implement crop associations to modify the crop category in his declarations.

Lastly, an Ig2 farmer shared that in 2012, he had to establish a cover crop after processing pea crops to prevent leaching. This experience prompted him to explore no-till seeding methods, thereby encouraging the adoption of direct seeding.

4.3. Future changes in CA practices in the CA-types

The following section examines the evolution of different CA-types, specifically the willingness or plans of farmers to modify their CA practices and how these practices will be modified. Using the framework of farmers' practice change processes, this section analyses whether farmers' change processes are directed toward an increase, stabilization, or reduction of CA practices within their cropping system.

When asked about their intentions regarding practice modifications in the coming years, a majority (68%) of farmers express the intention to do so, indicating their desire to continue changing (Table 21).

Table 21 Status of farming practices among surveyed Walloon CA farmers
Explanatory notes: The term "Changing" indicates farmers with a clear desire or defined plans to change their practices. "Stable" signifies farmers who do not wish to change their practices. "No comment" refers to farmers who have not provided an opinion on the subject. Legend: Intermediate groups (IgI and II), 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).

Practices status	CIO	GEM	CIN	Ig1	Ig2	Total
Number of farmers	3	7	11	6	7	34
Changing	0	5	8	3	7	23
Stable	2	2	3	2	0	9
No comment	1	0	0	1	0	2

However, quantitative analysis has limitations. When presented with closed-ended questions, such as whether farmers intend to change their practices or not, respondents may feel compelled to provide binary responses. However, the reality is often more complex than a simple ‘yes’ or ‘no’ answer suggests. The use of qualitative analysis enables exploration of the intricacies of farmers’ perceptions and actions regarding changes in their practices associated with the fifteen variables used for categorization (Figure 29).

Farmers may interpret what constitutes a change in practice differently, which may result in them considering their practices stable, while the researcher perceives them as changing. Therefore, we will examine the concrete aspects of the evolution of practices among CA farmers by analyzing the practices associated with the fifteen variables used for categorization (Figure 29).

The changes in CA practices primarily focus on the first (minimum mechanical soil disturbance) and third (maximum crop species diversification) pillars, while farmers have demonstrated minimal intent to change practices associated with the second pillar (maximum soil organic cover).

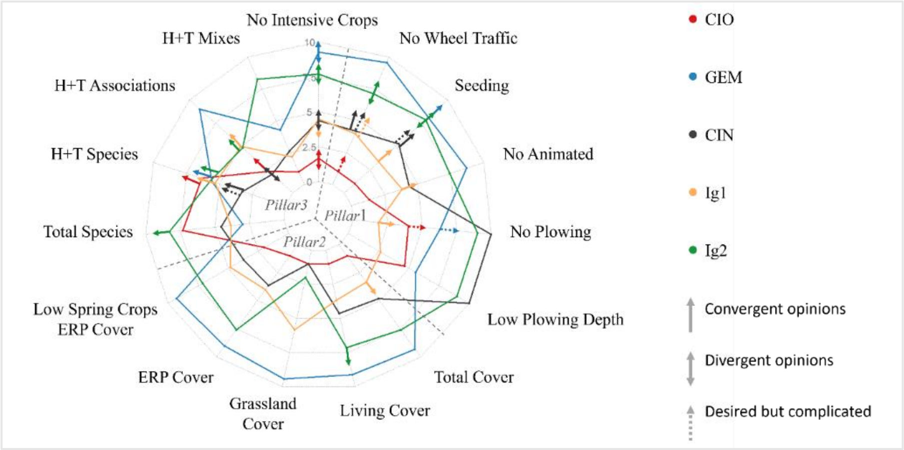


Figure 29 Changes in CA practices according to farmers’ belonging to a specific CA-type, based on radar charts showing average scores of the CA-types for the fifteen variables

Explanatory notes: Solid lines with a unidirectional arrow denote practice changes where farmers of the same CA-type agree, while bidirectional arrows illustrate divergent opinions among farmers of the same CA-type. Dashed arrows represent practice changes desired by farmers but challenging to implement. Legend: Intermediate groups (IgI and II), cash tillage-intensive crops organic farmers (CIO), cash tillage-intensive crops non-organic farmers (CIN), temporary grassland and tillage-extensive crops with organic and non-organic farmers (GEM), Erosion risk period (ERP), Annual crops (A), Temporary grassland (T).

CIO farmers (tillage-intensive crops, organic farmers) have not shown a specific desire to change practices (Table 21). These farmers highlight the challenges of reducing tillage in organic agriculture, whether for cultivating vegetable crops such as carrots and onions, or for managing weeds like black grass. However, farmers did mention an intention to lengthen their cropping sequence, some by introducing more vegetables, others by increasing the share of cereals. One farmer plans to start cultivating rapeseed in crop associations.

GEM farmers (temporary grassland and tillage-extensive crops, organic and non-organic farmers) have the desire or the project to further reduce tillage. One farmer will purchase a direct seed drill, and another will decrease the wheel traffic for tillage operations. Others have expressed their wish to reduce tillage, but livestock has been identified as a constraint. Indeed, (i) the destruction of temporary grassland is challenging without plowing, (ii) livestock encourages to maintain or increase the proportion of maize (classified as a tillage-intensive crop in tillage) in the crop sequence, and (iii) it is complicated to include non-harvested cover crops that compromise forage needs.

CIN farmers (tillage-intensive crops, non-organic farmers) are moving toward two distinct horizons:

1) Some aim to reduce tillage, increase the share of tillage-extensive crops such as sunflower and rapeseed, while promoting cereal-legume associations;
2) Others cannot or do not want to reduce tillage due to tillage-intensive crops, constraints imposed by industries, or the management of regrowth. They do also not wish to lengthen their rotations with less profitable crops (i.e., often tillage-extensive) and avoid associations to avoid complicating weed control operations.

All Ig1 farmers (tillage-intensive crops, some farmers have temporary grassland) intend to reduce their tillage, whether by investing in equipment such as a direct seed drill, adopting strip-till, replacing plowing with scalping, or eliminating combined seeders. Organic certification has been identified as a barrier to reduce tillage, as accepting the presence of weeds is challenging due to industrial requirements. Additionally, livestock hinders farmers' projects, as animals can compact the soil, potentially requiring more tillage. Nevertheless, agropastoral practices encourage the diversification of cover crops. Regarding rotations, farmers aim to decrease the share of tillage-intensive crops, substituting silage maize with crops like meslin, barley, or flax, and incorporating more crop associations.

All Ig2 farmers (tillage-extensive crops, no temporary grassland) intend to modify their practices. Two directions of change are observed:

1) The majority (5 out of 7) of these farmers plan to reduce tillage through direct seeding, decreased stubble plowing, and reduced use of powered tools. They aim to decrease tillage-intensive crops in their rotation and increase the share of tillage-extensive crops, particularly cereals. One farmer considers introducing more cover crops to reduce periods of uncovered soil, while another plans to generalize the use of associated and perennial cover crops in rapeseed cultivation.
2) Two farmers intend to maintain or increase their tillage. One farmer plans to stay in simplified cultivation techniques (SCT) and replace sugar beet with potatoes. Another farmer intends to stop direct seeding and return to no-till, by resuming the potato cultivation he had abandoned, to improve the farm's profitability and provide an income for his joining son.

5. Discussion

5.1. A diversity of drivers of change behind the diversity of CA practices

Prager and Posthumus (2010) propose three entry points for implementing CA by farmers: voluntary adoption, participation in agro-environmental soil conservation programs, and compliance with legislation to avoid penalties. Interviews with Walloon CA farmers show that they primarily transition to CA through voluntary adoption. Additionally, certain legal obligations (Ecological Focus Areas, organic certification, and green manure) have served as secondary drivers for the transition to CA. Soil conservation programs, although more recent, have been occasionally cited to receive compensation for already established practices, functioning more as incentives to maintain current practices or progress further. These programs have also been noted as drivers for landowners to prompt farm managers to implement conservation practices.

The transition to CA involves a series of processes of change (Chantre and Cardona 2014). For Walloon farmers with several years of experience in CA, this change process begins with questioning conventional tillage and adopting simplified cultivation techniques (SCT, or TCS in French) (Vankeerberghen and Stassart 2016). During this process, the change in the agricultural model is not deeply questioned, and farmers remain anchored in a productivity goal through the substitution of plowing with SCT. It is only afterwards that a more general questioning emerges, with a redesign of the system, fueled by the establishment of the other CA pillars (Vankeerberghen and Stassart 2016). This transition process is also illustrated in the French magazine “TCS”. In its early days, over 20 years ago, the magazine was dedicated to farmers practicing SCT and direct seeding, named “TCSistes” and “SDistes” in French. It now focuses more on soil conservation agriculture and targets farmers practicing CA, named “AC(S)istes” in French (F. Vanwindekens, personal communication, February 23, 2024).

There is a diversity of factors driving the transition to CA. No single driver of change has been identified that can be attributed to a single CA-type, and no CA-type appears to be the result of a particular combination of factors. While one might expect CA-types to group farmers motivated by similar incentives and constraints, it has been observed that the transition of farmers within the same CA-type was motivated by diverse incentives and constraints. As Verret et al. (2020) previously observed, the consequence of this is that the transfer of knowledge and experience becomes less straightforward. It would have facilitated agronomic guidance to have direct correlations between specific drivers of change and corresponding CA practices. Conversely, correlating CA practices with incentives and constraints would facilitate the adoption of specific CA-types at the policy level. However, one driver of change emerged as strongly associated with CA-types: the link to the market, and in particular the link to market access and prices. A strong correlation was demonstrated between the CA-types and the incentives mentioned by farmers for this driver. This correlation is expected, given that CA-types are distinguished based on organic certification and crop sequences, while farmers’ crop selection is heavily influenced by market access and pricing considerations.

All categories of drivers of change presented in Table 18 were raised during the interviews. However, within the subcategories, several differences were observed compared to the existing literature.

Farmers have rarely cited economic and political incentives as significant drivers for adopting SCT and CA practices. Interviews have not emphasized the role of investment capacity, such as access to credit and existing capital, while legislative measures, subsidies, or penalties have been particularly undermentioned as drivers of change (see Table 20). Despite the usual significant impact of the political and economic context on the adoption of specific agricultural practices (Chantre and Cardona 2014), several reasons may account for this observed difference in this study. Firstly, the limited mention of these categories by farmers could be attributed to the sensitive nature of the “economic” topic or the tendency of farmers to consider their favorable financial situation for granted, leading them to pay less attention to it despite its role in the transition. Similarly, the political environment (at least during the interviews in 2020/21) can be perceived as unchangeable. Additionally, it is crucial to consider the influence of the categorization of drivers of change. Indeed, certain drivers, such as risk acceptability (classified here under cultural and social drivers) or market linkage, could be regarded as economic and political attributes (Prager and Posthumus 2010).

The characteristics of farmers (such as age and experience) were not explicitly mentioned, and neither was the size of the farms. However, it is noteworthy that CA farms, regardless of the CA-type, exceed the average size of Walloon specialized arable farms, standing at 71.6 hectares (SPW 2023b). Variability in structural variables within the same CA-type is observed for both utilized agricultural area (UAA) and the age and experience of farmers in CA and OCA. This suggests that the CA-type to which farmers' activities converge is not contingent on these characteristics.

In terms of interactions with stakeholders, the interviews highlighted the influence of specific interactions on the transition to CA, such as interactions between livestock breeders and cultivators, with landowners, and with companies that purchase agricultural products.

5.2. The dynamic evolution of CA practices

The majority of surveyed farmers have reported that their CA practices are still evolving, as shown in Table 21. This observation is unsurprising given the dynamic nature of the drivers of change over time (Vanwindekens et al. 2013). Chantre and Cardona (2014) have also previously observed that farmers who have already changed their practices would naturally continue to refine them. However, in contrast to Chantre and Cardona's (2014) findings, nine surveyed farmers reported that their current practices are stable (cf. Table 21).

Drivers of change that motivated farmers to implement SCT and CA do not necessarily determine the course of future decisions and the type and intensity of practices implemented. Farmers belonging to a CA-type do not necessarily share desires or plans for changing their CA practices. It is not surprising that if different drivers have led farmers to practice the same CA-type, farmers grouped within a particular CA-type will continue to evolve toward different practices, motivated by their unique drivers, thereby leading to changes in CA-types. For CIO farmers, the common trend lies in their willingness to extend their crop sequence, whether through the implementation of tillage-intensive or tillage-extensive crops. GEM and Ig1 farmers show a desire to apply more conservation practices. The CIN and Ig2 farmers stand out for their division into two directions: some aim to reduce tillage and increase the proportion of tillage-extensive crops and crop associations, while others aim to maintain or increase the proportion of tillage-intensive crops, with the maintenance or increase of tillage.

Changes in practices mentioned by farmers relate mostly to tillage (first pillar of CA) and crop sequence (third pillar). Conversely, farmers made very few references to changes in soil organic cover (second pillar). This can be explained either because it is more challenging for farmers to deliberately influence this pillar, or because within the established cropping sequences, they perceive no room for improvement within this pillar.

Most of the practice changes mentioned by farmers point toward practices more closely linked to the pillars of CA. However, it is noteworthy that none of the farmers mentioned an imminent change in the use of mixed varieties or temporary grassland. These were already the practices least used by Walloon CA farmers (cf. results of Chapter 4). One farmer pointed out that cereals are not financially attractive enough to produce varietal mixtures.

The increase in tillage-intensive crops was the only change in practice mentioned by farmers that resulted in a move away from standard CA practices. Currently, technical processes within the industry, including seeding, harvesting, and seed sorting, are not perfectly tailored to CA practices such as reduced tillage, retention of crop residues, as well as cereal-legume intercropping (Lamé et al. 2015). The agricultural production has limited means to impose its specifications onto the industry (Meynard et al. 2017). Nonetheless, some farmers in the sample highlighted that they had successfully pressured downstream stakeholders to continue implementing CA practices within these crops, similar to what CA farmers in Picardy have achieved (Meynard et al. 2017). Another issue is the economic optimization logic and the pursuit of economic growth, which hinder the long-term maintenance of robust CA practices. Direct seeding appears to plateau in its returns, reaching a point where, to earn more, it seems necessary to cultivate crops that make it more difficult to optimize CA principles. Indeed, crops that are better suited to CA practices, such as cereals, often have lower economic interest. Consequently, farmers aim to maintain or increase the proportion of tillage-intensive crops in their crop rotations to sustain or boost farm profitability. Therefore, the higher profitability of tillage-intensive crops compared to extensive ones acts as a barrier to reducing tillage and, more broadly, to the development of certain CA-types. Although economics were not extensively cited as a driving force for adopting SCT and CA practices, it appears to be a crucial factor for their maintenance. Verret et al. (2020) had previously emphasized that economics constituted the primary obstacle to crop diversification. However, policies can influence the revenues generated by these more soil-impacting crops, in order to favor extensive tillage-based crops.

Several practices have been identified by farmers as both barriers and drivers to the CA transition. Through the implementation of temporary pastures or forage breaks, livestock farming has demonstrated its potential to increase soil cover and reduce soil tillage. However, the destruction of temporary pastures typically requires intensive tillage, such as plowing. Additionally, livestock farming is often associated with the production of forage maize, a tillage-intensive crop. Indeed, the need for forage production competes with the cultivation of cover crops.

Organic certification and the cultivation of tillage-intensive crops serve as tools to enhance the diversification of cultivated species (the third pillar of CA) but act as impediments to reducing tillage (the first pillar) and soil cover (the second pillar).

The control of weeds and the management of crop residues are both barriers to reducing tillage and, at the same time, are cited by farmers as incentives to cease plowing and maximize diversification (by crop associations) and soil cover (by temporary pastures or permanent cover crops).

5.3. Methodological limitations

Before concluding this chapter, it is important to identify the methodological limitations of the approach that has been adopted.

Unlike the study by Chantre and Cardona (2014) our analysis did not track the evolution of transition factors over time. The interviews conducted provided insights into specific points of change rather than a continuous, step-by-step progression. These points of change were identified primarily at three distinct time points: (i) the transition to SCT, (ii) the transition to current CA-types, and (iii) anticipated future practice changes. This method relies on predictions and assumptions about what farmers intend or wish to achieve in the coming years, with each farmer potentially having a unique perception of this time scale.

It would have been insightful to compare the practices before implementing SCT to the current CA practices, and to compare current CA practices to those envisioned after practice changes. Sequential analysis could have revealed the durations of processes of change and whether they were continuous or built on radical changes (Mawois et al. 2019). This approach would enhance understanding on the agronomic logic behind CA practice implementation, i.e., coherence between practices (cf. chapter 4) and farmers' motivations (cf. chapter 6) (Lamé et al. 2015).

Furthermore, farmers could have been asked to categorize drivers by importance to assess their significance beyond mere mention frequency.

We collaborated with farmers to address the study objectives: exploring the drivers of change leading to the adoption of specific CA practices and understanding farmers' intentions regarding future CA practice changes. Farmers offer diverse perspectives and serve as a valuable starting point for such inquiries, compared to other actors in the agri-food system who may extend beyond the agricultural sector's boundaries. However, not all farmers are necessarily comfortable with the exercise of anticipating and drawing forward-looking scenarios.

To our knowledge, we are the first to analyze drivers of change toward CA after the practices have been implemented for several years. This strength also poses a challenge. We aimed to understand the transition process of farmers with well-established CA practices, but this implies that their shift toward CA took place several years ago. Therefore, this study relies on farmers' memories, which may introduce biases due to subjectivity and retrospective reconstruction of events (Chantre and Cardona 2014). The temporal gap between the initiation of the first soil conservation practices and the inquiry into transition factors may potentially result in overlooking elements that played a crucial role in the early stages of the transition process. Ideally, it would have been preferable to chronologically document all decisions, factors influencing the transition, and practices implemented from the initiation of soil conservation practices until the present. Among the transition factors presented here, certain incentives and constraints may no longer be relevant, while others may have emerged recently.

In addition, the changes mentioned by farmers related to desired or planned modifications for the upcoming cropping seasons, within a relatively short temporal scale—likely too brief to discern a significant shift in practices. This time frame may not capture a change potent enough to signify a farmer's transition from one CA-type to another.

Initially, we hypothesized that the CA-type practiced would be the primary driver of incentives for CA practices and future changes. However, it seems that other factors, such as individual farmer characteristics, geographical factors, or external influences stemming from the environmental, social, or cultural context, may play a more significant role in farmers' transition.

This study did not address the factors encountered by farmers that potentially hindered their transition to CA. For instance, while we were surprised by the limited mention of financial drivers by farmers, it is possible that financial considerations served more as a barrier than an incentive to transition. For example, constraints such as limited financial flexibility to innovate and initiate new practices, or the impact of crop profitability on rotation choices, may have played a significant role.

Changes in practices were confined to those related to the three pillars of CA. Consequently, when farmers referred to external modifications, such as organic certification, these changes were not incorporated and do not manifest on the radar charts. However, these modifications can indirectly influence the pillars of CA. For instance, organic certification may, in certain instances, demand increased soil preparation and result in diminished ground coverage.

6. Conclusion and perspectives

Our study investigated the link between farmers' belonging to a specific CA-type and the drivers of change that led farmers to engage in this CA-type. We found that, when analyzing farmers' drivers after several years of CA adoption, their drivers of change can be divided into two processes of change: those related to the implementation of simplified cultivation techniques and those associated with the adoption of CA as a whole. Additionally, we have observed that there is a diversity of factors driving the transition to CA, and this diversity does not appear to be related to the CA-type practices adopted, with the exception of market-related incentives.

The study also revealed that the majority of surveyed farmers have reported that their CA practices are still changing, due to the dynamic nature of the drivers of change over time. Within the same CA-types, CA practices are maintained, increased or decreased. Changes in CA practices are typically manifested through reduced tillage or increased diversity of cultivated species. When farmers mention a setback with regard to CA pillars, it is often due to the inclusion of tillage-intensive crops in the rotation. These crops pose challenges in reconciling the pillars of CA with the requirements of the agri-food industries and are typically more profitable and thus more appealing to cultivate.

This study presented the first analysis of CA practices as a long-term change process on farms, with a comparative analysis of five CA-types. The link between drivers of change and CA-types could not be established directly, making it difficult to simplify the message for users in the field. However, we believe that the findings, notably the radar chart, offer valuable insights for farmers to visualize their CA practices and assess the potential consequences of practice changes on the three pillars of CA.

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Chapter 7 General Discussion

In this thesis, we argued that not one, but three elephants were occupying the space of thinking around CA:

1) The definitions of CA and its three pillars exhibit discrepancies across scientific literature, resulting in a lack of clarity that prevented its consistent application.
2) A diversity of CA practices exists between distinct geographic areas and within the same region, but this diversity was excluded from CA analysis.
3) The integration of this diversity of CA practices, likely to result in diverse outcomes and potential benefits, was not considered in the CA assessment.

This thesis has identified the diversity of CA practices on a regional scale and assessed how this diversity influences CA impacts.

In this chapter, we review the strengths and weaknesses of our approach, summarize our main findings, and provide some perspectives.

To facilitate reading, we organize our general discussion according to three reading axes and further divide each section into five parts. The three reading axes are: (i) reflections on the methodology, (ii) the results obtained and the added value of this work, and (iii) the implications of carrying out a interdisciplinary work involving farmers and spanning the disciplines of agronomy, soil science, and social science. The five main parts revolve around (i) the definition of CA, (ii) the diversity of CA practices, (iii) the categorization of this diversity, the repercussions of this categorization on (iv) the assessment of the impact of CA-types on soil quality indicators, and (v) the transition processes of farmers practicing CA according to their CA-type.

1. The thesis anatomy

1.1. The philosophy

The implementation of this thesis, from its objectives to its methods and the sought-after added value, has been guided by a general philosophy.

Our goal was to fill the scientific gaps mentioned earlier while also addressing the concerns of stakeholders on the ground. We intended to generate interest among these stakeholders while providing results that they could mobilized. In this regard, we chose to root ourselves in the complexity of the fields.

Furthermore, our strategic orientation was marked by the choice to tame three elephants instead of one: (i) an ambiguous definition of CA, (ii) an understudied diversity of CA practices, and (iii) the hidden diversity of CA outcomes behind the diversity of practices. To achieve this, we (i) proposed an operational definition of CA, (ii) studied the diversity of CA practices, and (iii) analyzed the impact of this diversity on soil quality indicators and farmers' transition processes.

This deliberate choice reflects our desire to prioritize comprehensive coverage of these three aspects rather than delving into the details of each theme. We thus opted for an approach that allowed us to survey the elephants to grasp their magnitude but did not afford us sufficient time to delve into each facet. This comprehensive approach enriched our understanding of the CA system while providing a holistic perspective on the challenges and opportunities inherent to CA.

1.2. The body

This thesis can be conceived as an organic whole that forms a continuous and meaningful entity.

Firstly, the diversity of practices can be likened to the prominent element of the thesis, the head, as it guided the chosen direction and influenced the decisions made. Although the diversity of CA practices has been discussed in the scientific literature for at least a decade (Lahmar 2010; Scopel et al. 2013), the consideration of diversity within studies remains generally overlooked. The three pillars of CA are seldom taken into account (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)), with CA often reduced to no-till, while the diversity of the application of each pillar is also rarely explored. Several reasons may explain why this diversity remains obscured in the scientific landscape, despite its obvious importance which makes it one of the three elephants in the thesis. Firstly, we argue that CA is often reduced to the first pillar because it is the easiest to characterize, quantify, and binary categorize (no-till vs. deep plowing). This pillar serves as a focal point, as it is linked to practices that are relatively simple to understand, visualize, and test in the field. In contrast, considering the three pillars and their inherent diversity complicates the concept of CA, making it less straightforward and, therefore, more challenging to grasp.

Furthermore, examining the three pillars and their diversities requires a precise understanding of practices that differentiate them, involving a clear and operational definition of CA in the field. However, the terms used to define the pillars of CA are vague, as noted by Sumberg and Giller (2022), and the sources used as references to define CA do not provide consistent indications (e.g., FAO (2019), FAO (2023a), Kassam et al. (2009), Vanlauwe et al. (2014)). Currently, the lack of consensus within scientific literature regarding the definition of CA and each of its pillars hinders this examination. This is another of the thesis's three elephants. Based on these observations, a research question arises: what is the diversity of practices in CA, and how can it be identified and characterized appropriately?

The categorization of CA practices through a typology constitutes the heart, the driving force of this thesis, as it enables the identification and classification of the diversity of practices while facilitating their in-depth study. The typology of practices represents the pivotal point of the thesis, a converging point that we had to overcome to address the research questions.

Lastly, the study of the integration of the diversity of CA practices can be seen as forming the two legs of this thesis. Although CA is often mentioned as a solution to various challenges, such as food security and climate change (Kassam 2022), or singled out for its reliance on glyphosate (Reboud et al. 2017; Antier et al. 2020), these discussions often overlook the diversity of practices within CA that are nevertheless likely to produce different outcomes and benefits (Cristofari et al. 2017, 2018). This is the third elephant in the room. We have integrated this diversity into the assessment of the impacts of CA by comparing CA-types on soil quality indicators and the transition processes of CA farmers.

2. The methodology used

2.1. To define the CA system

To develop an operational definition of CA, we synthesized various publications from the FAO on CA, as the FAO was the first organization to define CA in 1998 (Kassam 2022), along with reference articles that address the shortcomings of the FAO definitions. This approach has enabled us to construct a definition that can be applied in the field on a regional scale. We believe that we are among the first to challenge existing definitions of CA, to reassess what was taken for granted, to outline the limitations of current definitions, and to explicitly address the key issues hindering the establishment of an operational definition of CA.

Although our method is designed to be rigorous, it relies on arbitrary choices. To improve the analysis, it may be beneficial to extend the selection period of articles and to revise or expand the criteria for defining CA reference articles.

2.2. To explore the diversity of CA practices

To explore the diversity of practices in CA, we examined the practices implemented by farmers engaged in CA. Investigating practices within the three pillars of CA entails considering a complex combination of practices. Since the diversity of these practices remains unknown, it would be impossible to identify all existing combinations. Therefore, conducting on-site visits proved imperative to discover the various combinations of practices in use and focus on these specific configurations.

In pursuit of methodological rigor, a protocol was devised to enforce standardized data collection procedures across a heterogeneous sample of farmers. The interrogation framework was intentionally configured in an open-ended format, affording flexibility to accommodate the idiosyncrasies and diverse operational paradigms inherent in each farmer’s practices.

Prior to its operational deployment, the questionnaire underwent scrutiny by diverse stakeholders to validate the pertinence of the inquiries. This process served the dual purpose of affirming that specific information could exclusively be garnered through direct engagement with the farmers and corroborating the participants’ comprehension of the posed questions. Additionally, the pre-application assessment verified the farmers’ possession of requisite knowledge, obviating the inclusion of queries that might exceed the temporal constraints of the interview.

Moreover, this preparatory phase assumed paramount importance by discerning which pieces of information require a more delicate approach and should only be explored after establishing a trusting relationship with the farmers.

Information collection could not be conducted through an online questionnaire for several reasons. Firstly, online questionnaires require maximum conciseness, and the topic addressed here is too complex to conform to such a constraint. Secondly, the need for a visual representation of the farmer’s cropping sequence necessitated the deployment of a board (here coming from the Réseau CIVAM du Haut-Bocage). This board aimed to verify communication and understanding of information by visually illustrating the farmer's statements. Thirdly, the need to adapt to the diversity of each farmer's practices rendered online questionnaires inadequate due to their lower flexibility. Finally, online questionnaires typically result in low response rates and complicate the selection of interviewees.

2.3. To create a typology of CA practices

To capture the diversity of practices within the three pillars, the use of a typology proved essential to identify and facilitate the subsequent analysis of this diversity, as already noted by Fouillet et al. (2023).

Starting from the operational definition of CA and its adaptation to the Walloon context, questions were developed within the framework of interviews to gather data that would later be transformed into variables and subjected to categorization. We deliberately chose to assign equal weight to each of the three pillars of CA. According to data from literature reviews, this decision is based on the lack of justification for prioritizing one of these pillars over the others (cf. the first question resolved in section 3.2. of Chapter 2). However, depending on the geographical context, implementing one pillar may be more complex than another, which could justify a hierarchy. For example, in a situation where farmers face significant challenges in diversifying their cropping sequences, assigning the same level of discrimination to the third pillar as to the other two pillars in the typology would be inappropriate.

The uniform weighting of each pillar was easily accomplished here by translating each pillar into five variables, which were then standardized. It would also have been conceivable to use a different number of variables and weight them in a way that maintains a balance between the pillars.

Regarding the first pillar, soil tillage intensity could have been assessed using the Soil Tillage Intensity Rating (STIR) index, as in the study by Champagne et al. (2019). This index comprises four components: operational speed of tillage equipment, tillage type, tillage depth, and percent of the soil surface area disturbed (Lightle 2020). However, STIR was not employed in this study because two out of the four elements of the model, operational speed and the proportion of soil disturbed, were not considered. The former was excluded because operational speed is not part of the definition of the first pillar of CA. The latter was omitted because strip tillage and direct seeding is uncommon in Wallonia. Additionally, collecting data for these two components would have significantly increased the data collection burden and is not available for all farmers surveyed.

Some variables exhibit notable correlations, such as tillage and soil cover, or the correlation between soil cover attributed to dead mulch and that attributed to living mulch. In the context of Principal Component Analysis

(PCA), these correlations are acceptable, as correlations between variables are necessary for dimensionality reduction. In this case, no single variable took the lead over the others, and variables from each pillar contributed significantly to one of the first two dimensions of the PCA. In addition, the goal of the variables was also to convey information to the involved stakeholders. A strong correlation between two variables does not automatically imply that the information provided to stakeholders is redundant, justifying the retention of the two distinct variables.

We could have categorized the diversity of trajectories instead of practices, based on the evolution of farmers' practices over time, as demonstrated in the study by Fouillet et al. (2023). This study, published after our data collection, uses a methodology that, if applied to our research, would require a meticulous multi-year data collection process and a comprehensive characterization of each practice under the three pillars of CA. Like many studies, our investigation could have yielded richer insights if additional data were available. The robustness of scientific inquiry is often enhanced by the availability of more extensive datasets.

2.4. To compare soil quality of CA-types

Initially, our primary objective was to assess the adaptive capacity and mitigation potential of different CA-types in response to climate change.

In terms of adaptation, we wanted to assess the influence of CA-types on adaptation to erosive rainfall. The planned measures (such as collecting tanks in bounded erosion plots, Gerlach troughs, field splash cup, simple-ring method, etc. (Morgan 2005)) proved to be either insufficiently sensitive to the agricultural practices associated with the CA pillars, requiring several years of data collection for meaningful results, difficult to apply to a wide variety of practices, or too complex to be used on a large number of sites as part of a regional-scale implementation.

Regarding climate change mitigation, one of our goals was to evaluate soil carbon sequestration and/or emissions generated at farm level. However, a comprehensive assessment of the various methods, models and tools available (such as ClimAgri, INSPIA, COMET-Farm, CoolFarmTool, Adapt2climate.be, Cap'2Er, RothC, ARMOSA, etc.) demonstrated that they were insufficiently explicit and/or inappropriate for the desired objectives. Disagreement regarding the potential for carbon storage in soils and the emissions generated by agricultural practices is partially attributed to differences in methodology, leading to significant discrepancies in results depending on the model used (Jordon et al. 2024).

The evaluation of the impact of CA-types ultimately focused on soil quality, an aspect directly linked to the initial objectives of CA (FAO 2023a) and more accessible to assess within the framework of this thesis.

This evaluation required that the CA practices have been implemented over several years (three to seven, according to Hobbs (2007)) making it impractical to conduct this study within trial plots. Moreover, given the variations in the economic, socio-pedo-climatic context among different agricultural regions, our field of investigation had to expand to the entire Walloon territory to reflect the diversity of CA practices.

One of the main constraints of this exploratory research lies in the limited duration of the four-year thesis, which was insufficient to tame the three elephants in the room sequentially, which are, as a reminder, (i) constructing an operational definition of CA, (ii) studying the diversity of CA practices, and (iii) analyzing the consequences of this diversity of practices on soil quality indicators and farmers' transition processes. Although it would have been ideal to assess and compare CA-types once the categorization was established (to obtain sufficient fields within each CA-type), a sequential approach, where one waits for the end of the results to move on to the next stage, was not feasible due to time constraints and the scope of the targeted objectives (three elephants).

Despite our intention to adopt an inclusive and systematic approach, we became representative and non-balanced. For instance, out of the 28 fields analyzed for soil quality assessment, the majority belonged to the CIN type, while we had no plots belonging to the CIO type. These results raise questions about our initial criteria for achieving inclusivity: organic certification and livestock. In the end, the analysis revealed three factors explaining the diversity of CA-types: the proportion of tillage-intensive crops in the crop sequence, the share of temporary grasslands in the crop sequence, and organic certification.

2.5. To understand the transition processes of CA-types

The increasing expansion of CA in Wallonia since 1980 (Vankeerberghen and Stassart 2016) introduces a temporal dimension to this dynamic, which cannot be solely apprehended through statistical approaches. Semi-structured interviews with farmers proved indispensable for examining the transition processes at the level of CA-type practices, i.e., how these practices will evolve in the coming years. This methodological choice emerged as the most effective means to gather in-depth information, addressing complex questions such as the direction in which these practices will be evolving, how this transition is taking place, and why these changes are being considered.

The decision to focus exclusively on farmers, without questioning other stakeholders, stems from the reality that they are the ones who will ultimately decide to modify or not their agricultural practices based on factors such as their interactions with other actors. Farmers provide a broad range of viewpoints, making them an essential entry point for such investigations, particularly when compared to actors within the agri-food system whose interests may extend beyond the agricultural sector. However, it is important to remember that farmers may not be comfortable with the task of anticipating and drawing forward-looking scenarios.

To understand the temporal dynamics, it was important to interview farmers with at least five years of experience. This duration was considered sufficient to enable farmers to master the CA practices (Derrouch et al. 2020) and to have the necessary perspective to anticipate possible developments in their practices. However, this implies their transition to CA occurred several years before the interviews were conducted. Consequently, this study rely on farmers' memories, which may introduce biases due to retrospective reconstruction of events (Chantre and Cardona 2014).

Unlike Chantre and Cardona's (2014) study, our analysis did not track the evolution of transition factors over time. Sequential analysis could have revealed the durations of change processes and whether they were continuous or built on radical changes (Mawois et al. 2019).

We could have categorized CA-types based on temporal organization or outlets targeted by farmers, as Verret et al. (2020) did for crop mixtures. However, we opted to categorize based on farmers' actions, their practices, rather than their stated objectives. Nevertheless, classifying CA-types based on stated objectives would likely have facilitated establishing connections with drivers of change.

3. Results and added value

3.1. An operational definition of CA

This thesis wanted to tame three elephants in the room. The ambiguous definition of CA was identified as the first one. Therefore, the primary objective was to develop an operational definition of CA to facilitate the categorization and evaluation of the diversity of CA practices. The existing definitions were found to be either too vague (Sumberg and Giller 2022) or contained thresholds that were challenging to understand and apply at a regional scale (e.g., in FAO (2023a), cf. Chapter 2).

This study, conducted within Chapter 2, addressed the question of who has the authority to define and delineate CA.

Publications from the FAO and articles considered as reference for defining CA predominantly adhere to a top-down approach. This approach provides a framework for cross-study comparisons but may be disconnected from local realities and constraints, potentially resulting in the exclusion of certain types of CA in specific regions worldwide. Alternatively, constructing a definition of CA based on input from local stakeholders (following a bottom-up approach) would entail considering local constraints (e.g., establishing thresholds for CA pillars based on available tools and crops in the region) to define local thresholds, facilitating the analysis of practice diversity within a given territory. However, this approach presents challenges in comparing CA across different regions.

Our proposed definition of CA and its three pillars seeks to harmonize the two approaches. It offers a general framework with thresholds that can be implemented wherever CA is practiced. In addition, the definition enables studies that concentrate on implementing CA at the regional level to adjust the thresholds for identifying and comparing CA practices.

This adapted definition holds significance both academically, providing researchers with a general and adaptable foundation to study the diversity of CA practices while considering local specificities, and practically for users of CA practices (farmers). The adaptation of this definition was necessary to enable farmers who practice CA to position their practices at the regional level. This facilitates the implementation of the definition and allows for an in-depth analysis of the diversity of CA practices.

Defining farming systems is a challenging task that goes beyond CA and extends to other systems such as agroecology, regenerative agriculture, and conventional agriculture (Newton et al. 2020; Sumberg and Giller 2022; FAO 2024). Delineating a farming system, by improving or constructing its definition so that it can be operationalized in the field, may therefore have echoes in other systems.

3.2. A method for categorizing farming practices

Within the scope of this thesis, an innovative methodology has been developed to categorize CA practices at the regional level. This approach, specifically tailored to the Walloon context, exhibits flexibility that makes it applicable in various regions of the world and for different agricultural systems.

For the study of CA in other regions, researchers can utilize the general definition provided in Chapter 2 and adjust the practices within each pillar based on the specificities of the studied context as detailed in section 2 of Chapter 4 (e.g., tools used or the possibility of cultivating cover crops or diversifying the rotation). The choice and number of variables need to be modified according to the knowledge specific to each region. Similarly, the criteria for sampling during data collection are conditioned by the initial assumptions about the origin of the diversity of CA practices. Assessing the diverse range of CA practices in the study area requires direct engagement with farmers. Data collected through intermediaries may lack the necessary precision. The data analysis steps, as well as the cross-referencing of the two classification methods outlined in Chapter 4, remain applicable regardless of the region.

For other agricultural systems (e.g., conventional agriculture, organic farming, agroecology, etc.), an operational definition of the studied system will serve as the foundation for the typology process. The following steps can then be replicated with adaptations similar to those described for other world regions.

3.3. CA-types identified at the regional scale

After proposing an operational definition of CA and by employing the categorization method, we were able to address the second elephant in the room: the often-overlooked diversity of practices within CA. Our aim was to identify and categorize this diversity at the regional level, focusing specifically on Wallonia.

To effectively categorize this diversity, it was essential to ensure comprehensive coverage of all existing CA-types. To achieve this, it is preferable to transcend the boundaries of a strict definition of CA rather than stopping prematurely and inadvertently excluding a CA-type.

Consequently, we decided to broaden the definition of CA rather than impose overly strict criteria. Therefore, when targeting the population of interest (refer to Chapter 3), we chose to include certified organic CA farmers who occasionally till their plots in the inventory of CA farmers. Consequently, our inventory and subsequent sample for categorizing CA-types (cf. Chapter 4) notably included a significant number of these farmers practicing both organic and CA, referred to as OCA farmers. This decision was further motivated by political goals. By 2030, Wallonia aims to increase the percentage of certified organic agricultural land from 13% to 30% (SPW 2021, 2023a), while Europe aims to achieve 25% (European Commission 2024). Within this framework, our aim was to integrate organic agriculture without stigmatizing it. Additionally, it demonstrated the possibilities and trade-offs of glyphosate-free CA.

Based on this extended definition, and thus on a sample of farmers with very different practices, a categorization of CA-types was made in Chapter 4. Within this categorization, the CIO type deserves special attention. As a reminder, the CIO type, which includes three out of the twenty organic farmers in the sample (i.e., 15% of organic CA farmers and less than 1% of the total sample) is characterized by a combination of organic certification and a high proportion of tillage-intensive crops in the crop sequence. The analysis of its indicators related to tillage (first pillar) and soil cover (second pillar) raises questions: can we accept a CA-type that entails an average of ten soil tillage passes per year, plowing more than once every two years to a depth of 13 cm, and with a soil cover of less than 230 days per year (see Appendix L)? Can this type of agriculture be legitimately included in the CA system, or has it crossed the boundary of CA to be more closely associated with organic farming (OF)? To address this question, it will be necessary to characterize the OF system to identify its characteristics regarding the three pillars of CA. Indeed, it is plausible that the CIO type exhibits significantly lower soil tillage (first pillar) and superior soil cover (second pillar) and species diversification (third pillar) compared to other types of organic farming.

Through this methodological choice (the inclusion of CA farmers practicing organic agriculture with occasional inversion tillage), significant differences may arise compared to other countries. France has a higher number of CA farmers practicing organic agriculture than Belgium (Casagrande et al. 2016). However, within the agricultural magazine TCS which aims to inform farmers about CA techniques, articles referring to OCA predominantly focus on cereals[16]. The only article found discussing potatoes in OCA described the experience of farmers who implemented potatoes after a temporary grassland. French CA stakeholders appears to exclude certified organic crop sequences with a high proportion of tillage-intensive crops (i.e. beets, chicory, potatoes, maize, and other vegetables) from the boundaries of CA (M.-H. Jeuffroy, personal communication, February 23, 2024).

In Chapter 3, the cultivated area under CA was estimated at 38,000 hectares in the Walloon region. However, this estimation is based on extrapolation from the average area derived from a sample of sixty farmers. These farmers were included based on their engagement in the first pillar of CA, namely the reduction of soil tillage practices[17]. The question arises as to whether these 38,000 hectares solely represent the area where tillage is reduced or if they reflect the implementation of all three pillars of CA. Upon examining the radar chart presented in Chapter 4 (see Figure 21), it is clear that no type of CA exhibits significantly reduced tillage (corresponding to the maximization of the first pillar) while also having very low soil cover and crop diversification. Consequently, it can be inferred that these 38,000 hectares signify the

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[16] Some examples: https://agriculture-de-conservation.com/Ble-bio-en-SD-derriere-sarrasin.html; https://agriculture-de-conservation.com/Semer-deux-cultures-dans-un-meme-champ-en-bio.html; https://agriculture-de-conservation.com/Orge-de-printemps-bio-derriere-Biomax-a-pres-de-200-u-N.html; https://agriculture-de-conservation.com/De-belles-vaches-pour-de-belles-pommes-de-terre.html.

[17] For non-certified farmers, this entails no-tillage, while for certified organic farmers, it involves cessation of systematic plowing and/or plowing depth below 15 cm (refer to Section 2.1 of Chapter 3).

comprehensive adoption of CA, a figure substantially higher than those reported by Kassam (2022) and ECAF (2023).

3.4. Soil quality indicators differs between CA-types

Once we had categorized the diversity of CA practices at regional level (cf. Chapter 4), we were able to tackle the third and final elephant in the room: integrating this diversity into CA evaluation. This integration has been studied from two dimensions: soil quality, in chapter 5, and the process of changing practices, in chapter 6.

In Chapter 5, our aim was to compare CA types in terms of their impact on soil quality indicators. This chapter revealed that considering and categorizing the diversity of CA practices leads to variable impacts on soil quality indicators. This observation could explain the variability in findings in the scientific literature, as highlighted e.g. in the study by Chenu et al. (2019), regarding the attributed benefits of CA. Based on the results obtained from the soil indicators studied, it seems probable that comparable variabilities would be observed among CA-types if they were compared using other indicators, such as their dependence on glyphosate (which is already known to be absent for CA-types under organic certification like CIO), their carbon sequestration potential (which is certainly higher in the GEM type than in the CIN type), their working hours, or their income. Attributing specific benefits or criticisms to an entire farming system, whether it be CA, organic, or conventional agriculture, may be risky.

The initial aim of this study was to determine which CA-type to prioritize over another. However, throughout the thesis, it became evident that favoring one CA-type over another was impossible. Each CA-type has its legitimacy as it arises from specific trade-offs at farm level. At a meso-level including the calibration of policies and the extension services, the choice to prioritize expanding a specific CA-type is also closely tied to societal orientations and the agricultural models that Wallonia aims to encourage. Important questions arise, such as whether Wallonia should reduce its share of tillage-intensive crops or promote temporary grasslands, which are beneficial for soil quality but may conflict to reduce beef consumption. In the Walloon context, it was observed that evaluating CA could only be done with considering crop sequences and organic certification.

Our study allows for the identification of CA-types present in a given region. Understanding these types and their impacts on soil quality indicators enables a more specific advisory approach to farmers, tailored according to the CA-type that resonates with the farmer, considering their constraints and opportunities. The findings presented in Chapter 5 facilitate farmers in establishing a connection between their practices and their impact on soil quality. This knowledge can influence future agricultural decisions based on each farmer's specific objectives, such as increasing the carbon-clay ratio. By acknowledging and embracing the diversity of practices within CA, we recognize that not all actors follow the same trajectory (cf. Chapter 6) and that all trajectories are not equivalent (cf. Chapter 5).

3.5. Identify transition and changes in practices once CA has been implemented

The third and final elephant in the room, concerning the integration of the diversity of CA practices into the analysis of CA, is explored along a second dimension within Chapter 6. The Chapter 6 aims to explore the various drivers of change that led Walloon farmers to implement a certain CA-type, as well as how farmers plan to change their CA practices in the coming years.

While most research focuses on farmers' adoption and non-adoption of CA (e.g., Lahmar (Lahmar 2010), Knowler (2015), Serebrennikov et al. (2020)), our study distinguishes itself by focusing on farmers who have already implemented and mastered CA practices to examine their transition process, considering the diversity inherent in their practices. The transition to innovative practices is composed of a set of processes of change, i.e. a series of events that occur in succession over a period of time and lead to one or more changes in practices (Chantre and Cardona 2014).

For Walloon farmers, the transition to CA was divided into two processes of change: (i) adopting CA through the implementation of simplified cultivation techniques (SCT), and (ii) diversiying practices toward a specific CA-type. Chapter 4, Table 8, shows that no-till is the most common practice among CA farmers, indicating its importance as a gateway to transitioning to CA. However, it raises the question of whether sampled farmers have indeed progressed beyond this stage to achieve system redesign. Radar chart in Figure 21 illustrates that the other two pillars are not neglected, despite the challenge of maximizing all three pillars simultaneously. Regarding drivers of change, Table 20 highlights that most drivers aim at reducing soil tillage (whether technical, biophysical, organizational, or financial). Nonetheless, farmers from each CA-type demonstrated a system reassessment beyond mere tillage substitution. This was illustrated in their consideration of environmental factors and their view of soil as a living organism, which aligns with Vankeerberghen and Stassart's (2016) concept of a holistic redesign of conventional practices.

There is a diversity of factors driving the transition to CA, which does not appear to be related to the CA-type adopted, suggesting that each farmer has its own transition process driven by specific incentives and constraints (Revoyron et al. 2022). As a result, the transfer of knowledge and experience becomes less straightforward (Verret et al. 2020).

Farm size was not cited by farmers as a factor influencing their transition process. However, Chapter 3 unveiled that the average agricultural area managed by CA farmers was three times larger than the regional average for Walloon farms specializing in arable crops. Therefore, farm size likely facilitates farmers' transition to CA, possibly because tools required to significantly reduce soil labor are more easily amortized on larger farms.

Analysis of the transition process post-initiation is essential to assess the stability and sustainability of practices. Surveyed results indicate that most farmers are still in the process of evolving their CA practices (Table 21). Farmers who belong to a CA-type do not necessarily share desires or plans for changing their CA practices. Most of the practice changes mentioned by farmers point toward practices more closely linked to the pillars of CA. Changes in practices relate mostly to tillage (first pillar) and crop sequence (third pillar). Conversely, farmers made very few references to changes in soil cover (second pillar). This can be explained either because it is more challenging for farmers to deliberately influence this pillar, or because within the established cropping sequences, they perceive no room for improvement within this pillar.

The increase in the proportion of tillage-intensive crops was the only change in practice mentioned by farmers that resulted in a move away from CA practices. Financial considerations emerge as the primary driver incentivizing farmers to cultivate more tillage-intensive crops, given their higher profitability. Additionally, a technical barrier persists as current industrial processes such as seeding, harvesting, and sorting are not perfectly suited to soil conservation practices such as reduced tillage, retention of crop residues, as well as cereal-legume intercropping (Lamé et al. 2015).

At the field level, the radar chart developed in Chapter 6 (Figure 29) can provide to farmers a visual tool that facilitates understanding and visualization of the consequences of their decisions on the three pillars of CA. This approach allows for an in-depth analysis of post-adoption pathways, contributing to a better understanding of CA practices' long-term sustainability and evolution.

4. The choice of a complementary approach

This thesis integrates three disciplines: agronomy, soil science, and social science. Agronomy plays a central role, by facilitating the construction of an operational definition of CA, exploring the diversity of CA practices implemented by farmers, and establishing a typology relevant for both academic and field stakeholders. Soil science expertise is utilized to evaluate the impact of different CA-types on soil quality. This includes selecting appropriate methods and indicators, conducting laboratory manipulations, and understanding the relationships between agricultural practices and the results obtained. Finally, social science skills are used to develop an interview guide, conduct semi-structured interviews, and analyze qualitative data to identify the connections between implemented practices and the incentives and constraints that influence farmers' decision-making.

Simultaneously addressing multiple disciplines in this thesis required multiple phases of learning to become familiar with each of them. An illustrative example is the initial shift in the focus of Chapter 5, transitioning from evaluating the impact of CA-types on the adaptation and mitigation of practices to climate change to assessing soil quality (this change is explained above in the section 2.4.). This underscores the complexity of interdisciplinarity and the necessary adjustments it may entail throughout the research process.

To speed up the learning process and ensure consistency across disciplines, frequent exchanges with experts were organized (reflected in the long list of acknowledgments in each chapter). In contrast to the conventional approach of a thesis, which tends to favor acquiring in-depth expertise in a specific discipline, this research explored several disciplines more superficially rather than concentrating exhaustively on one. This was illustrated by the desire to tame three elephants rather than just one.

Thesis is typically conducted within specialized laboratories focused on a specific field. However, when undertaking an interdisciplinary thesis, gaining access to information and infrastructure related to other disciplines beyond the expertise of the parent laboratory can prove more challenging. As an illustration, accessing the laboratories and protocols necessary to address the soil science aspects of the research have proven more intricate than if the thesis had been conducted under the supervision of an expert affiliated with a specialized soil analysis laboratory.

The implementation of participatory research, involving immersion in practical field practices, proved to be a complex endeavor. Consultations and collaborations with farmers revealed a mismatch between the terminology used in the scientific community, which often aggregates different tools and techniques under a single name, and the rich diversity of terminology used in the field to describe agricultural practices. Managing this divergence has been challenging, requiring a balance between accurately representing agricultural practices and mutual understanding within the scientific community. In addition, the perfect translation of terms from French to English, especially those related to agricultural tools and machinery, also proved to be a challenging task.

5. Regrets

Although four years may seem lengthy to some, it has felt rather too short from our perspective. Can a thesis be achieved without any regrets?

5.1. Difficulties encountered

Reduction of initially ambitious goals undoubtedly characterized the project outlined in this thesis. Nevertheless, we sought to preserve the breadth of the project by adopting an exploratory approach across multiple disciplines, rather than focusing intensively on one (choosing to tackle three elephants rather than just one).

Additionally, the scientific literature consistently directed us in the opposite direction from the path we wanted to take. Conducting exploratory research, exploring new avenues, and proposing a new approach to understanding a system, all while seeking to study and incorporate the diversity of CA practices throughout the thesis, constantly confronted us with the challenge of engaging in dialogue within the scientific community, which tends to standardize CA and/or reduce it to its primary pillar to extrapolate results.

Although every thesis involves a learning process, in our case, it unfolded on a general theme, Conservation Agriculture, which itself is in a learning phase. There lacked solid, unequivocal, and shared fundamental foundations within the scientific community upon which we could have relied to initiate and advance the thesis, as CA is still in its infancy stage.

5.2. Unexplored paths and potential avenues for further research

The possibilities for improvement were limited due to the nature of the object of study and its current unstable state. CA is currently underdeveloped in Wallonia compared to other regions of the world. Furthermore, the available data on CA at the regional level is limited and varies among studies.

This thesis represents a compromise between the aspiration to deepen our understanding of the diversity and limitations of CA and the constraints encountered in the Walloon context over the past four years.

However, several improvements could have been made at different levels, and various aspects that we would have liked to explore could not be addressed due to time constraints.

In Chapter 2, a more comprehensive literature review would have been conceivable if we had more time, for example, considering the application of the PRISMA method.

In Chapter 3, it would be interesting to study the prevalence of organic certification and livestock farming among all Walloon CA farmers. Additionally, updating the 2020 inventory to assess any potential increase in the number of CA farmers would be valuable. The population inventory can be updated by relying on the actors identified during mapping (Figure 15).

Chapter 4 could have provided a more detailed exploration of the implementation of various pillars to enhance the understanding of the complexity on the ground. For instance, it would have been interesting to provide more details on the cover crops species, crop associations, double cropping, the order of succession of crops, the type of varieties selected, etc. Furthermore, it would have been valuable to conduct design workshops and/or knowledge capitalization sessions (such as those described by Quinio et al., (2021)) to develop technical itineraries for reducing soil tillage within crop sequences involving tillage-intensive crops, or to minimize herbicide usage in CA-types.

Regarding Chapter 5, the excessive sieving of soils hindered the physical separation of stable and labile carbon according to the van Wesemael et al. (2019) method. In the same chapter, due to the non-sequential nature of different parts of the thesis, unlike tillage-intensive crops and temporary grasslands, it was not possible to study the impact of organic certification on soil quality, as there were no farmers of the CIO type in the sample. The imbalance in the plan is likely related to the insufficient presence of CA practitioners in all regions of Wallonia, and not all CA-types represented across agricultural regions. One conceivable solution would have been to match the CA fields with control plots. It is unfortunate that no biological indicators were compared between the different CA-types.

In Chapter 6, it would have been desirable to broaden the range of actors to include stakeholders other than farmers to conceptualize potential future changes of CA practices in Wallonia. The complexity of this chapter lies in the difficulty of describing the dynamics of changes in CA practices based on the conducted interviews, which only provide a static snapshot of the farmer at a given moment. Additionally, the temporal gap between the interview and the start of the transition can influence responses to questions about drivers of change, as the transition dates back at least five years. Finally, the practice changes farmers discuss focused on the short term, concerning the upcoming growing seasons.

Consequently, based on the results, it is challenging to anticipate the evolution of CA-types in several years.

We would also have been intrigued by the potential link between the actors interacting with farmers (Chapter 3), the practices adopted (Chapter 4), as well as the future pathways (Chapter 6).

Additionally, we would have liked to delve deeper into the analysis of pesticide use, with a particular focus on herbicide use, especially glyphosate. The aim would have been to verify hypotheses and preconceived ideas circulating about this in CA. Relevant questions could have been explored, such as the potential trend of CA-types to use more herbicides, as well as the comparison of quantities of insecticides, fungicides, etc., used compared to other agricultural systems.

6. Perspectives

The results of the thesis still need to be communicated to farmers to gather their feedback on the identified CA-types in Wallonia, the specific CA-type each farmer has been associated with, and what they think of their assignment. Furthermore, obtaining their opinions on their willingness to belong to a certain CA-type in the near or distant future will be interesting.

We hope this work has contributed to transform how the CA system can be approached in sciences (agronomic, soil, and social sciences). We have climbed several steps, from proposing an operational definition in the field to suggesting a method for categorizing CA-types at a regional level and presenting evidence that within CA, different CA-types can yield different results regarding soil quality and transition processes. However, despite making significant progress, we do not consider that we have reached the summit, and we gladly pass the torch to the future elephant tamers.

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Appendices

Appendix A Guide d'entretien

Note d'information : l'ensemble des sections du guide d'entretien n'a pas pu être traité dans cette thèse.

Présentation du sujet de recherche et mise en confiance

Merci de consacrer un peu de votre temps à cette étude et merci de me recevoir.

Rappel du projet et signature du formulaire de consentement :

Comme dit au téléphone, je m'appelle Manon Ferdinand et je réalise une thèse à l'UCLouvain dans l'équipe Systèmes & Transitions (Sytra) avec le Prof. Philippe Baret. L'objectif premier de ma thèse est de montrer qu'il existe plusieurs façons de faire de l'AC en Wallonie. Pour ce faire, je rencontre une série d'agriculteurs qui font de l'AC, comme vous, pour comprendre leur manière de faire de l'AC. Au départ des informations recueillies, je vais établir des catégories d'AC. Ensuite, je vais mesurer l'aptitude de ces différentes catégories d'AC à faire face aux changements climatiques. Enfin, je vais étudier les raisons qui incitent ou pas un agriculteur à tendre vers un autre modèle d'AC. Passons ensemble le formulaire de consentement.

Déroulement : Si vous êtes d'accord, je vais enregistrer la discussion. Puisque les données récoltées resteront purement confidentielles et anonymes, vous pouvez me parler en toute confiance. Concrètement, je vais d'abord vous poser quelques questions sur votre identité professionnelle et les caractéristiques générales de l'exploitation. Le but est que cette partie prenne 30 minutes maximum. Ensuite, on va choisir ensemble une de vos rotations sur laquelle vous pratiquez l'AC. Sur cette rotation, on va parcourir les cultures implantées, et quelques éléments essentiels en AC, c'est-à-dire le travail du sol, et l'usage des produits phytos et des fertilisants. Cette seconde partie va prendre beaucoup plus de temps, sans doute une heure.

Caractéristiques de l'agriculteur et de l'exploitation

Thèmes	Questions	Informations
Profil de l'agriculteur	Quelle est votre année de naissance ? Décrivez-moi votre parcours au métier d'agriculteur. Quelles formations avez-vous suivies ?	Age / année de naissance : Parcours vers le métier d'agriculteur : Formations agricoles :

Antécédents	Quand avez-vous repris l'exploitation ? Quelles étaient les pratiques ?	Héritage / reprise : Pratiques du prédécesseur :
Caractéristiques exploitation	Combien d'hectares gérez-vous ? Quelles sont les cultures qui composent habituellement votre assolement ? Combien d'ha cultivez-vous en A(B)C ? Avez-vous des bêtes ?	SAU [ha]: Prairie permanente [ha] : Prairie temporaire [ha] : Assolement habituel : AC [ha]: ABC [ha]: Bio [ha]: Conversion en bio depuis : Élevage [race] : [#têtes] :
Activités secondaires	Y a-t-il des activités secondaires ?	Directement liées à l'exploitation : Pas directement liées :
Main-d'œuvre	Qui travaille avec vous de manière régulière ? Et de manière occasionnelle ?	MO régulière [éq. tps plein] : MO occasionnelle ou saisonnière [pers/an] : [j/pers/an] :
Parcours vers l'A(B)C	Vous m'avez dit au téléphone pratiquer l'AC depuis…ans, pouvez-vous me décrire votre parcours vers l'AC ? Pourquoi avoir adopté l'AC ?	Expérience AC [ans] : ABC [ans] : Parcours vers l'A(B)C : Facteurs d'adoption :

Définitions AC et piliers

Thèmes	Questions	Informations
Définitions AC et piliers	Connaissez-vous l'AC des sols ? Comment définissez-vous l'AC ? Pouvez-vous me définir les différents éléments cités ?	AC : P1 : P2 : P3 : Pratiques additionnelles ?

Pratiques agricoles

On va étudier ensemble une de vos rotations. Pour la choisir il faut que ce soit une rotation :

- Sur laquelle vous pratiquez l'AC ou l'ABC et ce sur l'ensemble de la rotation ;
- La plus représentative de vos pratiques (sur le plus d'hectares ou le plus souvent) ;
- Où chaque culture a déjà été implantée au moins une fois (je ne veux rien de nouveau).

Je vais utiliser l'outil Mission Ecophyt'Eau® conçu par le réseau CIVAM[18] pour représenter cette rotation avec vous. On va d'abord préciser l'ensemble des cultures de votre rotation. Ensuite, on va retracer les interventions culturales (travail du sol, phytos, fertilisations), et ce, du semis à la récolte.

1. Pour toutes les cultures destinées à la vente

Questions	Informations recueillies
Quelles cultures composent la rotation ? La pratique de l'AC influence-t-elle votre choix variétal ? Quand semez-vous et récoltez-vous ces cultures ? Que faites-vous avec les résidus : est-ce que vous les exportez, enfouissez ou semez en les laissant en surface ? Quelle partie est laissée sur le champ ? Avez-vous une idée de la quantité laissée sur le champ ? À quelle densité de semis semez-vous ?	Espèces : Variétés ? Dates semis et récolte : Résidus : Exportés / enfouis / laissés Partie(s) laissée(s) : Quantité laissée : Densité de semis [kg/ha] : Acteurs conseil / vente semence :

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[18] Centres d'initiatives pour valoriser l'agriculture et le milieu rural. Il s'agit de groupes d'agriculteurs et de ruraux pour une transition agro-écologique. Réseau de 130 associations pour des campagnes vivantes.

Êtes-vous conseillé pour le choix des cultures à implanter ?	

2. Pour toutes les cultures de couvertures

Questions	Informations recueillies
Que faites-vous entre deux cultures ? Construisez-vous la rotation pour en mettre ? Quelle(s) espèce(s) compose(nt) le couvert ? La pratique de l'AC influence-t-elle votre choix variétal ? Quand semez-vous le couvert ? Le couvert a-t-il été pâturé ? Les parties aériennes sont-elles en partie récoltées ? Quand détruisez-vous le couvert ? A quelle densité de semis semez-vous ? Êtes-vous conseillé dans le choix des couverts à mettre ?	Intercultures ? oui – non Aménagement de la rotation ? Espèces : Variétés ? Dates de semis : Pâturage des couverts ? oui – non Récolte partie aérienne : oui – non Date de récolte ou destruction : Densité de semis [kg/ha] : Acteurs conseil / vente semence :

3. Pour chaque opération mécanique (semis, récolte, travail du sol, destruction des couverts, travail manuel, traitements…)

Questions	Informations
Quelle opération a été effectuée ? Quel outil a été employé ? À quelle profondeur maximale l'outil travaille-t-il ? Quelle proportion de la superficie est travaillée ? Vous êtes conseillés pour le choix/achat de vos engins ?	Opération : Outils : Profondeur [cm] : Superficie travaillée [%] : 5-30-100 Acteurs conseil/vente/CUMA :

4. Rendements des cultures

Questions	Informations
Avez-vous une comptabilité de gestion ?	Comptabilité ? oui – non
Connaissez-vous les rendements des cultures ?	Méthode calcul des rdts :
Comment les calculez-vous ?	Si pas : estimation max et min
Sur combien d'année peut-on remonter ?	Rdt de 2015 à 2019 :
Pour chaque culture, quel est le facteur le plus impactant ?	Facteur impactant/culture :

Nous passons maintenant en revue l'usage des produits phytos et de la fertilisation sur les cultures présentées ici.

5. Pour chaque intervention (herbicides, fongicides, insecticides, régulateurs, engrais,…)

Questions	Informations
Avez-vous des fiches de cultures ? De 2015 à 2019 ?	Fiches ? Jusque 2015 ?
Quel est le nom commercial du produit ?	Nom du produit :
Quelle dose a été appliquée ?	Dose [/ha] :
Quelles sont les techniques employées pour pulvériser ?	Techniques de pulvérisation :
À quel volume travaillez-vous ?	Volume de bouillie :
Ce volume est-il toujours le même ?	Changement du volume ?
D'où viennent vos engrais ?	Provenance des engrais :
Qui vous conseille dans le choix et l'utilisation des phyto ?	Acteurs vente & conseils :

6. Évolution des pratiques

Questions	Informations
Vos pratiques sont plutôt stables ou changeantes ?	Stables / changeantes
Quelle(s) sont les modification(s) récente(s) ?	Modifications récentes :
Quelle(s) sont les modification(s) que vous envisagez ?	Modifications futures :

Perceptions des bienfaits personnels et globaux de faire de l'AC

Thèmes	Questions	Informations
Bienfaits personnels	Qu'elles sont selon vous les trois bienfaits principaux que vous tirez à faire de l'AC ?	Bienfaits personnels : 1) … 2) … 3) …
Bienfaits globaux	À l'échelle globale et non plus personnelle, qu'elles sont les trois principales raisons de promouvoir l'AC ?	Bienfaits globaux : 1) … 2) … 3) ….
Mesures à faire	Pour savoir si votre modèle d'AC permet une meilleure atténuation et adaptation aux changements climatiques, quelles sont les mesures que vous voudriez que les scientifiques fassent ?	Mesures scientifiques pour évaluer : Adaptation : Atténuation :

Boule de neige

Connaissez-vous des agriculteurs qui pratiquent l'AC comme vous et très différemment ?

Nom	Pratiques	Localisation	Coordonnées

Remerciements et restitution des résultats

Encore un immense merci d'avoir consacré une partie de votre temps à la recherche. Je vous ferai part des résultats une fois ceux-ci obtenus.

- Est-ce que vous avez une adresse email ? Plus facile pour vous faire parvenir les résultats. J'organiserai sans doute une discussion autour des résultats.
- Seriez-vous intéressés de participer aux prochaines étapes de la thèse ?

Chapitre 3 – Appendices

Appendix B Caractéristiques générales des ACistes Wallons interrogé·es

Code	Année de l'entretien	Région agricole	SAU totale	SAU bio	SAU sous prairies ou cultures permanentes	SAU AC ou ABC	adoption AC	adoption ABC	Elevage	Labour	SD
0	2020-2021	Limoneuse	75	73	40	35	1995	2017	oui	oui	non
1	2020-2021	Limoneuse	187	187	5	182	1999	2012	oui	oui	non
2	2020-2021	Sablo-limoneuse	580		10	570	2009		non	non	non
3	2020-2021	Limoneuse	120		20	100	2001		oui	non	non
4	2020-2021	Sablo-limoneuse	1000	300		1000	2014		non	non	non
5	2020-2021	Limoneuse	450	450		450		2011	oui	oui	non
6	2020-2021	Condroz	108,5			108,5	1998		non	non	oui
7	2020-2021	Condroz	285		32	253	1985		oui	non	oui
8	2020-2021	Fagne	145	145	80	65	2014	2015	oui	oui	non

9	2020-2021	Fagne	200	30	60	140	2015	2017	oui	oui	non
10	2020-2021	Condroz	170	125	43	127	2000	2013	oui	non	non
11	2020-2021	Condroz	500		5	495	1991		oui	non	non
12	2020-2021	Famenne	115		50	65	2017		oui	non	oui
13	2020-2021	Limoneuse	144		3	141	2001		non	non	oui
14	2020-2021	Haute Ardenne	130		60	70	2018		oui	non	non
15	2020-2021	Haute Ardenne	200	5	50	150	2007		oui	non	non
16	2020-2021	Ardenne	74	74	44	30		2020	oui	non	oui
17	2020-2021	Ardenne	100		15	85	2020		non	non	non
18	2020-2021	Limoneuse	234		10	224	2017		oui	non	oui
19	2020-2021	Herbagère	169		104	65	1991		oui	oui	oui
20	2020-2021	Herbagère	80		72	8	2011		oui	oui	non
21	2020-2021	Jurassique	148	58	68	80	2011	2015	oui	non	non
22	2020-2021	Limoneuse	154		25	129	2005		oui	non	non
23	2020-2021	Condroz	86	86	7	79	1992	2018	oui	non	non

24	2020-2021	Jurassique	120		65	55	2011		oui	non	non
25	2020-2021	Limoneuse	100		18	82	2000		oui	non	oui
26	2020-2021	Limoneuse	75	75	13	62	2005	2014	oui	oui	non
27	2020-2021	Ardenne	95		4,5	90,5	1998		non	oui	non
28	2020-2021	Limoneuse	290		6,33	283,67	2001		non	non	non
29	2020-2021	Limoneuse	1100	250		1100	2001	2018	non	oui	non
30	2020-2021	Condroz	150		3	147	1991		non	non	oui
31	2020-2021	Sablo-limoneuse	128		9	119	2001		oui	non	oui
32	2020-2021	Condroz	200		47	153	1991		oui	non	oui
33	2020-2021	Sablo-limoneuse	177		1,1	175,9	1991		non	non	non
34	2020-2021	Limoneuse	144,88	105	26	118,88	2007	2016	oui	non	non
35	2020-2021	Limoneuse	270		2,09	267,91	2006		non	non	oui
36	2020-2021	Limoneuse	78		8,6	69,4	2003		non	non	oui
37	2020-2021	Condroz	90	90	6,5	83,5	2016	2018	oui	non	non
38	2020-2021	Condroz	291	291	20	271		2017	oui	oui	non

39	2020-2021	Limoneuse	210	110	0	210		2015	non	oui	oui
40	2020-2021	Condroz	140		2,6	137,4	1995		non	non	non
41	2020-2021	Famenne	85	85	65	20	2001	2020	oui	oui	non
42	2020-2021	Limoneuse	135	33	5	130	2001	2008	non	oui	non
43	2020-2021	Sablo-limoneuse	300	150	0,5	299,5	2006	2016	non	oui	non
44	2020-2021	Limoneuse	100	70	10	90	2000	2016	non	non	non
45	2020-2021	Limoneuse	410	100	14	396	2002	2018	non	oui	oui
46	2020-2021	Condroz	150	30	0	150	1998	2015	non	non	non
47	2020-2021	Limoneuse	150	60	0,5	149,5	2003	2018	non	oui	non
48	2019		500	300	20	480	1995	1998	non	oui	non
49	2019		115	57,5		115		2015	non	oui	non
50	2019		115	90		115	2003	2010	non	oui	non
51	2019		85	70	25	60		2013	non	oui	non
52	2019		113	113		113	1980	2008	oui	non	non
53	2019		220	220	20	200	1998	2000	oui	oui	non
54	2019		350			350	1998		non	oui	non
55	2019		230			230	1998		non	oui	non

56	2019		200			200	1998		non	non	non
57	2019		330			330	1998		non	non	non
58	2019		124			124	2004		non	non	non
59	2019		600			600	1994		non	non	non
60	2019		110		2,2	107,8	1990		non	non	non
61	2019		45		15	30	2005		oui	non	non

Appendix C Analyse comparative des superficies sous prairies dans la province du Luxembourg (sud de la Belgique) entre STATBEL et le SIGEC

Notes explicatives : Cette étude a été réalisée par Noé Vandevoorde (NV) en septembre 2023. La catégorie « SIGEC (corrigé NV) » se base sur les parcelles pour lesquelles une déclaration PAC de 2010 à 2020 est fournie, et où d'éventuelles classifications erronées ont été corrigées par NV.

	Superficies (en hectares) en Province du Luxembourg							
	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**Moyenne**	**Écart avec Statbel**
SIGEC								
Prairies temporaires	17696	21212	19695	19542	18697	18407	19208	+14%
Prairies permanentes	107072	104307	106210	105849	106050	105654	105856	+6%
Total des prairies	124768	125518	125904	125391	124747	124061	125065	+7%
SIGEC (corrigé NV)								
Prairies temporaires	22324	22991	23270	23745	23428	22092	22975	+36%
Prairies permanentes	99004	99165	99418	98607	98395	99187	98962	-1%
Total des prairies	121327	122156	122688	122352	121823	121279	121937	+4%
STATBEL								
Prairies temporaires	16115	17765	17193	16832	16913	16328	16857	+0%
Prairies permanentes	98512	100266	97023	102312	101457	102231	100300	+0%
Total des prairies	114627	118031	114217	119144	118369	118559	117157	+0%

Appendix D Superficies gérées par les 62 ACistes de l'échantillon

Code	SAU			
	Totale	Bio	Prairies / cultures permanentes	A(B)C
0	75	73	40	35
1	187	187	5	182
2	580		10	570
3	120		20	100
4	1000	300		1000
5	450	450		450
6	108,5			108,5
7	285		32	253
8	145	145	80	65
9	200	30	60	140
10	170	125	43	127
11	500		5	495
12	115		50	65
13	144		3	141
14	130		60	70
15	200	5	50	150
16	74	74	44	30
17	100		15	85
18	234		10	224
19	169		104	65
20	80		72	8
21	148	58	68	80
22	154		25	129
23	86	86	7	79
24	120		65	55
25	100		18	82
26	75	75	13	62
27	95		4,5	90,5
28	290		6,33	283,67
29	1100	250		1100
30	150		3	147
31	128		9	119
32	200		47	153
33	177		1,1	175,9
34	144,88	105	26	118,88
35	270		2,09	267,91
36	78		8,6	69,4
37	90	90	6,5	83,5

38	291	291	20	271
39	210	110	0	210
40	140		2,6	137,4
41	85	85	65	20
42	135	33	5	130
43	300	150	0,5	299,5
44	100	70	10	90
45	410	100	14	396
46	150	30	0	150
47	150	60	0,5	149,5
48	500	300	20	480
49	115	57,5		115
50	115	90		115
51	85	70	25	60
52	113	113		113
53	220	220	20	200
54	350			350
55	230			230
56	200			200
57	330			330
58	124			124
59	600			600
60	110		2,2	107,8
61	45		15	30

Chapter 4 – Appendices

Appendix E Details and calculation methods of the variables characterizing the pillars and used to collect data and make the typology of Conservation Agriculture types

Legend: Erosion risk period (ERP), Annual crops (A), Temporary grassland (T).

The characterization of farmers' CA practices was based on crop sequences rather than rotations, given the complex evolution of crop choices (Vandevoorde and Baret 2023).

Pillar	Variable	Detail	Calculation Method
1. Minimum Mechanical Soil Disturbance	Wheel Traffic	The average annual wheel traffic for tillage operations (no. of tillage operations/year).	Sum of tillage passes/length of the crop sequence. The following operations were excluded from the calculation: harvesting (except for tuber and root crops harvesting); mowing, tedding, windrowing, wrapping, etc.; treatment operations (spreading, fertilizing); rollers and shredders; manual and thermal weeding; spreading of straw or residues; and livestock grazing.
	Seeding	The proportion of seeding operations in relation to other tillage operations (%).	Sum of seeding passes (seeder alone or combined)/sum of tillage passes.
	Powered	The annual average of powered tillage passes (no. of powered passes/year).	Sum of soil preparation passes with powered tools/length of the crop sequence.
	Plowing	The annual average of plowing (no. of plowing operations/year).	Sum of plowing passes turning over the soil/length of the crop sequence.
	Plowing Depth	If horizons are turned over, the maximum depth of plowing (cm).	Deepest plowing turning over the soil throughout the crop sequence.
2. Maximum Soil	Total Cover	The average annual number of days the soil is covered (days/year)	Sum of periods when the soil is covered by dead mulch or sown with a crop/length of the crop sequence. In the case of direct seeding under cover,

			in order to avoid double-counting a day when the soil is covered, the end date of the previous crop is equal to the sowing date of the following crop minus one day.
	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)	Sum of periods when the soil is sown by live crop/length of the crop sequence.
	Grassland Cover	The proportion of days soil is covered by temporary grassland (%)	Sum of periods covered by a temporary grassland/sum of days covered by dead or live ground cover.
	ERP Cover	The proportion of days soil is covered during the ERP, which in Wallonia is from May to September (%)	Sum of periods when the soil is covered (by dead or live ground cover) between May and September/sum of the May to September periods in the crop sequence.
	Spring Crops ERP Cover	The proportion of days soil is covered by spring crops during ERP, which in Wallonia is from May to September (%)	Sum of days covered by spring crops between May and Sept/ sum of periods when the soil is covered (by dead or live mulch) between May and September.
3. Maximum Species Diversification	Total Species	The average annual number of different species in annual crops, temporary grassland, and cover crops) (no. of different species/year)	Sum of all the different species grown/length of the crop sequence. Different varieties are considered the same species.
	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)	Sum of different species harvested or grazed / length of the crop sequence.

	A+T Associations	The proportion of associations in annual crops and temporary grassland (%)	Number of crop seasons harvested or grazed with associated species/sum of crop seasons harvested or grazed.
	A+T Mixes	The proportion of mix of varieties in annual crops and temporary grassland (%)	Number of crop seasons harvested or grazed with varietal mixes/sum of crop seasons harvested or grazed.
	Tillage-intensive Crops	The annual average number of tillage-intensive crops (no. of species/year)	Number of tillage-intensive crops harvested/length of the crop sequence.

Appendix F Conservation Agriculture Population and sample characteristics

	Survey n farmers	Sample n farmers			
Agricultural Region		Not organic No Livestock	Not organic Livestock	Organic No Livestock	Organic Livestock
Sandy Loam	13	4	2	2	0
Loam	111	12	2	13	9
Condroz	45	4	3	4	8
Campine Hennuyère	0	0	0	0	0
Herbagère	3	0	2	0	0
Fagne	4	1	1	0	2
Famenne	3	0	1	0	1
Haute Ardenne	3	0	2	0	0
Ardenne	4	2	0	0	2
Jurassic	5	0	1	0	2
Total	191	23	14	19	24

Appendix G Summary of variables for each farmer

Part 1

		Farmer's code										
Variables	Units	0	1	2	3	4	5	6	7	8	9	10
Ca experience	years	26	22	12	20	7	0	23	32	7	6	21
OCA experience	years	4	9	0	0	0	10	0	0	6	4	8
Organic	yes (1) or no (0)	1	1	0	0	1	1	0	0	1	0	0
Livestock	yes (1) or no (0)	1	1	0	1	0	1	0	1	1	1	1
Wheel traffic	no./year	1.4	4.7	3.0	4.0		3.5	2.8	1.8	2.8	2.2	5.2
Seeding	%	57.1	17.9	58.3	31.3		28.1	64.7	100.0	52.6	54.6	29.0
Powered	no./year	0.0	1.0	0.0	0.3		0.2	0.3	0.0	0.0	0.2	0.8
Plowing	no./year	0.2	0.5	0.0	0.0		0.2	0.0	0.0	0.2	0.2	0.0
Plowing depth	cm	25.0	10.0	0.0	0.0		13.0	0.0	0.0	20.0	17.0	0.0
Total cover	days/year	363.9	330.4	330.3	356.3		331.4	352.7	364.4	356.5	357.2	343.7
Living cover	days/year	346.0	319.9	297.7	348.2		315.1	344.8	364.4	356.5	333.1	299.3
Grassland cover	%	65.0	55.4	0.0	0.0		39.3	0.0	0.0	45.8	0.0	0.0
ERP cover	%	100.0	96.0	92.8	97.4		88.0	97.3	100.0	95.0	96.2	92.5
Spring crops ERP cover	%	0.0	17.4	37.9	51.3		23.3	22.4	0.0	0.0	20.8	50.5
Total species	species/year	1.4	2.7	1.3	2.8		2.0	3.7	3.5	2.1	2.4	1.0
A+T species	species/year	1.2	2.2	0.8	0.8		1.5	1.5	1.1	1.0	0.8	0.7
A+T associations	%	100.0	75.0	0.0	0.0		42.9	16.7	0.0	60.0	0.0	0.0

A+T mixes	%	0.0	0.0	0.0	0.0	0.0	50.0	33.3	40.0	60.0	0.0
Tillage-intensive crops	species/year	0.0	0.2	0.5	0.5	0.2	0.2	0.0	0.0	0.2	0.3

Part 2

		Farmer's code										
Variables	Units	11	12	13	14	15	16	17	18	19	20	21
Ca experience	years	30	4	20	3	14	0	1	4	30	10	10
OCA experience	years	0	0	0	0	0	1	0	0	0	0	6
Organic	yes (1) or no (0)	0	0	0	0	0	1	0	0	0	0	1
Livestock	yes (1) or no (0)	1	1	0	1	1	1	0	1	1	1	1
Wheel traffic	no./year	3.8	2.3	2.9	2.2	1.5	0.6		3.3	0.9	3.0	4.6
Seeding	%	40.0	85.7	60.9	55.6	44.4	100.0		46.2	50.0	50.0	45.5
Powered	no./year	1.4	0.0	1.5	0.0	0.0	0.0		0.5	0.2	1.7	0.0
Plowing	no./year	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.2	0.3	0.0
Plowing depth	cm	0.0	0.0	0.0	0.0	0.0	0.0		0.0	20.0	15.0	0.0
Total cover	days/year	319.5	355.8	342.8	363.6	359.5	363.9	358.5	281.2	359.6	352.5	344.5
Living cover	days/year	313.6	356.2	325.7	363.6	359.5	363.9	358.5	262.3	358.5	350.3	344.5
Grassland cover	%	0.0	0.0	0.0	53.4	65.4	91.4	40.9	0.0	90.9	26.4	0.0
ERP cover	%	87.3	97.0	90.9	99.7	98.6	100.0	98.1	95.6	99.1	94.6	97.9
Spring crops ERP cover	%	47.6	34.4	46.8	48.5	16.9	13.9	16.1	68.2	7.8	65.6	45.2
Total species	species/year	1.4	4.3	1.8	0.8	1.3	1.4	2.3	3.8	0.6	1.2	3.4

A+T species	species/year	0.6	3.0	0.6	0.5	1.3	1.4	1.5	1.0	0.6	1.1	1.3
A+T association	%	0.0	25.0	0.0	0.0	50.0	50.0	33.3	0.0	50.0	28.6	33.3
A+T mixes	%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.3	0.0
Tillage-intensive crops	species/year	0.4	0.3	0.4	0.5	0.2	0.0	0.1	0.8	0.1	0.5	0.0

Part 3

		Farmer's code										
Variables	Units	22	23	24	25	26	27	28	29	30	31	32
Ca experience	years	16	29	10	21	16	23	20	20	30	20	30
OCA experience	years	0	3	0	0	7	0	0	3	0	0	0
Organic	yes (1) or no (0)	0	1	0	0	1	0	0	1	0	0	0
Livestock	yes (1) or no (0)	1	1	1	1	1	0	0	0	0	1	1
Wheel traffic	no./year	4.4	0.5	3.9	2.8	8.3	4.3	3.5	8.0	1.8	2.2	2.2
Seeding	%	33.3	100.0	40.0	38.1	18.0	30.0	42.9	20.3	85.7	76.9	68.2
Powered	no./year	0.9	0.1	1.3	0.3	1.8	0.9	0.7	1.3	0.0	0.3	0.1
Plowing	no./year	0.0	0.0	0.0	0.0	0.2	0.9	0.0	0.5	0.0	0.0	0.0
Plowing depth	cm	0.0	0.0	0.0	0.0	20.0	25.0	0.0	18.0	0.0	0.0	0.0
Total cover	days/year	340.6	364.1	321.0	347.4	309.0	320.6	344.3	290.0	362.4	356.3	346.9
Living cover	days/year	324.0	364.1	321.0	319.4	294.3	320.6	318.6	264.8	341.7	353.7	329.0
Grassland cover	%	0.0	60.5	0.0	42.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ERP cover	%	91.0	100.0	83.8	94.7	89.2	80.9	90.2	91.1	99.0	97.0	93.6

Spring crops ERP cover	%	29.1	0.0	44.4	35.5	67.5	30.6	55.4	41.8	15.5	26.0	35.2
Total species	species/year	1.0	0.9	1.6	2.0	2.7	1.0	1.7	1.3	2.5	2.7	1.5
A+T species	species/year	0.6	0.9	1.1	1.6	1.7	0.9	0.7	0.6	1.8	0.8	0.8
A+T association	%	0.0	25.0	0.0	33.3	28.6	0.0	0.0	0.0	75.0	16.7	10.0
A+T mixes	%	0.0	25.0	0.0	0.0	14.3	0.0	50.0	0.0	0.0	33.3	40.0
Tillage-intensive crops	species/year	0.2	0.0	0.3	0.4	0.7	0.1	0.5	0.5	0.0	0.3	0.2

Part 4

		Farmer's code														
Variables	Units	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
Ca experience	years	30	14	15	18	5	0	0	26	20	20	15	21	19	23	18
OCA experience	years	0	5	0	0	3	5	6	0	1	13	5	5	3	6	3
Organic	yes (1) or no (0)	0	1	0	0	1	1	1	0	1	1	1	1	1	1	1
Livestock	yes (1) or no (0)	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0
Wheel traffic	no./year	3.3	5.4	4.5	4.6	2.9	3.6	4.8	3.0	0.8	11.3	11.3	8.8	2.9	3.1	3.4
Seeding	%	40.0	19.2	41.7	33.3	42.9	32.0	24.1	41.7	66.7	14.6	15.6	15.8	29.4	27.8	38.5
Powered	no./year	0.2	1.7	1.5	1.2	0.2	0.7	1.3	0.3	0.3	2.0	2.3	1.4	0.7	0.0	0.5

Plowing	no./year	0.0	0.0	0.0	0.0	0.0	0.6	0.7	0.0	0.3	0.8	1.0	0.0	0.5	0.0	0.3
Plowing depth	cm	0.0	0.0	0.0	0.0	0.0	20.0	15.0	0.0	12.0	20.0	20.0	0.0	15.0	0.0	15.0
Total cover	days/year	354.0	281.4	342.9	343.5	355.7	337.3	296.5	344.7	358.7	239.1	265.7	178.0	289.2	334.2	353.4
Living cover	days/year	345.0	270.3	321.0	302.4	348.7	337.0	260.5	314.6	358.7	236.8	255.4	168.9	289.2	334.2	353.4
Grassland cover	%	0.0	46.5	0.0	0.0	41.2	32.6	47.5	0.0	50.5	0.0	0.0	0.0	66.7	0.0	0.0
ERP cover	%	95.1	95.6	93.7	88.9	95.9	94.5	97.2	93.0	98.6	84.5	86.1	78.0	93.9	92.7	94.4
Spring crops ERP cover	%	34.6	57.7	29.6	35.7	11.3	14.2	41.3	26.9	24.0	60.9	42.2	75.4	25.4	25.1	20.0
Total species	species/year	1.5	3.1	1.8	1.9	2.3	6.5	2.3	2.3	1.0	2.7	2.8	1.6	1.2	1.0	3.1
A+T species	species/year	0.7	3.1	1.1	1.4	0.8	2.7	1.2	1.8	1.0	1.2	1.0	1.2	0.8	0.9	2.3
A+T association	%	16.7	20.0	12.5	16.7	25.0	50.0	20.0	25.0	80.0	16.7	0.0	0.0	25.0	60.0	75.0
A+T mixes	%	0.0	0.0	0.0	50.0	25.0	16.7	0.0	50.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0
Tillage-intensive crops	species/year	0.3	0.6	0.4	0.2	0.0	0.1	0.5	0.3	0.0	0.8	0.5	0.7	0.3	0.0	0.0

Appendix H Scores of each farmer where their distribution is sorted according to the sum of the scores of all variables

Code	No Wheel Traffic	Seeding	No Powered	No Plowing	Low Plowing Depth	Total Cover	Living Cover	Grassland Cover	ERP Cover	Low Spring Crops ERP	Total Species	A+T Species	A+T Associations	A+T Mixes	No tillage-intensive crops	Sum
29	1	2	3	2	2	2	2	1	3	4	3	2	1	1	3	32
42	1	1	1	1	2	1	1	1	1	1	8	7	5	1	1	33
43	1	1	1	1	2	1	1	1	1	4	9	5	1	1	3	33
27	3	3	4	1	1	3	5	1	1	6	2	4	1	1	8	44
44	1	1	2	10	10	1	1	1	1	1	5	7	1	1	1	44
26	1	1	1	4	2	2	2	1	2	1	8	9	7	8	1	50
10	2	3	4	10	10	5	3	1	3	2	2	2	1	1	5	54
11	4	5	2	10	10	3	3	1	2	3	4	2	1	1	4	55
39	2	2	3	1	3	2	1	9	8	4	7	7	6	1	3	59
22	3	4	4	10	10	4	5	1	3	6	2	1	1	1	7	62
24	4	5	3	10	10	3	5	1	1	3	5	6	1	1	5	63
45	7	3	5	2	3	2	2	10	5	7	2	4	7	1	4	64
18	5	7	5	10	10	1	1	1	6	1	10	5	1	1	1	65
13	7	9	2	10	10	5	5	1	3	3	5	1	1	1	4	67
2	6	8	10	10	10	3	3	1	4	4	3	3	1	1	2	69

28	5	6	4	10	10	5	4	1	3	2	5	2	1	10	3	71
34	2	2	1	10	10	1	2	8	7	2	9	10	6	1	1	72
35	3	6	2	10	10	5	5	1	5	6	5	6	4	1	4	73
20	6	7	1	2	3	7	8	7	5	1	3	6	7	8	3	74
3	4	3	6	10	10	8	8	1	8	2	9	3	1	1	2	76
5	5	3	7	3	4	4	4	7	2	7	6	9	8	1	6	76
1	2	1	3	2	4	3	4	9	7	8	8	10	10	1	7	79
33	5	5	8	10	10	7	7	1	6	5	4	2	5	1	5	81
36	3	4	3	10	10	5	3	1	2	5	6	8	5	10	7	82
46	6	2	10	10	10	4	6	1	4	7	2	4	9	1	10	86
9	9	8	7	3	3	9	6	1	7	8	7	3	1	10	6	88
47	5	5	5	3	3	7	8	1	5	8	9	10	10	1	10	90
38	4	4	5	1	2	4	6	7	5	9	10	10	9	8	8	92
25	7	4	6	10	10	6	4	8	6	5	6	9	8	1	3	93
32	8	9	8	10	10	6	6	1	4	5	4	3	4	9	6	93
14	8	8	10	10	10	10	10	9	10	3	1	1	1	1	3	95
19	10	7	7	4	2	9	9	10	9	10	1	1	9	1	8	97
40	6	6	6	10	10	6	3	1	4	6	7	9	7	10	6	97
21	3	7	10	10	10	6	7	1	9	3	9	7	8	1	10	101
31	9	9	6	10	10	8	9	1	8	6	8	4	5	9	5	107
41	10	9	6	3	4	9	9	9	9	7	2	5	10	8	10	110
0	10	8	10	3	1	10	7	10	10	10	4	7	10	1	10	111

8	8	7	10	4	2	8	9	8	6	10	6	5	9	9	10	111
12	8	10	10	10	10	8	9	1	7	5	10	10	7	1	5	111
6	7	9	6	10	10	7	7	1	8	8	10	8	5	10	7	113
37	7	6	7	10	10	7	8	8	7	9	7	3	7	9	10	115
15	9	6	10	10	10	9	10	10	9	9	3	8	9	1	7	120
30	9	10	10	10	10	9	6	1	9	9	7	9	10	1	10	120
7	9	10	10	10	10	10	10	1	10	10	10	6	1	9	10	126
23	10	10	8	10	10	10	10	9	10	10	1	5	7	9	10	129
16	10	10	10	10	10	10	10	10	10	9	4	8	9	1	10	131
Mean	5.5	5.6	5.7	7.2	7.2	5.5	5.5	3.8	5.5	5.5	5.6	5.6	5.2	3.6	5.7	82.9

Appendix I Alpha coefficients of each farmer and each archetype

Code	A1	A2	A3	A4
0	0	0.90858791	0	0.09112499
1	0.23060736	0.374474	0	0.39470407
2	0	0.11367113	0.88603407	0
3	0	0	0.83960025	0.16014457
5	0.25530555	0.45425009	0.09054876	0.19961389
6	0	0.15621342	0.43010797	0.41344961
7	0	0.4675221	0.23216865	0.3000598
8	0.04830805	0.77386202	0	0.17750952
9	0	0.31689523	0.51293294	0.16988816
10	0.05998647	0.00131298	0.93842131	0
11	0.11441862	0	0.88531628	0
12	0	0.00101898	0.19096683	0.80784702
13	0.0067555	0.04643349	0.94611774	0.00040473
14	0	0.38643572	0.61328663	0
15	0	0.70174328	0.2063294	0.09159327
16	0	0.9592903	0	0.04038769
18	0.21985844	0	0.63541416	0.14451585
19	0.04070042	0.95897423	0	0
20	0.20138965	0.3239457	0.46469141	0.00968752
21	0	0.13415437	0.48742408	0.3781682
22	0.01730086	0.13987134	0.84252996	0
23	0	0.92048133	0.07919273	0
24	0.1179451	0	0.85177539	0.03000518
25	0.01168535	0.24677002	0.5093452	0.23191354
26	0.53836332	0	0.26779342	0.19364626

27	0.52654036	0.42369454	0.04950266	0
28	0	0	0.99973251	0
29	0.59451698	0.18379851	0.22145853	0
30	0	0.54137173	0.0755289	0.38282319
31	0	0.2841035	0.55854375	0.15708636
32	0	0.29099036	0.70871472	0
33	0	0.23277814	0.75644319	0.0104759
34	0.3708946	0	0.17657002	0.4523487
35	0.07215791	0.0951987	0.73216174	0.10020086
36	0.02150541	0	0.81997954	0.15824004
37	0	0.51213993	0.38108891	0.10645838
38	0.03209558	0	0	0.9678288
39	0.54727322	0.38626173	0	0.06622519
40	0	0.10498316	0.59796272	0.2967956
41	0.04161599	0.91061309	0.00239611	0.0450195
42	0.99685615	0	0	0.00299631
43	0.90330949	0.04511507	0	0.05141093
44	0.86725233	0	0.13265038	0
45	0.40801568	0.59172083	0	0
46	0.00687678	0.42239686	0.54329228	0.02709816
47	0.06578689	0.30038799	0	0.6335874

Appendix J Farmers' membership of HCPC clusters

Code	Cluster	Code	Cluster	Code	Cluster
0	6	18	3	34	4
1	4	19	6	35	3
2	3	20	2	36	3
3	3	21	5	37	5
5	2	22	3	38	4
6	5	23	6	39	2
7	5	24	3	40	5
8	6	25	3	41	6
9	5	26	1	42	1
10	3	27	2	43	1
11	3	28	3	44	1
12	4	29	2	45	2
13	3	30	6	46	3
14	3	31	5	47	4
15	6	32	5		
16	6	33	3		

Appendix K Farmers' membership of Conservation Agriculture types where the farmers' distribution is sorted according to the sum of the scores of all variables

Code	Sum of scores	CAM	Code	Sum of scores	CAM
29	32	Ig1	36	82	CIN
42	33	CIO	46	86	unclassified
43	33	CIO	9	88	Ig2
27	44	Ig1	47	90	unclassified
44	44	CIO	38	92	unclassified
26	50	unclassified	25	93	unclassified
10	54	CIN	32	93	unclassified
11	55	CIN	14	95	unclassified
39	59	Ig1	19	97	GEM
22	62	CIN	40	97	Ig2
24	63	CIN	21	101	Ig2
45	64	Ig1	31	107	Ig2
18	65	unclassified	41	110	GEM
13	67	CIN	0	111	GEM
2	69	CIN	8	111	GEM
28	71	CIN	12	111	unclassified
34	72	unclassified	6	113	Ig2
35	73	CIN	37	115	Ig2
20	74	Ig1	15	120	GEM
3	76	CIN	30	120	unclassified
5	76	Ig1	7	126	Ig2
1	79	unclassified	23	129	GEM
33	81	CIN	16	131	GEM

Appendix L Summary of raw variables of each Conservation Agriculture type

This table provides the data for each variable, expressed in raw values, which were then averaged per CA-type.

In contrast, the values presented in Table 10 and Figure 21 were obtained by first converting the raw variables of each farmer into deciles, followed by calculating the average of these deciles per CA-type. As a result, differences can be observed between this Table and Table 10. For example, the variable "Plowing", in this table, indicates that Ig1 performs better than CIO (lower plowing frequency), whereas, in Table 10, the decile values present an opposite trend.

Variables	Units	CIO (RgI)	GEM (RgII)	CIN (RgIII)	Ig1	Ig2	Total sample
Number of farmers		3	7	11	6	7	46
With organic rotation		3	5	0	4	2	20
With the presence of livestock		0	7	5	2	5	28
Pillar 1 - Minimum Mechanical Soil Disturbance							
Wheel Traffic	no. /year	10.45	1.21	3.91	4.41	2.78	3.74
Seeding	%	15.30	67.27	40.97	30.33	60.88	45.83
Powered	no. /year	1.90	0.09	0.89	1.00	0.19	0.65
Plowing	no. /year	0.61	0.11	0.00	0.51	0.03	0.16
Plowing Depth	cm	13.33	11.00	0.00	16.83	2.43	6.52
Pillar 2 – Maximum Soil Organic Cover							
Total Cover	days/year	227.56	360.89	339.90	313.38	353.65	332.80
Living Cover	days/year	220.37	358.17	319.68	300.08	343.40	321.10
Grassland Cover	%	0.00	67.05	0.00	29.93	5.88	20.02
ERP Cover	%	82.89	98.76	91.23	90.94	96.75	93.66
Spring Crops ERP Cover	%	59.49	8.94	42.08	37.99	21.79	33.12
Pillar 3 – Maximum Species Diversification							
Total Species	species/year	2.35	1.24	1.60	1.49	2.88	2.10
A+T Species	species/year	1.13	1.07	0.81	1.01	1.15	1.21

A+T Association	%	5.56	59.29	4.17	19.41	16.67	25.96
A+T Mixes	%	0.00	12.14	9.09	2.38	35.95	11.40
Tillage-intensive Crops	species/year	0.67	0.04	0.35	0.36	0.14	0.28

Chapter 5 – Appendices

Appendix M Description and results obtained on three other QST indicators

Description of the indicators:

i. One indicator associated to the early increase in soil mass soon after soil immersion in water: “t_{max}”, which represents the time to reach the maximum mass value. A high tmax value means that the sample is filling with water gently without decomposing too quickly.
ii. One indicator related to slopes in the decreasing part of the curve: “$slope_{30\text{-}60}$”, which signifies the local slope linked to weight loss between 30 and 60 seconds.

The t_{max} and $slope_{30\text{-}60}$ indicators are highly correlated with the fast-wetting of Le Bissonnais, suggesting that slaking plays an important role in the early stages of the QST (Vanwindekens and Hardy 2023).

iii. One indicator linked to threshold values of mass loss: “$dt_{50\text{-}75}$”. t50 and t75 represent the time needed to achieve 50% and 75% of relative mass loss between the maximum and the final mass of soil at the end of the QST experiment. “$dt_{50\text{-}75}$” corresponds to the time between 50% and 75% of mass loss. This indicator correlates more closely to the slow-wetting test of Le Bissonnais, suggesting that clay dispersion and differential swelling play an important role in the intermediate to late stages of the QST (Vanwindekens and Hardy 2023).

Descriptive statistics of some QST indicators of the surveyed fields

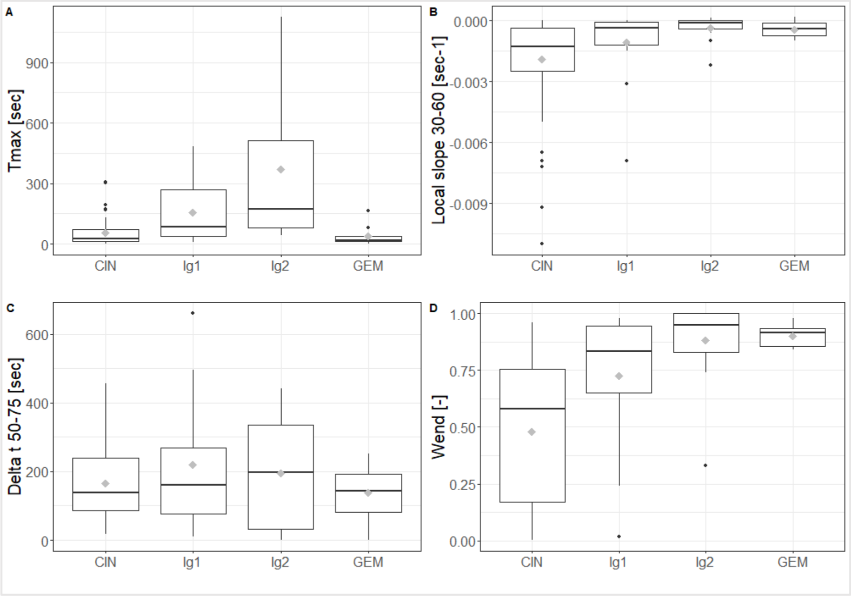
Indicator (unit)	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
t_{max} (sec)	1	16	49	143	143	1124
$slope_{30\text{-}60}$ (sec^{-1})	-1.10E-02	-1.50E-03	-4.70E-04	-1.24E-03	-1.38E-04	1.60E-04
$dt_{50\text{-}75}$ (sec)	0	79	142	176	248	662

Descriptive statistics of some QST indicators of the surveyed fields per CA-types (mean ± standard deviation)

Indicator (unit)	**CIN**	**Ig1**	**Ig2**	**GEM**	**All CA fields**
Number of fields	*10*	*3*	*4*	*2*	*19*
Number of samples	*59*	*16*	*21*	*12*	*140*
t_{max} (sec)	53 ±67	157 ±163	370 ±375	37 ±46	143±233
$slope_{30-60}$ (sec^{-1})	-1.93E-03 ±2.33E-03	-1.09E-03 ±1.81E-03	-3.60E-04 ±6.11E-04	-4.46E-04 ±3.95E-04	-1.24E-03 ±1.93E-0.3
dt_{50-75} (sec)	166 ±109	219 ±190	195 ±153	139 ±75	176 ±134

t_{max}, which represents the time required to reach the maximum sample mass, is shorter for GEM and CIN compared to Ig1 and Ig2. A higher t_{max} implies that the soil samples slowly fill with water without undergoing rapid decomposition. For the $slope_{30-60}$ indicator, a steeper slope is observed in CIN samples. No marked difference was observed for the dt_{50-75} indicator. CIN samples exhibit the lowest Wend values, which represents the fraction of the sample that has not undergone disaggregation.

It should be noted that t_{max} largely exceeds the values reported by Vanwindekens and Hardy (2023), where measurements were mainly within the range of 0 to 30 seconds for plowed fields and 0 to 90 seconds for reduced tillage fields.



Box fields of four of the QuantiSlake Test indicators across the four CA-types. The boxes represent the interquartile range (IQR) between the 25th and the 75th percentiles. The thin lines represent the minimum and the maximum values within 1.5 times the IQR from the lower and upper quartiles. Points beyond these lines are the outliers, represent by open dots. The thick line inside the box is the median. The grey diamond is the average.

Appendix N Raw values of soil characteristics, properties and quality indicators

Field code	Placement	CA type	Region	Soil type	tmax	Wend	slope 30-60	dt 50-75	SOC	C:N	pH KCl	CEC	Base saturation	pH	Clay (< 2 µm)	Silt (2 – 50 µm)	Sand (50-200 µm)	POXC	SOC:Clay	POXC : SOC
					sec	[-]	sec^{-1}	sec	%	[-]	[-]	cmol$_c$ kg^{-1}	%	[-]	%	%	%	mg/kg	[-]	[-]
1	A	unclassified	Lo	AbB	250.92	0.99	0.000052	107.4	1.235105	9.24219				7.94	15.7281	79.79131	4.480589	405.1393	0.078529	3.280201
1	B	unclassified	Lo																	
1	C	unclassified	Lo	Aba1	19.32	0.74	-0.0017	122.04	0.963957	8.610039	7.04	9.493952	100	7.89	14.73782	80.67018	4.591995	336.085	0.065407	3.486516
1	D	unclassified	Lo	AbB	4.69	0.91	-0.00084	133.99	1.038995	8.908303				7.97	14.98847	81.47578	3.535742	360.4082	0.06932	3.468815
1	E	unclassified	Lo		15.57	0.76	-0.0011	120.35												
1	F	unclassified	Lo	Aba1	3.84	0.85	-0.00044	92.11	1.069728	9.204506	6.89	16.18693	91.86837	8.01	14.99539	81.12888	3.875731	347.012	0.071337	3.243927
2	A	CIN	SLo	Aba(b)1	10.03	0.004	-0.0019	431.04	1.004716	8.445518	6.31	12.1154	97.98989	7.51	11.77764	80.87312	7.349246	334.1786	0.085307	3.326099
2	B	CIN	SLo		14.73	0.032	-0.0016	227.12												
2	C	CIN	SLo	Aba(b)1	9.64	0.0021	-0.0024	120.15	0.932411	8.765462				7.45	16.2037	76.00308	7.79321	329.2892	0.057543	3.531589
2	D	CIN	SLo	Aba(b)1	11.85	0.022	-0.0012	304.49	1.012916	8.191067				7.53	13.73836	80.14044	6.121202	347.558	0.073729	3.431263
2	E	CIN	SLo		15.78	0.018	-0.0026	142.46												

2	F	CIN	SLo	Aba(b)1	9.77	0.0039	-0.0017	152.89	0.888545	8.528817	6.62	9.048732	100	7.7	10.90226	80.07519	9.022556	333.2565	0.081501	3.750588
3	A	CIN	Lo	Aba1	23.41	0.69	-0.00057	262.75	0.910531	8.594862	5.76	10.66088	100	7.16	13.44499	81.05409	5.500922	362.4764	0.067723	3.980932
3	B	CIN	Lo		63.37	0.3	-0.00021	278.48												
3	C	CIN	Lo	Aba1	57.17	0.82	-0.00047	109.2	1.016855	9.054019				7.18	16.62543	77.7142	5.660377	424.3718	0.061163	4.173374
3	D	CIN	Lo	Aba1	172.86	0.81	-0.00025	65.61	1.133876	9.321143	6.14	10.86998	88.67283	7.29	12.36667	78.83753	8.795795	443.18	0.091688	3.90854
3	E	CIN	Lo		56.14	0.58	-0.00038	87.61												
3	F	CIN	Lo	Aba1	194.87	0.91	-3.1E-05	62	0.943881	8.699767				7.44	16.38577	77.63733	5.976904	356.7553	0.057604	3.779664
5	A	Ig1	Lo	Ldc	80.04	0.76	-0.00042	76.41	1.26761	10.69794				8.07	12.29445	45.71999	41.98556	365.1672	0.103104	2.880754
5	B	Ig1	Lo		111.05	0.82	-0.00038	659.61												
5	C	Ig1	Lo	Ldc	117.44	0.77	-0.00028	333.19	1.165891	9.57884	7.74	10.3949	100	8.23	12.09614	48.77478	39.12908	371.9863	0.096385	3.190574
5	D	Ig1	Lo	Ldc					1.400302	10.77948				7.85	10.45377	60.39957	29.14666	476.5534	0.133952	3.403219
5	E	Ig1	Lo		293.81	0.85	-0.0014	131.17												
5	F	Ig1	Lo	Ldc	260.23	0.93	0.000022	169.2	1.094971	9.687551	7.43	10.21245	100	8.09	11.59375	54.87711	33.52914	384.8398	0.094445	3.514611

6	A	Ig2	Con	A-Gbp1	57.17	0.77	-0.00035	196.6	1.116381	9.588468				7.46	14.43959	81.1739	4.386513	445.0883	0.077314	3.986883
6	B	Ig2	Con																	
6	C	Ig2	Con	A-Gbp1	42.35	0.83	-0.001	314.99	1.445675	10.09808	7.18	9.033004	100	7.93	15.37786	79.8184	4.803749	441.5276	0.09401	3.054127
6	D	Ig2	Con	A-Gbp1	78.4	0.74	-0.00063	354.79	1.176865	9.010703	6.37	9.794587	100	7.57	15.1751	79.76654	5.058366	476.163	0.077552	4.04603
6	E	Ig2	Con		56.26	0.33	-0.0022	440.89												
6	F	Ig2	Con	Aba1	43.68	0.74	-0.00031	240.88	1.209333	8.561977				7.37	22.09645	74.04249	3.861064	455.4465	0.05473	3.766096
8	A	GEM	Fag	Aba0	51.35	0.94	0.00016	166.78	1.882711	9.379094				7.35	20.33156	71.16046	8.507977	634.0936	0.0926	3.367982
8	B	GEM	Fag		81.39	0.84	-0.00011	76.67												
8	C	GEM	Fag	Aba0	15.9	0.86	-0.00047	225.35	1.417032	9.054696	5.79	12.33154	65.25602	6.82	13.17217	75.93368	10.89416	469.5918	0.107578	3.313912
8	D	GEM	Fag	kuAba2	26.35	0.87	-0.001	251.9	1.701265	8.992612				7.09	16.22624	76.49513	7.278628	559.029	0.104847	3.285961
8	E	GEM	Fag		14.61	0.95	-0.00013	221.81												
8	F	GEM	Fag	Aba0	32.13	0.93	-0.00043	152.94	1.645653	8.989035	6.04	15.39419	68.45293	7.12	16.67701	74.46478	8.858207	553.5535	0.098678	3.363731
10	A	CIN	Con	Aba1	20.59	0.085	-0.0072	22.74	1.342155	10.44199	7.23	11.3218	100	8.06	13.51978	75.71075	10.76947	335.3486	0.099273	2.498583
10	B	CIN	Con		7.59	0.16	-0.0043	147.85												

10	C	CIN	Con	Aba 1	25.8	0.33	-0.0028	185.31	1.089526	8.825626	7.25	12.08809	100	8.18	17.14998	74.05675	8.793264	342.8884	0.063529	3.147135
10	D	CIN	Con	Aba 1	34.57	0.48	-0.0021	120.11	1.035157	8.859796				8.09	16.3822	74.29137	9.326425	327.9876	0.063188	3.168483
10	E	CIN	Con		47.32	0.057	-0.0017	43.79												
10	F	CIN	Con	Aba 1	33.73	0.13	-0.00048	402.12	1.040401	8.662086				8.21	16.98579	74.11983	8.89438	344.8637	0.061251	3.314718
11	A	CIN	Con	(x)Aba	27.52	0.41	-0.0015	98.69	2.38165	13.40016				8.07	22.84343	66.59439	10.56218	522.793	0.10426	2.195087
11	B	CIN	Con		30.66	0.71	-0.00048	98.38												
11	C	CIN	Con	Aba 1	21.7	0.68	-0.0007	262.88	1.450945	8.532095	7.18	19.34114	85.63259	8.1	21.87749	59.2681	18.85442	503.785	0.066321	3.472116
11	D	CIN	Con	Aba 1	4.81	0.63	-0.003	138.52	1.297858	9.202547				8.19	18.51292	73.29606	8.191023	477.6896	0.070106	3.680599
11	E	CIN	Con		25.34	0.65	-0.0022	302.7												
11	F	CIN	Con	Aba 1	22.71	0.69	-0.00048	247.26	1.345468	8.898916	7.46	15.64402	100	8.23	18.18035	70.29735	11.5223	489.974	0.074007	3.641663
13	A	CIN	Lo	Aba 1	170.4	0.89	-0.00027	123.47	1.113242	9.844429	6.35	7.451477	100	7.37	9.161886	86.04207	4.796048	397.0009	0.121508	3.56617
13	B	CIN	Lo		80.16	0.9	-0.00074	153.32												
13	C	CIN	Lo	Aba 0	8.59	0.39	-0.0029	137.98	1.188972	8.854754				6.93	18.11	76.465	5.425	374.3168	0.065653	3.148238

13	D	CIN	Lo	Aba0	38.92	0.76	-0.00055	229.99	1.206361	10.41134				6.97	11.56484	82.94784	5.487319	392.5256	0.104313	3.253798
13	E	CIN	Lo		93.15	0.75	-0.00066	390.37												
13	F	CIN	Lo	Aba1					1.297328	10.24313	6.41	8.098983	100	7.28	12.02308	83.36005	4.616864	406.7078	0.107903	3.134966
19	A	GEM	Her	Gbbfi2	0.92	0.92	-0.00039	181.17	2.857314	8.972631	5.6	15.38336	56.62653	6.69	8.79397	71.18928	20.01675	583.8331	0.324917	2.043293
19	B	GEM	Her		22.22	0.92	-0.00035	82.12												
19	C	GEM	Her	fGbb2	6.66	0.84	-0.00098	110.24	3.212441	9.355352				6.5	11.96363	66.59754	21.43883	639.16	0.268517	1.98964
19	D	GEM	Her	Gbb0_1	15.31	0.91	-0.001	133.31	3.035943	9.269612				6.39	9.109632	71.68884	19.20152	634.0467	0.333267	2.088467
19	E	GEM	Her		10.71	0.85	-0.00064	64.71												
19	F	GEM	Her	Gbbfi2	166.45	0.98	-1.5E-05	0	2.765586	9.067622	5.88	14.8136	68.70642	6.78	12.33997	69.41231	18.24772	618.8364	0.224116	2.237632
20	A	Ig1	Her	Gbb0_1	394.87	0.97	-0.00001	10.96	2.083685	9.216445				6.6	25.44125	51.28001	23.27874	500.9128	0.081902	2.403975
20	B	Ig1	Her		91.83	0.94	-9.6E-05	76.51												
20	C	Ig1	Her	Gbb0_1	481.7	0.97	-1.6E-05	247.43	2.300939	9.322904				6.42	20.99111	59.26901	19.73988	537.9052	0.109615	2.337764
20	D	Ig1	Her	Gbb0_1	76.64	0.96	-0.00033	123.32	3.109768	10.99639	5.12	17.59452	62.17041	6.29	21.71775	55.3188	22.96345	567.8957	0.14319	1.826167

20	E	Ig1	Her		55.41	0.81	-0.0015	494.59												
20	F	Ig1	Her	Gbb0_1	447.58	0.98	-9.2E-06	247.58	2.133402	9.727254	5.46	14.18525	75.3564	6.61	15.06722	52.54211	32.39067	562.3211	0.141592	2.635796
21	A	Ig2	Jur	j-wLba2	456.56	1	-8.3E-06	0	1.232964	8.568056				6.7	13.50934	22.77289	63.71777	380.9756	0.091268	3.089916
21	B	Ig2	Jur		1123.92	1														
21	C	Ig2	Jur	j-wLba2					1.265616	8.436733	5.19	10.34872	70.50109	6.62	17.81113	28.04305	54.14582	367.2721	0.071058	2.901923
21	D	Ig2	Jur	j-wLba2	272.76	1	-4E-06	0	1.34943	8.385344	4.99	11.54317	74.09535	6.42	19.70676	25.61879	54.67444	366.7998	0.068475	2.718184
21	E	Ig2	Jur		512.82	1		0												
21	F	Ig2	Jur	j-wLba2	170.51	1	-3.2E-05	0	1.339405	8.743512				6.75	16.03281	22.74422	61.22297	368.7711	0.083541	2.753247
22	A	CIN	Lo	Aba1	6.36	0.1	-0.0014	417.21	0.969021	8.663964	6.53	11.57276	100	7.41	27.57353	68.3344	4.092072	315.6301	0.035143	3.257208
22	B	CIN	Lo		8.63	0.64	-0.0017	112.66												
22	C	CIN	Lo	Aba1	17.38	0.41	-0.002	120.88	1.130013	8.892889	6.71	12.39306	100	7.45	17.0834	78.81659	4.100016	439.2073	0.066147	3.886746
22	D	CIN	Lo	Aba1	76.68	0.95	-0.00049	277.93	0.98671	8.979673				7.61	16.36126	79.2612	4.377545	330.4536	0.060308	3.349044
22	E	CIN	Lo		9.62	0.6	-0.0014	273.38												
22	F	CIN	Lo	Abp(c)	17.27	0.77	-0.0013	455.36	1.019002	8.790131				7.46	9.340906	86.68361	3.97549	385.9392	0.10909	3.787424

25	A	unclassified	Lo	Aba1					1.345914	10.01683				7.09	19.65718	66.04812	14.2947	477.1294	0.068469	3.54502
25	B	unclassified	Lo		23.57	0.63	-0.00071	93.67												
25	C	unclassified	Lo	Aba1					1.248244	9.059593	6.13	10.96771	99.71736	7.07	13.2893	74.09794	12.61276	493.3051	0.093928	3.951993
25	D	unclassified	Lo	Aba1	44.38	0.93	-0.00032	87.87	1.417572	8.898129				6.9	19.93122	66.8282	13.24058	497.2515	0.071123	3.50777
25	E	unclassified	Lo		17.27	0.9	-0.0002	230.11												
25	F	unclassified	Lo	Aba1	18.15	0.74	-0.00072	153.32	1.176176	9.194221	5.84	12.47295	86.18938	6.85	16.13647	69.9247	13.93884	447.424	0.072889	3.804056
26	A	unclassified	Lo	Aca0	65.96	0.56	-0.00028	202.35	1.444602	8.582315	7.47	18.51756	100	8.06	19.0898	60.70556	20.20464	537.0183	0.075674	3.717413
26	B	unclassified	Lo		28.68	0.057	-0.0011	280.9												
26	C	unclassified	Lo	Aca0	9.55	0.065	-0.0072	56.52	1.17389	9.217921				7.13	14.49065	56.87582	28.63353	400.328	0.08101	3.410269
26	D	unclassified	Lo	Aca0	87.72	0.5	-0.00014	247.53	1.173828	8.505329	6.4	15.10992	97.86931	7.26	17.36898	61.54659	21.08443	404.7327	0.067582	3.447973
26	E	unclassified	Lo																	
26	F	unclassified	Lo	Aca0	79.94	0.92	0.0001	318.37	1.393311	8.521236				8.15	29.16795	48.74117	22.09088	498.6767	0.047769	3.579076
28	A	CIN	Lo	OE	44.05	0.28	-0.00018	154.62	1.354246	9.695745				7.84	15.19757	72.38841	12.41401	478.6468	0.089109	3.534415

28	B	CIN	Lo		17.07	0.24	-0.0045	81.6												
28	C	CIN	Lo	Aba(b)1	305.34	0.81	-0.00019	92.87	1.508837	11.27148	6.54	12.73847	98.40797	7.48	19.96986	73.474	6.556142	472.5906	0.075556	3.132152
28	D	CIN	Lo	Aba(b)1	103.3	0.7	-0.00021	109.17	1.60262	11.2837	6.37	12.10817	100	7.31	20.69019	74.17239	5.137414	432.2738	0.077458	2.697294
28	E	CIN	Lo		125.43	0.73	-6.5E-05	169.43												
28	F	CIN	Lo	Aba(b)1	90.35	0.72	-0.00011	153.79	1.313288	9.335478				7.65	16.18762	78.56918	5.243209	444.5854	0.081129	3.385285
30	A	unclassified	Con	ADa0	196.52	0.91	-0.00003	340.23	2.315845	11.10992	6.34	12.79289	100	7.31	18.49811	72.02456	9.47733	549.526	0.125194	2.372896
30	B	unclassified	Con		282.68	0.96	-0.00011	21.75												
30	C	unclassified	Con	Afp	87.19	0.83	-0.00001	87.53	2.799964	13.52787				7	17.47419	73.86815	8.657665	537.0183	0.160234	1.917947
30	D	unclassified	Con	ADa0	273.52	0.96	-4.8E-06	154.75	1.350905	9.516566	6.86	10.38318	100	7.7	17.88553	76.31161	5.802862	405.0938	0.075531	2.998684
30	E	unclassified	Con		630.3	0.98		62.13												
30	F	unclassified	Con	ADa1	756.65	1		0	2.156326	11.21174				8.13	19.47344	73.99907	6.527496	505.3369	0.110732	2.343508
31	A	Ig2	SLo	Abp	171.18	0.83	0.000018	145.15	1.000999	8.932096	6.39	7.993959	100	7.31	14.26369	67.46338	18.27294	363.447	0.070178	3.630842
31	B	Ig2	SLo		479.66	0.95		123.8												
31	C	Ig2	SLo	Abp					1.126612	8.898545	6.34	8.831002	100	7.18	15.3737	75.2917	9.334595	452.793	0.073282	4.019067

31	D	Ig2	SLo	Abp	116.69	0.88	0.00013	272.98	1.062605	8.964921				7.1	14.93946	72.73156	12.32898	432.2358	0.071127	4.067699
31	E	Ig2	SLo		173.8	0.75	-0.00012	335.5												
31	F	Ig2	SLo	AbB	135.41	0.86	-0.00041	376.98	1.026902	8.621615				7.34	20.85586	64.88491	14.25923	394.3903	0.049238	3.840584
32	A	unclassified	Con	Gbbk4	207.49	0.95	0.000033	228.91	1.353243	8.693763	5.96	8.600403	96.46408	6.72	17.75461	64.2188	18.02659	481.6528	0.076219	3.559249
32	B	unclassified	Con		271.97	0.98	-1.4E-05	22.02												
32	C	unclassified	Con	Gbax4	207.47	0.94	-0.00012	151.71	1.533513	9.048584				6.86	24.91567	62.86415	12.22018	551.6074	0.061548	3.597018
32	D	unclassified	Con	Gbax4	115.32	0.81	-0.00039	72.8	1.066352	9.604205				6.79	15.36159	61.44635	23.19206	379.6109	0.069417	3.559902
32	E	unclassified	Con		502.11	0.97	-1.6E-05	186.11												
32	F	unclassified	Con	Gbbk4	1095.9	1			1.294285	9.279461	5.72	15.12485	79.65769	6.96	28.8291	60.61502	10.55588	481.4634	0.044895	3.719919
33	A	CIN	SLo	Aba1	119.89	0.83	-0.00041	120.09	0.9922	9.27972				6.85	14.43988	78.27937	7.280742	326.8969	0.068712	3.294668
33	B	CIN	SLo		82.55	0.83	-0.00035	98.52												
33	C	CIN	SLo	Aba1	130.35	0.86	-4.8E-06	152.99	1.050711	10.13481	5.64	9.632162	85.33642	6.66	14.10061	78.125	7.77439	316.0502	0.074515	3.007966
33	D	CIN	SLo	Aba1	125.24	0.94	-0.00033	207.85	1.008653	9.133296	5.75	9.018319	100	6.76	14.92423	77.68253	7.393234	364.35	0.067585	3.612244

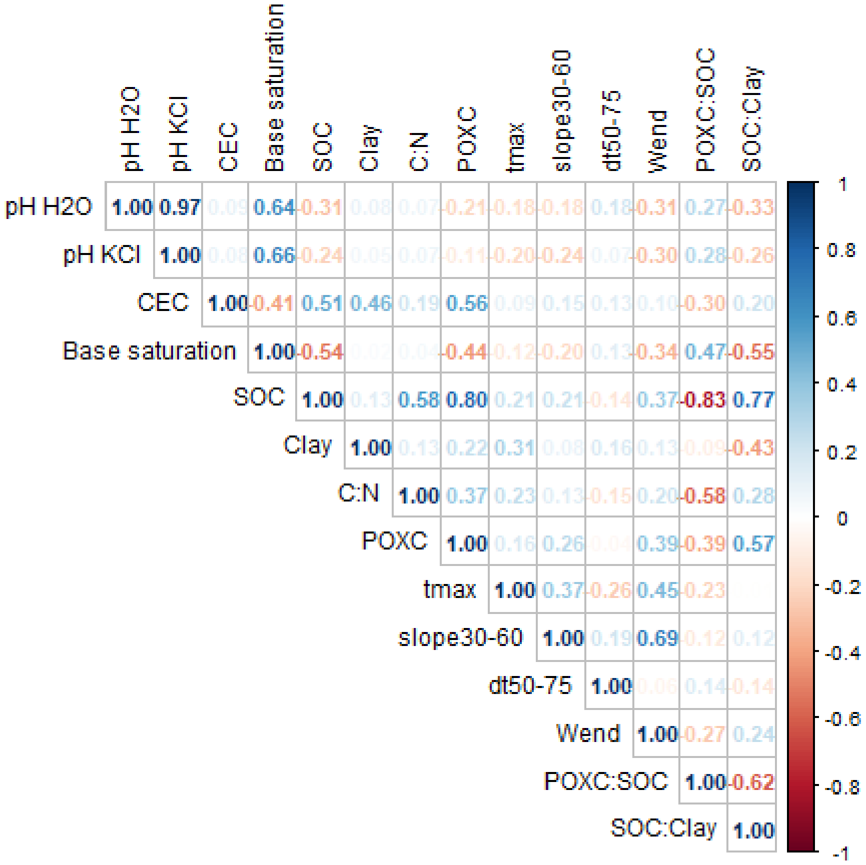
33	E	CIN	SLo		63.05	0.9	-4.8E-06	54.83												
33	F	CIN	SLo	Abp0_1	304.56	0.96	9.6E-06	116.22	1.002815	8.682655				6.84	17.22248	75.93549	6.842023	374.6341	0.058227	3.735824
35	A	CIN	Lo	Aba(b)0	12.8	0.0074	-0.0065	16.86	1.03658	8.910383	6.2	9.406589	94.39304	7.04	15.32097	78.13697	6.542056	336.7269	0.067658	3.24844
35	B	CIN	Lo		15.05	0.014	-0.011	64.11												
35	C	CIN	Lo	Aba(b)0	13.43	0.18	-0.0032	64.26	1.098612	9.097764				7.73	14.14157	79.11634	6.742088	428.0286	0.077687	3.896085
35	D	CIN	Lo	Aba(b)0	14.09	0.24	-0.005	64.37	1.201638	9.095361	6.52	9.586712	100	7.38	14.81597	78.75858	6.425452	485.9236	0.081104	4.043845
35	E	CIN	Lo		26.8	0.31	-0.0023	87.2												
35	F	CIN	Lo	Aba(b)0	14.69	0.073	-0.0029	65.68	1.149792	9.046691				7.13	14.17064	76.4469	9.382458	441.5463	0.081139	3.840226
36	A	CIN	Lo	Aca1	12.71	0.73	-0.0019	75.15	1.113339	8.667098	6.88	11.75352	100	7.74	19.81103	75.8153	4.373666	417.6715	0.056198	3.751521
36	B	CIN	Lo		7.05	0.58	-0.00053	251.88												
36	C	CIN	Lo	Adp(c)	7.74	0.21	-0.0092	146.57	0.813349	7.855022	6.73	12.02263	100	7.67	21.54177	75.39621	3.06201	309.5121	0.037757	3.805402
36	D	CIN	Lo	ADa1	31.79	0.53	-0.00036	76.63	0.963274	8.353615	7.43	12.44362	100	8.12	19.9819	76.15744	3.860654	412.7758	0.048207	4.285135
36	E	CIN	Lo		0.95	0.21	-0.0038	321.23												
36	F	CIN	Lo	ADp0_1	9.43	0.05	-0.0069	44.63	1.11088	8.035631	7.68	10.16618	100	8.1	16.05505	78.74618	5.198777	407.6105	0.069192	3.669258

38	A	unclassified	Con	sAba2_3	8.81	0.8	-0.0006	433.42	1.696379	9.644942				7.9	20.27448	73.30006	6.425452	529.8476	0.083671	3.123404
38	B	unclassified	Con		755.75	0.99		0												
38	C	unclassified	Con	sAba2_3	24.21	0.84	-0.0003	461.93	1.662248	10.26615				7.97	23.64812	64.63818	11.7137	470.4297	0.070291	2.830082
38	D	unclassified	Con	Aba1	35.99	0.94	-0.00015	662.3	1.390965	9.415428	7.34	13.84499	100	7.96	21.18318	74.71884	4.097982	466.1123	0.065664	3.351001
38	E	unclassified	Con		50.56	0.91	-0.00026	32.82												
38	F	unclassified	Con	Aba1	6.4	0.59	-0.0014	307	1.687414	10.5698	7.09	16.92011	93.03223	7.79	22.46321	72.03719	5.499613	528.0836	0.075119	3.129543
39	A	Ig1	Lo	Aba(b)1	7.63	0.018	-0.0069	53.73	1.472428	10.29243	6.26	13.24981	85.41837	7.2	16.44222	77.12183	6.435954	448.3023	0.089552	3.044646
39	B	Ig1	Lo		9.06	0.32	-0.0031	149.29												
39	C	Ig1	Lo	Aba(b)0					1.737956	10.25123				7.15	18.03639	74.89021	7.0734	515.9245	0.096358	2.968571
39	D	Ig1	Lo	Abp(c)	22.13	0.93		10.77	1.918575	10.88963				7.23	20.02198	72.23618	7.741835	565.3891	0.095823	2.946922
39	E	Ig1	Lo		23.98	0.32	-0.00097	230.37												
39	F	Ig1	Lo	Aba(b)1	41.61	0.24	-0.001	496.49	1.227002	9.786086	6.14	16.18445	85.27042	7.11	20.1145	74.65573	5.229769	417.6715	0.061001	3.404
40	A	Ig2	Con	GbBK2	122.83	0.91	0.000012	131.56	2.141752	11.35244				7.38	23.94411	70.26221	5.793688	559.5339	0.089448	2.612505

40	B	Ig2	Con		1006.04	1														
40	C	Ig2	Con	A-Gbp1	1002.82	1			1.656592	9.54154				7.22	23.14452	72.57178	4.283697	483.1097	0.071576	2.916287
40	D	Ig2	Con	A-Gbp1	73.82	0.96	-0.00014	349.71	1.657306	9.335957	5.36	10.62263	89.89323	6.44	18.25385	75.73404	6.012117	368.2185	0.090792	2.221789
40	E	Ig2	Con		1036.12	1														
40	F	Ig2	Con	A-Gbp1	633.41	0.98		30.94	3.077877	15.35685	7.29	15.90911	100	7.79	20.64803	52.81131	26.54066	550.1483	0.149064	1.787428
30	G	unclassified	Con																	

Appendix O Correlation coefficients of soil properties and soil quality indicators

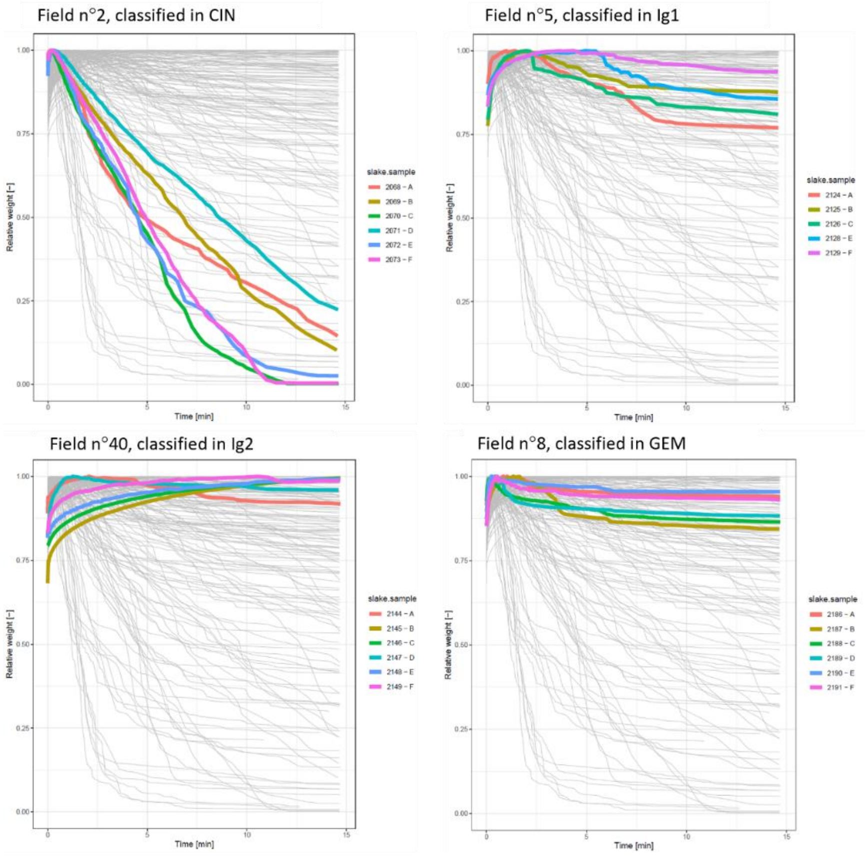
It should be noted that samples for QST were taken at depths ranging from 2 to 7 cm, distinct from those collected for chemical properties (0-30 cm).



	pH H2O	pH KCl	CEC	Base saturation	SOC	Clay	C:N	POXC	tmax	slope30-60	dt50-75	Wend	POXC:SOC	SOC:Clay
pH H2O	1.00	0.97	0.09	0.64	-0.31	0.08	0.07	-0.21	-0.18	-0.18	0.18	-0.31	0.27	-0.33
pH KCl		1.00	0.08	0.66	-0.24	0.05	0.07	-0.11	-0.20	-0.24	0.07	-0.30	0.28	-0.26
CEC			1.00	-0.41	0.51	0.46	0.19	0.56	0.09	0.15	0.13	0.10	-0.30	0.20
Base saturation				1.00	-0.54	0.02	0.04	-0.44	-0.12	-0.20	0.13	-0.34	0.47	-0.55
SOC					1.00	0.13	0.58	0.80	0.21	0.21	-0.14	0.37	-0.83	0.77
Clay						1.00	0.13	0.22	0.31	0.08	0.16	0.13	-0.09	-0.43
C:N							1.00	0.37	0.23	0.13	-0.15	0.20	-0.58	0.28
POXC								1.00	0.16	0.26	-0.04	0.39	-0.39	0.57
tmax									1.00	0.37	-0.26	0.45	-0.23	[illegible]
slope30-60										1.00	0.19	0.69	-0.12	0.12
dt50-75											1.00	-0.06	0.14	-0.14
Wend												1.00	-0.27	0.24
POXC:SOC													1.00	-0.62
SOC:Clay														1.00

Appendix P QST curves of four CA fields, representative of their respective CA-type.

Curves are designed by Vanwindekens and Hardy (2023). The figure shows the QST curves of four different fields. Some soil samples were completely degraded (e.g. field 2), while others have practically remained intact after immersion (e.g. field 40).



Chapter 6 – Appendices

Appendix Q Summary of variables by farmer

Legend: Utilised agricultural area (UAA), Conservation Agriculture (CA), Organic Farming (OF), Organic Conservation Agriculture (OCA)

Farmer's code	**CA-type**	**Agricultural region**	**Livestock**	**UAA (ha)**	**Farm takeover**	**Start of CA**	**Conversion to OF**	**Start of OCA**
0	GEM	Limoneuse	yes	75	1992	1995	2017	2017
1	unclassified	Limoneuse	yes	187	1987	1999	2012	2012
2	CIN	Sablo-limoneuse	no	580	2003	2009		
3	CIN	Limoneuse	yes	120	1983	2001		
4		Sablo-limoneuse	no	1000	2010	2014		
5	Ig1	Limoneuse	yes	450	2020		2011	2011
6	Ig2	Condroz	no	109	1998	1998		
7	Ig2	Condroz	yes	285	1983	1985		
8	GEM	Fagne	yes	145	1996	2014	2020	2020
9	Ig2	Fagne	yes	200	2008	2020	2019	2017
10	CIN	Condroz	yes	170	2008	2000	2013	2013
11	CIN	Condroz	yes	500	1986	1991		
12	unclassified	Famenne	yes	120	1998	2017		

13	CIN	Limoneuse	no	144	1987	2001		
14	unclassified	Haute Ardenne	yes	130	2006	2018		
20	GEM	Haute Ardenne	yes	200	2006	2007		
16	GEM	Ardenne	yes	74	2002		2020	2020
17		Ardenne	no	100	2020	2020		
18	unclassified	Limoneuse	yes	234	2000	2017		
19	GEM	Herbagère	yes	169	1980	1991		
20	Ig1	Herbagère	yes	80	2002	2011		
21	Ig2	Jurassique	yes	148	2001	2011	2014	2020
22	CIN	Limoneuse	yes	204	1988	2005		
23	GEM	Condroz	yes	86	2005	1992	2018	2018
24	CIN	Jurassique	yes	120	1994	2011		
25	unclassified	Limoneuse	yes	100	1988	2000		
26	unclassified	Limoneuse	yes	75	2002	2005	2014	2014
27	Ig1	Ardenne	no	95	1997	1998		
28	CIN	Limoneuse	no	130	1986	2001		
29	Ig1	Limoneuse	no	0	1990	2001	2000	2018
30	unclassified	Condroz	no	200	1974	1991		
31	Ig2	Sablo-limoneuse	yes	128	1985	2001		

32	unclassified	Condroz	yes	200	1993	1991		
33	CIN	Sablo-limoneuse	no	177	2000	1991		
34	unclassified	Limoneuse	yes	45	1986	2007	2020	2016
35	CIN	Limoneuse	no	70	2006	2006		
36	CIN	Limoneuse	no	78	1985	2003		
37	Ig2	Condroz	yes	90	1980	2016	2018	2018
38	unclassified	Condroz	yes	291	2020		2007	2017
39	Ig1	Limoneuse	no	210	2020		2020	2020
40	Ig2	Condroz	no	140	1989	1995		
41	GEM	Famenne	yes	85	1988	2001	2000	2020
42	CIO	Limoneuse	no	135	2012	2001	2008	2008
43	CIO	Sablo-limoneuse	no	300	2016	2006	2020	2016
44	CIO	Limoneuse	no	100		2000	2014	2016
45	Ig1	Limoneuse	no	410	1984	2002	2018	2018
46	unclassified	Condroz	no	200	2002	1998	2020	2020
47	unclassified	Limoneuse	no	200	2001	2003	2020	2018

Appendix R French version of verbatim

[1] « Le fermier, il a peur de rater. Il a peur de faire moins (de rendement) que le voisin. Moi, ce n’est pas mon cas. » (31)

[2] « Moi la routine... Bah je ne vous cache pas, moi il y a des jours où j'ai mal au ventre (de stress). Parce que quand on fait des choses où on ne connait pas le résultat, il y a des jours où ce n’est pas évident. Mais jusqu'à maintenant, ça (le risque) m'attire plus que de ne pas changer (mes pratiques). » (36)

[3] « Je le fais aussi parce que moi je suis en fin de carrière, et que tant qu’à faire, puisque mes enfants s’intéressent à (reprendre) la ferme, autant que ce soit moi qui prenne le risque de la conversion (vers le non-labour en bio) plutôt qu’eux. » (37)

[4] « Donc la propriétaire m'a dit : « *prénom*, ça c'est la ligne. Bio non-labour, je veux arriver à ça, ok ? », j'ai dit : « Wow, pour y arriver il va falloir mettre des moyens et ça doit venir de partout. ». Elle a dit « Faut ce qu'il faut ». » (5)

[5] « Il faut faire le gros dos pendant 2-3 ans, financièrement quoi. » (37)

[6] « On a encore besoin de tracteurs. On a encore besoin de matériel et peut-être même plus qu’avant. Mais il faut travailler dans le sens de la nature quoi. Donc c'est vraiment acheter ou inventer du matériel qui est adapté aux objectifs qu’on veut se fixer. » (37)

[7] « […] ici je veux garder des bovins car il faut vraiment avoir une liaison avec le sol et ce qu’il produit. Dans cette région-ci, le fourrage a sa place. Et pour le valoriser, il faut un ruminant. » (10)

[8] « Bah ça c'est une évolution, c'est une réflexion assez profonde. L'agroforesterie, c'est une réflexion assez profonde. Du jour au lendemain, vous commencez les TCS, et tout ça. Vous ne voyez pas l'importance de ça. Et pourtant ça a beaucoup d'importance. C'est l’avènement d'un système. Et vous commencez à bien le maîtriser et à comprendre que toutes ces petites sources de bienfaits pour la terre, forment quelque chose de génial au final. » (31)

[9] « Donc en fait depuis que je travaille à l’extérieur j’ai quand même diminué fortement certaines activités : j’ai arrêté les betteraves, les pommes de terre, en 2011 j’ai arrêté les betteraves quand l’Europe a fait la réforme en sucre. Et que le prix de vente est passé de 45 EUR la tonne à 25. Là j’ai considéré que ce n’était plus intéressant. Et pomme de terre, j’ai arrêté quand je suis passé en bio parce que, quand je suis passé en bio, ça n’avait pas de sens de produire des pommes de terre bio et de devoir les vendre en conventionnel, tu ne sais pas rentabiliser. Et là j’ai arrêté parce que je n’ai pas le temps. Il fallait que je simplifie. » (0)