CH10 -Advances in the reduction of herbicide use in Conservation Agriculture systems

Stéphane Cordeau, Violaine Deytieux, Maé Guinet, Nicolas Munier-Jolain, Guillaume Adeux

To cite this version:

Stéphane Cordeau, Violaine Deytieux, Maé Guinet, Nicolas Munier-Jolain, Guillaume Adeux. CH10 - Advances in the reduction of herbicide use in Conservation Agriculture systems. Weed management in conservation agriculture, 2025. ⟨hal-04982344⟩

HAL Id: hal-04982344

https://hal.inrae.fr/hal-04982344v1

Submitted on 7 Mar 2025

CH10 - Advances in the reduction of herbicide use in Conservation Agriculture systems

Publisher:	*Burleigh Dodds Science Publishing*
Manuscript ID	BDSP-BK-2024-0086.R2
Manuscript Type:	Book
Date Submitted by the Author:	n/a
Complete List of Authors:	Cordeau, Stephane; INRAE, Agroécologie, AgroSup Dijon, INRAE, Univ. Bourgogne, Univ. Bourgogne Franche-Comté DEYTIEUX, Violaine; U2E Domaine d'Epoisses GUINET, Maé; Agroécologie MUNIER-JOLAIN, Nicolas; Agroécologie ADEUX, Guillaume; Agroécologie
Keywords:	weeds, multiperformance, cropping system experiment, farmer network, CA-SYS platform, Agroecology

Weed management in Conservation Agriculture systems - Chapter 10

Advances in the reduction of herbicide use in conservation agriculture – French case studies

Stéphane Cordeau[1]*, Violaine Deytieux[2], Maé Guinet[1], Nicolas Munier-Jolain[1], Guillaume Adeux[1]

[1] Agroécologie, INRAE, Institut Agro, Univ. Bourgogne, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France

[2] INRAE, U2E, Unité Expérimentale du domaine d'Epoisses, F-21110 Bretenière, France

* Correspondence:

Stéphane Cordeau,

Agroécologie - INRAE, 17 rue Sully, BP 86510, F-21065 Dijon Cedex, France

stephane.cordeau@inrae.fr

ORCID

Stéphane Cordeau: https://orcid.org/0000-0003-1069-8388

Maé Guinet: https://orcid.org/0000-0001-9904-4692

Nicolas Munier-Jolain: https://orcid.org/0000-0002-0871-3692

Guillaume Adeux: https://orcid.org/0000-0003-0903-391X

Abstract

Conservation agriculture (CA) appears as a promising agricultural pathway to achieve multiperformance but is currently questioned due to its reliance on herbicides for weed management, especially glyphosate. One limit in the development of CA-based agroecological cropping system less reliant on herbicide use is the strict definition of CA based on technical means (i.e. the three principles) rather than targeted objectives. In this chapter, we mobilize research carried out on experimental stations (e.g. CA-SYS platform) and farmer networks (e.g. French DEPHY-farm network) to synthesize knowledge on how herbicide-free no-till agriculture could be achieved. We provide insights on the multiperformance of herbicide-free and nature-based CA systems compared to reference CA systems. Designing cover crops to ensure growth in a context of unpredictable weather conditions and facilitate mechanical termination, and ensuring crop establishment in absence of tillage and herbicides represent major research avenues for the development of pesticide-free CA systems.

Keywords: weeds, multiperformance, cropping system experiment, farmer network, cover crops, crop rotation, design, Agroecology, CA-SYS platform

1 Introduction

According to the FAO, conservation agriculture (CA) is defined as a farming system or production strategy which implements three principles simultaneously and permanently over time (FAO, 2021): (i) absence of soil disturbance (exception made of the disturbance generated by the seeder); (ii) crop diversity in time (crop sequence, rotation) and space (intercropping, companion plants, cover crops); and (iii) maximum soil coverage by crop residues or sown cover crops (annual or permanent cover). This definition highlights that CA is currently characterized based on the technical means implemented, which have been described in greater depth and geographically contextualized in numerous studies (Kassam et al., 2009; Kassam and Friedrich, 2011; Friedrich et al., 2012; Kassam et al., 2019). More specifically, CA systems are defined as those in which no mechanical disturbance of the soil is carried out except by the seed drill (less than 15cm wide or 25% of the cultivated area), a practice known as no-till, no-tillage or zero-tillage, which grow more than three different crop species in pure stands or mixtures (of varieties or species), and which cover at least 70% of the soil surface with stubble, crop residues or dead or living cover crops at the time of sowing (Kassam et al., 2019). CA systems combine a diverse set of agricultural management practices (rotation, cover, sowing, fertilization, weeding, etc.) which may change as the system evolves (Knowler and Bradshaw, 2007; Vankeerberghen and Stassart, 2016; Derrouch et al., 2020).

Managing weeds has always been a challenge in no-till systems. The development of non-selective, effective, and inexpensive foliar herbicides for burn-down weed control prior to crop sowing such as aminotriazole (1958), paraquat (1963), glyphosate (1975) and glufosinate (1986) helped to control the development of perennial weeds, which are a major threat in reduced-tillage systems (Evans, 1972; Watson, 1974; Hoss et al., 2003). These herbicide applications at crop sowing (or just before) help managing all the weeds that established during the summer fallow period, that may compete with crops in its early stage and become difficult to control late in season, even with high dose of herbicide. The development of no-till and the increase use of glyphosate was then encourage by the development of herbicide-tolerant GM crops in 1996 (Green, 2018).

The number of herbicide active ingredients on the market is decreasing (Chauvel et al., 2022), thereby limiting the number of chemical solutions for farmers. Irrational use of a single herbicide over a long period of time may result in the development of resistant weed biotypes (Délye et al., 2013), shifts in weeds flora and negative effects on the succeeding crops (Owen, 2008; Grundy et al., 2011). Worldwide, the first glyphosate-resistant population of blackgrass (*Alopecurus myosuroides*) was identified in France in 2023 (R4P, 2023).

Nowadays, managing weeds remains challenging during and after the transition to CA (Derrouch et al., 2020) because banning tillage and favoring the accumulation of organic matter on the soil surface limit the number of weed management techniques or their efficacy (Cordeau, 2022). In CA, there are fewer weed control options because tillage is not allowed, and in-crop mechanical weeding is not possible due to the presence of living or dead mulch (Chauhan et al., 2012). This impacts weed community's taxonomic or functional composition (Derrouch et al., 2021a) and thus weeding tactics over time (Derrouch et al., 2020). Weed (including crop volunteer) management, as well as cover crop termination, mainly relies on herbicides such as glyphosate (Antier et al., 2020).

Reducing herbicide use in conservation agriculture is a challenging priority. This chapter gathers French data and experiences collected since 2007 by INRAE on long-term cropping systems experiments, factorial experiments and farmers' network with the objective of quantifying the performance of CA systems aiming to reduce pesticide use, especially in terms of weed management, crop performance and other technical and economic indicators.

2 Transitioning from tillage-based systems to conservation agriculture while using herbicide to manage weeds

Integrated weed management (IWM) promotes the use of multiple techniques to achieve sustainable weed control while reducing the reliance on chemical control. However, IWM strategies which reduce both herbicide usage and tillage intensity remain difficult to implement, because tillage is a pivotal weed management tool (Nazarko et al., 2005; Lechenet et al., 2016). Combining several weed management tactics such as crop diversification, cover cropping and increased seeding rates is encouraged to ensure that weed pressure does not transcribe into yield loss. CA proposes to diversify crop rotations and use cover crops to increase ecosystem services. However, the effects of diverse crop rotations including cover crops on weeds remain to be studied in the no-till system context (Chauhan et al., 2012; Adeux et al., 2021).

2.1 Long-term integrated weed management cropping system experiment

A unique technique rarely enables ambitious objectives to be achieved (Cordeau et al., 2020a). An in-depth redesign of the system is often necessary to achieve enhanced multi-performance (Hill and MacRae, 1995). In 2000, INRAE set up a long-term cropping system experiment to compare the efficacy of four IWM systems along a gradient of herbicide use, in comparison to a reference system.

The field experiment was conducted from harvest 2000 to harvest 2017 at the INRAE experimental farm in Bretenière (47° 14′ 11.2″ N, 5° 05′ 56.1″ E), 15 km southeast of Dijon, France. The site is subject to an oceanic climate (but with a greater temperature range than the Atlantic coast), characterized by cold wet winters (average daily temperature of 4 °C and average monthly precipitation of 43 mm) and hot summers (average daily temperature of 18 °C and average monthly precipitation of 69 mm). The experiment was set up as a completely randomized block design. The set of decision rules characterizing each of the CS was replicated on two blocks. To avoid complete overlap between crop:year and CS effects, the two plots (1.7 ha) of each CS did not start with the same entry point (i.e., crop).

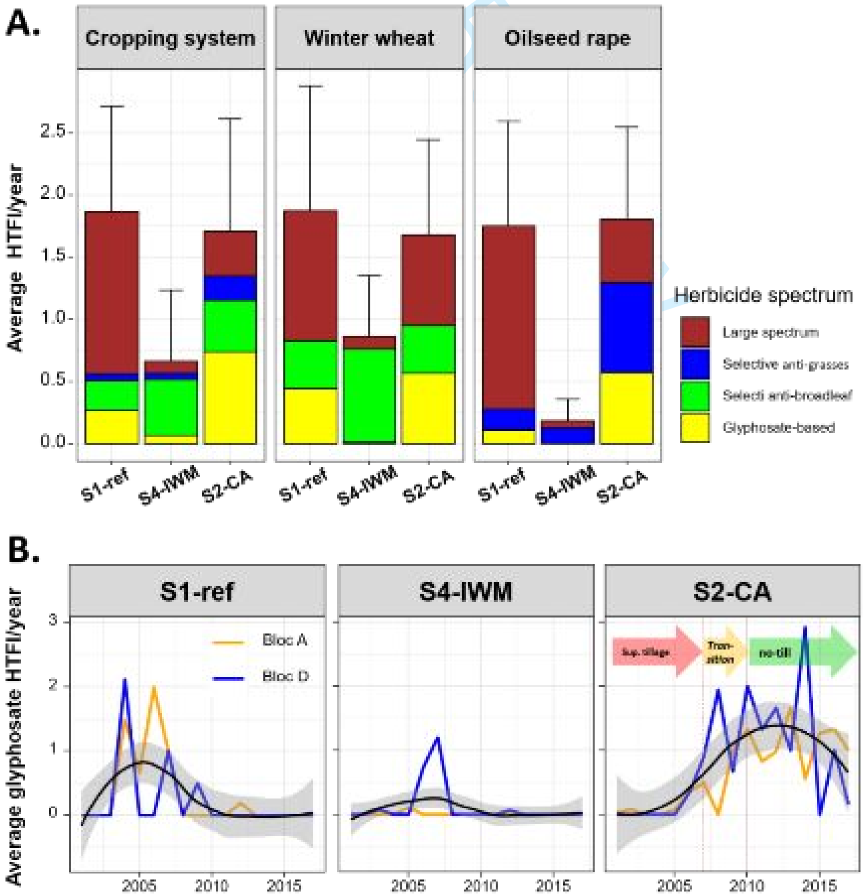
Over the 17 years of experiment, the cropping system called S2 hereafter implemented IWM principles during its transition toward CA. Indeed, no-plough, but quite frequent minimum tillage was applied for the first ten years. Then, no-till was applied in S2 over the last 7 years of the experiment, soil was covered with highly diversified grass/legume based cover crops during the summer fallow period and crops were directly seeded into glyphosate-terminated cover crops. Recent literature showed that fields conducted with CA principles are effectively CA after 5 years of permanent implementation of CA (Derrouch et al., 2020), particularly due to the shift in weed flora (Derrouch et al., 2021a; Derrouch et al., 2021b). That means that even the 7 first years of implementing CA principles in our experiment cannot be assessed as the effects of CA, but rather the effect of recently implemented CA principles, i.e. the initial and transitional phase to permanent CA. We thus considered here that the 17 years was a system simulating a farmer transitioning from minimum tillage-based to CA over the 17 years. Weed community before and after in-crop weed management, weed/crop biomass at crop flowering and crop yield at harvest were assessed over the 17 years.

We present here the conclusions for 3 out of 5 cropping systems (Adeux et al., 2019; Adeux et al., 2022b; Cordeau et al., 2022): the reference standard system (S1), the IWM system transitioning to CA (S2) and the tillage-based system mixing mechanical/herbicide weed management (S4). S1 was the reference cropping system, typical of the Burgundy region, designed to maximize financial return. It was characterized by a triennial oilseed rape—winter wheat—winter barley rotation, systematic moldboard ploughing in summer-autumn, and herbicides as sole curative weed management tool. Nitrogen fertilization aimed to ensure the full needs of the crop. S4 was designed to mimic farmers aiming to reduce herbicide reliance and resulted in a more complex 6-year rotation which included winter sown crops (winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.), triticale (× *Triticosecale* Wittm. ex *A. Camus*) or faba bean (*Vicia faba* L.)), autumn sown oilseed rape (*Brassica napus* L.), spring crop (oat (*Avena sativa* L.), sugarbeet (*Beta vulgaris subsp. vulgaris* L.), faba bean, lupin (*Lupinus albus* L.), spring barley or mustard (*Brassica juncea* (L.) Czern)) and summer-sown crops (maize (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), soybean (*Glycine max* (L.) Merr.), or sunflower (*Helianthus annuus* L.)). S4 differed from S1 and S2 by the tillage intensity and weed management strategies. S4 implemented moldboard ploughing once every two or three years and a wide array of preventive and cultural weed management tools such as false seedbed technique, delayed sowing of winter cereals, and higher seeding rates. Herbicide was the only in-crop weed management in S1 at recommended dose, while S4 resorting preferentially to preventive measures and mechanical weeding. However, applications of specialized herbicides on target species remained possible in S4 when weather conditions were not suitable for mechanical weeding or to control weeds with a low sensibility to mechanical weeding. More detailed information concerning crop sequence, pesticide application, soil tillage, sowing, and harvest dates can be found in Adeux et al. (2019), Deytieux et al. (2012) and Chikowo et al. (2009).

2.2 *Similar herbicide use in CA compared to the reference*

The S1 reference system resulted in an average annual herbicide treatment frequency index (HTFI) of 1.9. Weed management relied mainly on broad-spectrum herbicides typically used in winter cereal-based rotations (Figure 1). On average over the 17 years, the S2 system reduced herbicide use by 9% compared with S1. Half of herbicide use was represented by glyphosate-based herbicides applied to terminate crop volunteers, weeds and cover crops before sowing (Figure 1). The proportion of the HTFI used to control grass weeds was higher than in the other systems, which clearly indicates high grass weed pressure (*e.g. Alopecurus myosuroides*). The use of glyphosate increased during the transition from superficial tillage to no-till, even though the doses of individual treatments declined (about 2 kg/ha of active ingredient before 2010, about 0.9 kg/ha after 2010). The S4 IWM system enabled a 64% reduction in HTFI compared with S1. This was made possible by the implementation of a number of weed management tools, such as crop diversification, occasional ploughing (approximatively every two years), mechanical weeding including hoeing of certain crops (maize), delayed sowing dates for winter cereals (wheat, barley), the use of smothering species (triticale), and false seedbed operations during the fallow period.

Figure 1. A) Herbicide treatment frequency index (HTFI) per year, average across the whole 2001-2017 period of the experiment in the three cropping system, or in the winter wheat and oilseed rapes only, colored by the spectrum of the herbicide; B) Dynamics of glyphosate TFI across the three cropping systems, repeated twice (blocs A and D). The trends (black line) are highlighted with a loess smoother and 95% confidence intervals (grey bands). According to Adeux et al. (2019)



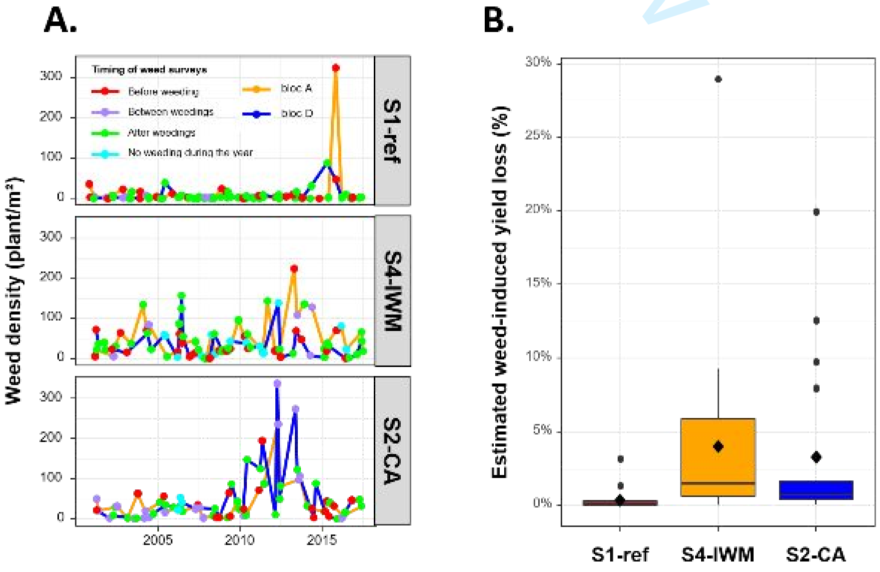
2.3 Containing weed pressure and yield loss

Weed control was considered satisfactory on all the plots. No increased weed pressure was observed on the plots over time (Figure 2A). Weed species often considered as highly problematic in cereal-based cropping systems of the Burgundy region (*e.g. Alopecurus myosuroides*) were contained. Weed abundance before weeding averaged (over 17 years) 25 plants/m² in S1, 54/m² in S2 and 45/m² in S4. After any weeding operation, weed abundance averaged (over 17 years) 2 plants/m² in S1, 12/m² in S2 and 20/m² in S4. Weed control efficiency (computed based on weed densities before and after curative weed control operations) averaged 78% in S1, 69% in S2 and 63% in S4, which we considered acceptable.

The implementation of 17 years of contrasted tillage and herbicide use shaped weed assemblages and dominant traits: short-life cycle, short-cycle winter annuals with a creeping growth form in S1, wind dispersed Asteraceae and perennial species in S2 and spring and summer species in S4. *Asteraceae* (*Sonchus asper, Senecio vulgaris*), grasses (*Lolium spp., Echinocloa crus-galli*) and perennials (*Convolvulus arvense*, *Taraxacum officinale*) dominated the weed community in S2 during the last 7 years of strict CA.

Weed-induced yield losses (estimated from weed biomasses and relationships between crop and weed biomasses, see Adeux et al., (2019)) were negligible in all systems (Figure 2B). The percentage of weed biomass was less than 5% in 100% of plot:years (i.e. case situations) in S1, in 66% in S2 and in 79% in S4. When S2 transitioned to CA, the percentage of weed biomass was sometimes higher, particularly when companion plants intercropped with oilseed rape (considered as “weeds”) were not winter-killed.

Figure 2. A) Dynamic of total weed density (plant/m²) over 2001-2017 period in the two blocs of the three cropping systems. Each dot corresponds to a weed survey colored according it relative timing to weedings. B). Weed-induced yield loss (%) estimated by the reduction of crop biomass due to increased weed biomass sampled at crop flowering each years. According to Adeux et al. (2019)



2.4 Lessons from the transition to CA applying IWM principles

S2 achieved satisfactory weed management. The weed densities observed remained containable. Herbicide use was reduced by -21% during the superficial tillage phase (2000-2010) and by -9% across the all 17 years of the experiment, compared to the standard reference system. During the no-till phase, social pressure on glyphosate use was not as pronounced as today in Europe (Antier et al., 2020), hence the strategy adopted was to use glyphosate before crop sowing in order to limit herbicide use during the crop cycle. As a consequence, total herbicide use was similar to the reference but composed of 50% of glyphosate-based herbicides. In certain crops, no herbicides were required for weed control due to important crop residues on the soil surface, as was the case for winter faba bean after sorghum. The success of this technique resides in obtaining in a sufficiently thick mulch to suppress weed emergence and establishment but not the crop (Teasdale and Mohler, 2000; Menalled et al., 2022).

However, reliance on glyphosate in S2 was high, even though the doses applied were reduced over time. It was often difficult to ensure maximum growth of cover crops due to high slug pressure, delayed sowing after harvest of the previous crop due to lack of manpower, and non-optimized sowing density. Optimizing cover crop mixture richness and composition (Smith et al., 2020), seeding rates of each species (Bybee-Finley et al., 2022) and sowing date in light of unpredictable weather conditions (Mirsky et al., 2017) remains a challenge to optimize weed suppression in cover crops (Osipitan et al., 2019). We observed the rapid evolution of weed communities towards *Asteraceae* species which easily establish in no-till (Cordeau et al., 2015b) thanks to wind dispersal. This flora has limited the possibilities of further reducing the frequency of herbicide treatments. The profitability of the S2 system was lower than the profitability in the S1 reference system, with a semi-net margin difference of -180€/ha/year, mainly due to the introduction of minor crops with a lower gross product.

3 Effect of strategic tillage on weed, crop yield and economy

3.1 Aims of strategic tillage after long-term no-till sequence

No-till ensures that weed seeds remain on the soil surface, a condition deemed to be unfavourable to weed seed germination because of poor seed:soil contact (Cordeau et al., 2015b) and increased weed seed mortality (Chauhan et al., 2006; Nichols et al., 2015). However, many studies have reported higher weed pressure under no-till than under ploughing (Cardina et al., 2002; Adeux et al., 2019). Occasional tillage could help to diversify selection pressures and cope with certain challenges encountered in no-till (Crawford et al., 2015), such as the management of herbicide resistant-weeds (Dang et al., 2015) or other pests (ex. slugs, voles) (Douglas and Tooker, 2012), soil compaction (Peixoto et al., 2019) or reduced crop productivity (Díaz-Zorita et al., 2004; Van den Putte et al., 2010; Çelik et al., 2019; Peixoto et al., 2019). Extensive research has focused on how tillage intensity drives weed dynamics and/or crop yields but few studies have investigated tillage effects in fields previously managed under CA principles for a long time. Strategic tillage as used in this chapter describes the use of occasional tillage implemented after a long sequence of no-till (Conyers et al., 2019; Peixoto et al., 2020), needed to manage an emerging agronomical issue due to the no-till phase (e.g. increased weed/slugs pressure).

We investigated weed community (density, species richness, composition) and winter wheat (yield, yield components, grain quality) response to different levels of tillage intensity (no-till, superficial tillage, ploughing) in fields previously managed with 2 out of 3 CA principles during 17 years (i.e. diversified crop rotation and soil cover) and with all 3 principles (i.e. adding no-till) over the last 7 years, i.e. fields of the S2 system previously presented in the long-term cropping system experiment (Adeux et al., 2019; Cordeau et al., 2020b; Cordeau et al., 2022).

3.2 Effect of tillage type

Within each S2 field, three strips were defined after main crop harvest in 2017: one strip was dedicated to conventional tillage (*i.e.* ploughing, CT), another to reduced tillage (*i.e.* superficial and non-inversion tillage, RT) and the last one was maintained under no-till (NT). Soil preparation prior to winter wheat sowing consisted in stubble cultivation in RT (8cm deep), ploughing with skim coulters in CT (25cm deep) and rotary harrowing in both RT and CT (8cm deep). Glyphosate was applied at 1080 g/ha during the fallow period in NT. All field strips were then sown with winter wheat at the same weeding date and rate, and all management practices (fertilization, weeding, etc.) were similar. Weed community composition was assessed before and after weeding. Weed biomass was sampled at crop maturity.

Following the methodology and reference prices of Lechenet et al. (Lechenet et al., 2014; Lechenet et al., 2017), production costs included mechanization, input and fuel costs. Gross products were computed as the mathematical product between observed mean yield in each treatment and the sell price of winter wheat. The gross margin was computed as the difference between the gross product and the sum of the production costs (mechanization, fuel, inputs).

Tillage treatments significantly affected weed communities before weeding: total weed density and species richness before weeding was greatest in RT, intermediate in CT and lowest in NT (Table 1). Indeed, in the S2 system, 77.1% of weed seeds were concentrated in the top 0-10cm soil layer (Cordeau et al., 2022), the only soil layer stimulated by stubble cultivation and rotary harrowing in RT. Higher weed emergence in CT than NT was however unexpected. Reasons which could explain this result include the upwelling of persistant weed seeds (*e.g. Fumaria officinalis* or *Sinapis* spp.) (Chancellor, 1986; Thompson et al., 1993; Mulugeta and Stoltenberg, 1997; Soltani et al., 2016) and/or the incomplete burial of weed seeds initially present in the top horizon (*e.g. Alopecurus myosuroides*) (Roger-Estrade et al., 2001). Differences in species richness and abundance transcribed into a significant tillage effect on weed community composition before weeding (12.17% of partial variation explained, P=0.009). Of the 10 most abundant species observed before weeding, four were associated to RT (*Sinapis* spp., *Sonchus asper*, *Veronica hederifolia* and *Viola arvensis*) and two to both NT and RT (*A. myosuroides* and *Lapsana communis*). Weed density (4 to 13 plants/m²), weed biomass (1 to 15 g of dry matter/m^2) and species richness after weeding were similar across tillage treatments Higher crop yields under CT probably resulted from increased mineralisation of soil organic matter (Alvarez et al., 1998) or enhanced soil structure (Peixoto et al., 2019), rather than lower weed:crop competition, as reflected by an overall low weed biomass after weeding, across all tillage treatments. Gross margin was significantly higher in RT than in CT and NT ($P<0.001$). Thus, higher winter wheat productivity in RT than in NT overcompensated for higher production costs, whereas it was not the case for CT.

Table 1. Effect of tillage treatments (CT: conventional tillage, RT: reduced tillage, NT: no-till) implemented before wheat sowing in fields conducted under CA principles during 17 years, on weeds and wheat yield and yield component. Tillage systems sharing identical letters are not significantly different at P<0.05. DM: dry matter. Credits: plowing by © INRAE / MAITRE Christophe, superficial tillage and direct seeding © INRAE / FARCY Pascal

Response variable	P	CT	RT	NT
Weed density before weeding ($plants/m^2$)	**<0.0001**	12 ± 4 b	33 ± 10 c	5 ± 2 a
Weed density after weeding ($plants/m^2$)	**<0.0001**	4 ± 1 a	13 ± 2 b	8 ± 2 b
Weed biomass at crop maturity (g DM/m^2)	**<0.0001**	1 ± 0 a	15 ± 10 b	3 ± 2 ab
Number of wheat grains per ear	**<0.0001**	40.1 ± 1.1 c	34.1 ± 0.9 b	30.7 ± 0.8 a
Wheat grain yield (t DM/ha)	**0.0002**	7.1 ± 0.4 b	6.1 ± 0.3 a	5.5 ± 0.3 a

These results shed light on the short-term effect of different types of tillage on weed communities, weed:crop interference and crop performance in fields conducted under CA principles for years (Blanco-Canqui and Wortmann, 2020; Peixoto et al., 2020).

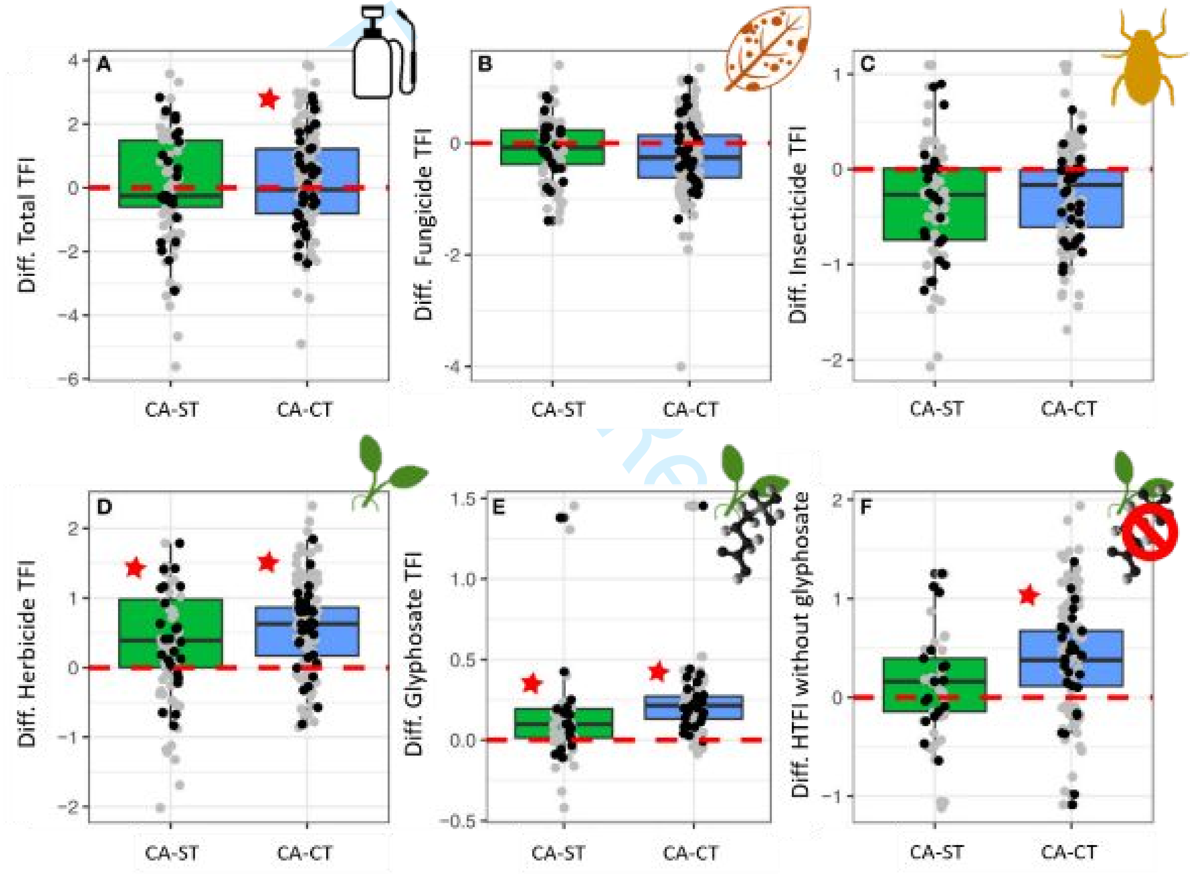
4 Multicriteria assessment of conservation agriculture

Decades after its development by pioneer farmers, CA acreage is increasing exponentially worldwide (Kassam et al., 2019), although very few studies have assessed its performances on a multicriteria basis, including environmental, economic and societal aspects (Craheix et al., 2016). Here, we mobilize data from the French AGROSYST database, which gathers all farming practices and performances of the 3000 farms involved in the French DEPHY farmers' network (Adeux et al., 2022a). Performances (13 indicators) of CA (CA, N=36) and pseudo-CA systems (pseudo-CA, N=19, allowing one occasional superficial tillage) were compared to those of conventional tillage (plowed, CT, N=135) and superficial tillage (ST, N=90) based systems sharing similar production situations (climate, soil type, presence of livestock or irrigation, etc.).

4.1 Pesticide use in CA systems of French farmers

On average, the conclusions of this study are that CA systems require as much fungicide as 'neighbouring' CT or ST systems in similar production situations, slightly less insecticides (although not significant), but more herbicides (2.1 HTFI points on average, with around +1 and +0.4 HTFI points compared to 'neighbouring' CT or ST systems). Overall, CA systems are more reliant on total pesticide use than their 'neighbouring' CT systems, with +1.1 total TFI points on average, but no difference in total TFI was observed between CA systems and their ST neighbours (Figure 3).

Figure 3. Difference in pesticide use between CA, conventional tillage (plowed, CT; blue) and minimum tillage (ST; green) based systems in the Dephy Farm French network, for the total treatment frequency index (Total TFI (A), fungicide TFI (B), insecticide TFI (C), herbicide TFI (D), glyphosate-based herbicide TFI (E) and herbicide TFI without glyphosate (F) (according to Adeux et al., (2022a)). Black dots represent average differences per similar production situation. Red stars indicate significant differences (P < 0.05).



4.2 Performances of CA on technical and economic indicators

We showed that CA (compared to STs and CTs, respectively) decreased time of traction/ha/year (-25 and -32%), fuel consumption (-21 and -39%), as well as mechanization costs (-20 and -26%), tended to slightly decrease profitability/ha (-7 and -19%, non-significant) due to slightly lower productivity (-19% and -25%) but resulted in better profitability per hour of field traction (+23% and +18%). Pseudo-CA did not implement the three CA principles since crop rotation were as diverse and cover crop as frequent as in ST and CT, and tillage occurred, albeit rarely. However, pseudo-CA decreased fuel consumption

(-25% compared to CTs), and resulted in similar productivity and economic profitability (per hectare and per hour of field traction).

Further analysis is needed to identify the determinants of multi-performance in a given production situations and track down innovative systems optimizing multiple performances and solving apparent trade-offs, such as tillage intensity and herbicide use and/or limited productivity.

5 Transitioning to pesticide-free conservation agriculture: the CA-SYS platform

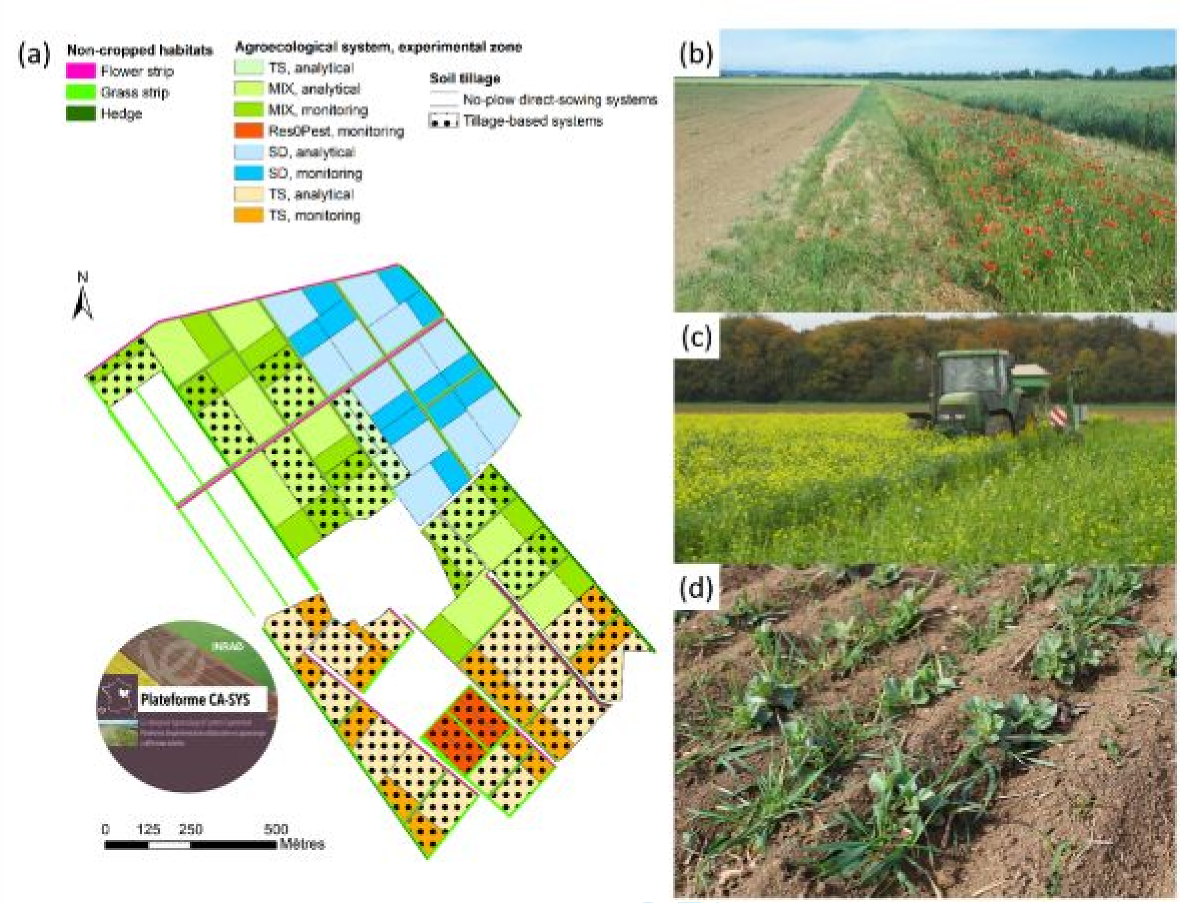
Agriculture faces the complex challenge of transforming the way in which we produce food to ensure global food security whilst minimizing or avoiding environmental harms (Foley et al., 2005; Vanbergen et al., 2020) and considering all facets of sustainability. Arguably, the most profound transformation would involve shifting the conventional paradigm of production towards an ecological intensification of agriculture. The implementation of ecological intensification therefore requires designing productive, sustainable agricultural systems that fundamentally integrate ecosystem services delivered by biodiversity into crop production by the manipulation of biotic interactions that assure profitable yields (i.e. high yield and/or low production cost) and minimize disservices (e.g. pests damage, soil degradation, greenhouse gas emission) (Dore et al., 2011; Garnett et al., 2013; Gaba et al., 2014).

5.1 Biodiversity-based systems at the core of the CA-SYS platform

Since summer 2018, different agroecological systems mobilizing diverse rotations of arable crops are experimented on the CA-SYS platform (Cordeau et al., 2015a), such as wheat, barley, rapeseed, buckwheat, soybean, faba bean, *etc*. The CA-SYS platform covers 125 ha of the INRAE 'U2E AgroEcology Experimental and Innovation Facility' experimental unit (47°14′11.2″N, 5°05′56.1″E, located close to Dijon, Eastern France (Figure 4)) and is divided into 42 fields of 2.5 ha which are surrounded by 10 ha of ecological infrastructures .

The overarching objective of CA-SYS is to design pesticide-free agricultural systems that resort to both wild and cultivated biodiversity as means of sustaining agricultural production, i.e. biodiversity-based systems (Petit et al., 2018; Petit et al., 2021). All pesticides are excluded even bio-products and those authorized in organic farming. The CA-SYS platform is an agroecological system experiment testing nature-based solutions, defined by Maes and Jacobs (2017) as any transition that use ecosystem services with decreased input of non-renewable natural capital and increased investment in renewable natural processes.

Figure 4 A) Map of the CA-SYS platform (Hugard R. and Deytieux V. © INRAE 2018); B) 3-m wide flower strip bordered by two 3-m wide grass strips (Cordeau S. © INRAE 2019); C) Direct drilling in field conducted in Conservation Agriculture (Farcy P. © INRAE 2018); D) Winter wheat intercropped with winter fababean (Cordeau S. © INRAE 2019), according to Vanbergen et al., (2020)

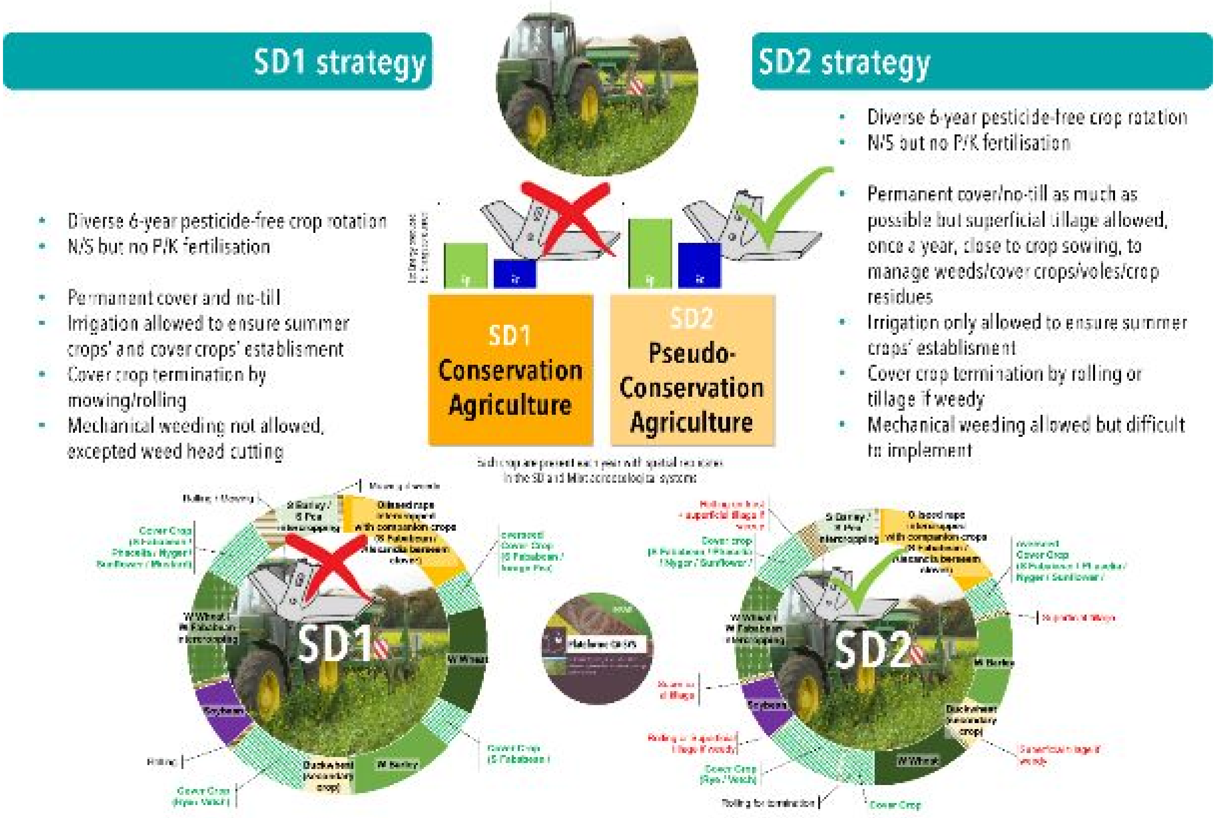


5.2 *Conservation agriculture systems tested on the CA-SYS platform*

A crucial aspect in the design of the CA-SYS platform has been the active co-design with farmers and other agricultural stakeholders to guide the implementation of ambitious but practicable biodiversity-based management systems. Four pesticide-free cropping systems are being tested on the CA-SYS platform, according to two agricultural pathways: (1) a plowing/tillage-based system (TS) inspired by organic agriculture (Crowder et al., 2010; Saffeullah et al., 2021); (2) a no-plow/no-till direct-sowing system (SD) maximizing soil cover and inspired by conservation agriculture (Kassam and Friedrich, 2011; Reicosky, 2015).

We will focus here on the two SD cropping systems (Figure 5) since they are defined as pesticide-free forms of CA (SD1 system) or occasional-tillage (SD2 system). Both systems implement a 6-year crop rotation including summer and spring crops in order to diversify the typical winter crop-based rotation of the region. Crops are not fertilized with phosphorus and potassium but fertilized with sulfur and nitrogen according to their need and targeted yields (e.g. 7t/ha in winter wheat, i.e. about 10% less than potential yield in conventional systems in the production situation). SD1 resorted to permanent cover and no-till whereas superficial tillage was allowed in SD2 when necessary, but no more than once a year per plot, essentially before crop sowing to terminate weeds, crop volunteers or cover crops. Irrigation is allowed to ensure the establishment of summer crops in both systems (*e.g.* soyabean), to limit hydric stress at crop flowering or to ensure maximum soil cover provided by summer sown cover crops in SD1 only. Cover crop termination is ensure by no-till methods in SD1 while superficial tillage is allowed in SD2 if necessary. Indeed, cover crop mixture were designed to be terminated without tillage, e.g. by avoiding species such as grasses that are difficult to terminate without soil disturbance in pesticide-free systems (Wortman et al., 2012; Keene et al., 2017). Mechanical weeding is allowed only in SD2 system since it disturbs the soil surface. However, it remains difficult to implement mechanical weeding in reduced tillage systems since crop and cover crop residues remain on the soil surface (Bates et al., 2012).

Figure 5. Farming strategies deployed in the SD1 and SD2systems in the CA-SYS platform over the 2018-2023 period.

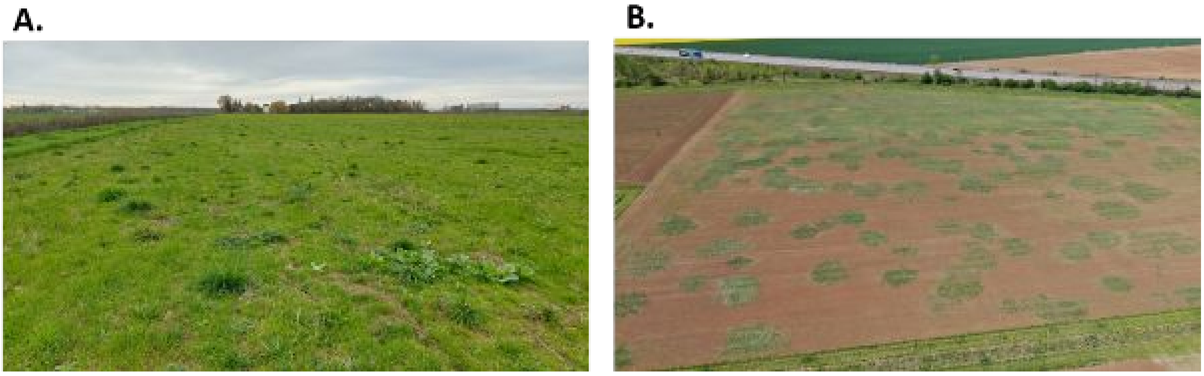


5.3 *Lessons learned from the 2018-2023 phase*

Managing pest and particularly weeds in reduced tillage (SD2) and no-till (SD1) pesticide-free systems was particularly challenging, especially during the first years (2018-2023). Our experience on reducing herbicide use in no-till systems presented above was useful (Adeux et al., 2019; Cordeau et al., 2022) but implementing pesticide-free systems was far more challenging as technical difficulties (e.g. direct sowing of a crop in perennial weeds) interacted with multiple pest pressure (e.g. slugs) and damages to accentuate yield loss or crop failure. Weed pressure increased because other pest. Even though alternative farming practices were combined across and within cropping seasons, pest pressure reduced crop growth and stunted crops were not able to suppress weeds. Despite their chaotic population dynamics over the years, voles and slugs were a major issue. In SD1, the initial crop rotation was re-designed to facilitate management of crop volunteers and grass weeds. Indeed, the prohibition of tillage and herbicides greatly complicated the management of crop volunteers during the fallow period, especially for winter cereals and oilseed rape (volunteers of summer crops being killed by frost in our region). We observed that weed communities rapidly evolved towards *Asteraceae*, grasses and perennials. Cover crop composition was adapted to ensure maximum efficacy of the termination method (see next section). We noted that climate change and dry summers challenged our ability to achieve/obtain well developed and suppressive cover crops, considering irrigation is frequently forbidden during dry summers in our region. Furthermore, as see I one of our previous factorial experiment, irrigation tended to increase weed biomass rather than enhancing, possibly due to synchronized weed/cover crop seed germination (Rouge et al., 2022; Rouge et al., 2023). Our previous factorial experiment also showed that nitrogen fertilization did not enhance the weed suppressive ability of cover crops (Rouge et al., 2022; Rouge et al., 2023). Increasing crop and cover crop seeding rate appears primordial in pesticide-free reduced (SD2) and no-till (SD1) systems to ensure satisfactory emerged density.

In SD2, we learnt that a single superficial tillage operation may limit the impact on soil organisms (Rincon-Florez et al., 2016) but does not ensure complete cover termination. The selection of the best tool for plant cover termination depends on weather conditions and targeted plant community (e.g. dominated by annual vs. perenial weeds, crop volunteers, or grasses etc.). The humid weather conditions during autumn in clay soils leave limit the number of days to implement termination and requently decrease the termination rate because of plant regrowth. The beneficial effects of superficial tillage are questioned since the development of *Cirsium arvense* appeared even quicker in this system. Indeed, alfalfa was established for 3 years in 7 out of 10 SD2 fields over the 2019-2023 phase to manage *Cirsium arvense.* The implementation of mechanical weeding remained challenging due to the presence of crop residues on soil surface. Only weed head cutting is feasible and allowed to limit weed seed shedding.

Figure 6. Main weed issues in SD1 plots (A, Cordeau S. © INRAE 2022) with annual and perennial grasses such as Lolium perenne, Lolium multiflorum, Alopecurus myosuroides, Vulpia myros, Bromus sterilis, and Asteraceae such as Sonchus asper, Taraxacum officinale, Picris hieracoides, Picris echioides; and in SD2 plots (B, Rodolphe Hugard and Guillaume Poussou © INRAE 2021) such as Cirsium arvense.



5.4 Redesign of pesticide-free cropping system transitioning to CA through a step-by-step process

An in-depth agronomic diagnosis of the SD1 and SD2 cropping systems over the first 5 years of the experiment led to the conclusion that the systems were in an agronomic deadlock, exhibiting different issues for different reasons. A redesign of the cropping system could not be circumvented and we opted for a new way to do so. All the CA-SYS system were prototyped in 2017-2018 with the help of many stakeholders following the *de novo* approach (Reau et al., 2015; Jeuffroy et al., 2022). It consisted in designing, during workshops involving experts with diverse and complementary knowledge, a few virtual cropping system prototypes (SD1 and SD2), tailored to farmers' aims and resources (Vereijken, 1997). Then, the designed cropping systems had been were implemented in the field without smooth and step-by-step transition, operating an abrupt contrast with the past farming practices. The knowledge required to design highly innovative agroecological cropping systems is often lacking and technical options ought to be reconsidered after witnessing unplanned effects. The process of cropping system design is not linear and ought to be considered as a series of decisions and actions forming a pathway towards a desired target. As shown by Darnhofer et al. (2010), the evolution of cropping systems is a continuous learning process, not only opening new perspectives for action, but also sometimes renewing or specifying targets.

For these reasons, a step-by-step process (Meynard et al., 2023) was adopted to design pesticide-free cropping systems transitioning to CA. The SD1 and SD2 systems were redesigned in workshops with experts. Particularly, we defined a set of common and specific targets/objectives for both cropping systems. We decided to target pesticide-free productive and resilient cropping systems that face climate change with enhanced soil health, that is:

- in SD1, maximize the use of biological regulation of pests, limit to its maximum the reliance on tillage (but if necessary, implement deep/inversion tillage such as plowing), and for which the economic profitability could rely on the payment of a diverse set of ecosystem services (i.e. carbon storage, biodiversity preservation, etc. amongst crop production)

- in SD2, make complementary use of biological and mechanical regulation of pests, limit to its maximum the depth of tillage when implemented (even if the frequency of tillage can be higher than in SD1), in order to achieve acceptable economic profitability mainly through the sale of agricultural products.

We now propose to explore whether avoiding tillage in synthetic pesticide-free cropping systems is feasible through two different pathways, which differ in their definition of minimum soil disturbance: deep tillage (potentially with soil inversion) but not frequent over time in SD1 as used in rotational no-till strategies (Mirsky et al., 2012) , and superficial tillage in SD2 although possibly more frequent than in SD1 as used in organic reduced tillage strategies (Newton et al., 2020). We advocate here that it is necessary to assess the way to transition to CA with a flexible and open-minded way of thinking since it is more important to see CA for the ecosystem services it can deliver than through the agronomic practices implemented to achieved it (Giller et al., 2015; Cordeau, 2024).

Since we observed that the crop establishment was crucial in synthetic pesticide-free no-till system, we now implemented strip-till in SD1 to clean the row before sowing the crop and allow the use of biocontrol to manage slugs, only on sensible crops (mustard, rye, oilseed rape) at their sensible growth stage (seedlings) and after field examination of high pest pressure with adapted protocols. The use of biocontrol was rethink to ensure crop establishment and valorization of fertilization at crop sowing, to ensure initial crop density and crop growth, in order to outcompete emerging weeds that may cause yield loss later.

6 Conclusions

Conservation agriculture relies on the implementation of no-till, permanent soil cover and diversification of crops in order to achieve multiple goals that can differ depending on farmers and production situations. However, reducing the use of herbicides in conservation agriculture systems remains challenging since the development of these farming strategies were made possible by the development of non-selective wide spectrum herbicides and the optimization of herbicide-based weed management strategies coupled with farm equipment being able to minimize soil disturbance. Assessing the potential to reduce herbicide use in the context of CA requires an analysis of farmers' motivations for implementing CA, their farming equipment and recent evolution, and finally their weed floristic context. We identified two pathways through which herbicide-free (or pesticide-free) no-till systems could be achieved, which are designed either in experimental stations or on commercial farms: i) if conventional CA has been implemented in the past years and tillage is not an option, continuing towards the reduction of herbicide use in no-till systems by optimizing crop rotation, cover cropping, farm equipment to manage weeds with various tactics; ii) if organic or pesticide-free agriculture has been implemented in the past years and strategic and occasional tillage is an option, looking for the minimal soil disturbance (e.g. strip-tillage) that allows quick crop establishment and growth, to compete with weeds later on and ensure the delivery of targeted ecosystem services (including crop production). Both pathways need to be explored and assessed to provide farmers with operational and scientific knowledge on how to achieve their agroecological transition towards pesticide-free CA with limited risk.

7 Acknowledgments

The authors thank the CA-SYS team and all the staff from the experimental farm U2E that every day strive for making these experiments existing, such as CA-SYS. We thank all the people (farmers and crop advisors) who took part of the workshops to design cropping systems and semi-natural habitats. We thank the farmers and farm advisors from the DEPHY network who shared and collected the data, respectively, as well as the AGROSYST team who extracted the data. The authors thank INRAE for their financial support. The authors acknowledge financial support from the French "Priority Research Program Alternative Crop Production and Protection", the ANR SPECIFICS project (ANR-20-PCPA-0008), the ANR BeCreative project (ANR-20-PCPA-0001), the European Horizon 2020 Adopt-IPM and IWM PRAISE, the French ministries for agriculture and environment and the Agence Française de la Biodiversité (DEPHY Expe II project ABC "Agroécologie en Bourgogne et Région Centre"), the Casdar projects RAID (Biological control of weeds) and Vancouver (Weeds management with cover crop), the French "Investissements d'Avenir" program and the project ISITE-BFC (contract ANR-15-IDEX-03), the Ecophyto COSTRAA project funded by OFB (Office Français de la Biodiversité), the INRAE SumCrop ASPECT project, and the COPRAA project which was supported by OFB as part of the Ecophyto call on "Global approaches to limit the use of phytopharmaceuticals: Combining preventive and curative products in sectors, from farmers to consumers" launched by the French Ministries in charge of Ecology, Agriculture, Health and Research.

8 References

Adeux, G., Cordeau, S., Antichi, D., Carlesi, S., Mazzoncini, M., Munier-Jolain, N.M., and Barberi, P. (2021). Cover crops promote crop productivity but do not enhance weed management in tillage-based cropping systems. *European Journal of Agronomy* 123**,** https://doi.org/10.1016/j.eja.2020.126221.

Adeux, G., Munier-Jolain, N., Courson, E., Guinet, M., Lecaulle, S., and Cordeau, S. (2022a). Multicriteria assessment of conservation agriculture systems. *Frontiers in Agronomy* 4:999960.

Adeux, G., Munier-Jolain, N., Meunier, D., Farcy, P., Carlesi, S., Barberi, P., and Cordeau, S. (2019). Diversified grain-based cropping systems provide long-term weed control while limiting herbicide use and yield losses. *Agronomy for Sustainable Development* 39**,** 42.

Adeux, G., Yvoz, S., Biju-Duval, L., Cadet, E., Farcy, P., Fried, G., Guillemin, J.-P., Munier-Jolain, N., Petit, S., and Cordeau, S. (2022b). Cropping system diversification does not always beget weed diversity. *European Journal of Agronomy* 133**,** https://doi.org/10.1016/j.eja.2021.126438.

Alvarez, R., Alvarez, C.R., Daniel, P.E., Richter, V., and Blotta, L. (1998). Nitrogen distribution in soil density fractions and its relation to nitrogen mineralisation under different tillage systems. *Soil Research* 36**,** 247-256.

Antier, C., Andersson, R., Auskalnienė, O., Barić, K., Baret, P., Besenhofer, G., Calha, L., Carrola Dos Santos, S., De Cauwer, B., Chachalis, D., Dorner, Z., Follak, S., Forristal, D., Gaskov, S., Gonzalez Andujar, J.L., Hull, R., Jalli, H., Kierzek, R., Kiss, J., Kudsk, P., Leonhardt, C., Leskovšek, R., Mennan, H., Messéan, A., Ņečajeva, J., Mullins, E., Neve, P., Pedraza, V., Pintar, A., Reboud, X., Redl, M., Riemens, M., Ringselle, B., Ruuttunen, P., Sattin, M., Simić, M., Soukup, J., Stefanic, E., Steinkellner, S., Storkey, J., Ulber, L., Weickmans, B., and Wirth, J. (2020). A survey on the uses of glyphosate in European countries. INRAE. https://doi.org/10.15454/A30K-D531.

Bates, R.T., Gallagher, R.S., Curran, W.S., and Harper, J.K. (2012). Integrating mechanical and reduced chemical weed control in conservation tillage corn. *Agronomy Journal* 104, 507-517.

Blanco-Canqui, H., and Wortmann, C.S. (2020). Does occasional tillage undo the ecosystem services gained with no-till? A review. *Soil and Tillage Research* 198, 104534.

Bybee-Finley, A.K., Cordeau, S., Yvoz, S., Mirsky, S.B., and Ryan, M.R. (2022). Finding the right mix: a framework for selecting seeding rates for cover crop mixtures. *Ecological applications* 32, e02484.

Cardina, J., Herms, C.P., and Doohan, D.J. (2002). Crop rotation and tillage system effects on weed seedbanks. *Weed Science* 50, 448-460.

Çelik, İ., Günal, H., Acar, M., Acir, N., Bereket Barut, Z., and Budak, M. (2019). Strategic tillage may sustain the benefits of long-term no-till in a Vertisol under Mediterranean climate. *Soil and Tillage Research* 185, 17-28.

Chancellor, R.J. (1986). Decline of arable weed seeds during 20 years in soil under grass and the periodicity of seedling emergence after cultivation. *Journal of Applied Ecology* 23, 631-637.

Chauhan, B.S., Gill, G., and Preston, C. (2006). Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (Lolium rigidum) seed bank. *Weed Science* 54, 669-676.

Chauhan, B.S., Singh, R.G., and Mahajan, G. (2012). Ecology and management of weeds under conservation agriculture: A review. *Crop Protection* 38, 57-65.

Chauvel, B., Gauvrit, C., and Guillemin, J.-P. (2022). From sea salt to glyphosate salt: a history of herbicide use in France. *Advances in Weed Science* 40.

Chikowo, R., Faloya, V., Petit, S., and Munier-Jolain, N. (2009). Integrated Weed Management systems allow reduced reliance on herbicides and long term weed control. *Agriculture, Ecosystems and Environment* 132, 237-242.

Conyers, M., Van Der Rijt, V., Oates, A., Poile, G., Kirkegaard, J., and Kirkby, C. (2019). The strategic use of minimum tillage within conservation agriculture in southern New South Wales, Australia. *Soil and Tillage Research* 193, 17-26.

Cordeau, S. (2022). Conservation agriculture and agroecological weed management. *Agronomy* 12, 867.

Cordeau, S. (2024). Moving conservation agriculture from principles to a performance-based production system. *Renewable Agriculture and Food Systems* 39, 1-7.

Cordeau, S., Adeux, G., and Deytieux, V. (2020a). Diversity is the key for successful agroecological weed management. *Indian Journal of Weed Science* 52, 204-210.

Cordeau, S., Baudron, A., and Adeux, G. (2020b). Is tillage a suitable option for weed management in conservation agriculture? *Agronomy* 10, 1746, https://doi.org/10.3390/agronomy10111746

Cordeau, S., Baudron, A., Busset, H., Farcy, P., Vieren, E., Smith, R.G., Munier-Jolain, N., and Adeux, G. (2022). Legacy effects of contrasting long-term integrated weed management systems. *Frontiers in Agronomy* 3, 769992.

Cordeau, S., Deytieux, V., Lemanceau, P., and Marget, P. (2015a). Towards the establishment of an experimental research unit on Agroecology in France. *Aspects of applied biology* 128: Valuing Long-Term sites and Experiments for Agriculture and Ecology, 271-273.

Cordeau, S., Guillemin, J.P., Reibel, C., and Chauvel, B. (2015b). Weed species differ in their ability to emerge in no-till systems that include cover crops. *Annals of Applied Biology* 166, 444–455.

Craheix, D., Angevin, F., Doré, T., and De Tourdonnet, S. (2016). Using a multicriteria assessment model to evaluate the sustainability of conservation agriculture at the cropping system level in France. *European Journal of Agronomy* 76, 75-86.

Crawford, M.H., Rincon-Florez, V., Balzer, A., Dang, Y.P., Carvalhais, L.C., Liu, H., and Schenk, P.M. (2015). Changes in the soil quality attributes of continuous no-till farming systems following a strategic tillage. *Soil Research* 53**,** 263-273.

Crowder, D.W., Northfield, T.D., Strand, M.R., and Snyder, W.E. (2010). Organic agriculture promotes evenness and natural pest control. *Nature* 466**,** 109-112.

Dang, Y.P., Seymour, N.P., Walker, S.R., Bell, M.J., and Freebairn, D.M. (2015). Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: I. Drivers and implementation. *Soil and Tillage Research* 152**,** 104-114.

Darnhofer, I., Bellon, S., Dedieu, B., and Milestad, R. (2010). Adaptiveness to enhance the sustainability of farming systems. A review. *Agronomy for Sustainable Development* 30**,** 545-555.

Délye, C., Jasieniuk, M., and Le Corre, V. (2013). Deciphering the evolution of herbicide resistance in weeds. *Trends in Genetics* 29**,** 649-658.

Derrouch, D., Chauvel, B., Cordeau, S., and Dessaint, F. (2021a). Functional shifts in weed community composition following adoption of conservation agriculture. *Weed Research* 62**,** 103-112.

Derrouch, D., Chauvel, B., Felten, E., and Dessaint, F. (2020). Weed Management in the Transition to Conservation Agriculture: Farmers' Response. *Agronomy* 10**,** 843.

Derrouch, D., Dessaint, F., Fried, G., and Chauvel, B. (2021b). Weed community diversity in conservation agriculture: Post-adoption changes. *Agriculture, Ecosystems & Environment* 312**,** 107351.

Deytieux, V., Nemecek, T., Knuchel, R.F., Gaillard, G., and Munier-Jolain, N.M. (2012). Is integrated weed management efficient for reducing environmental impacts of cropping systems? A case study based on life cycle assessment. *European Journal of Agronomy* 36**,** 55-65.

Díaz-Zorita, M., Grove, J.H., Murdock, L., Herbeck, J., and Perfect, E. (2004). Soil structural disturbance effects on crop yields and soil properties in a no-till production system. *Agronomy Journal* 96**,** 1651-1659.

Dore, T., Makowski, D., Malezieux, E., Munier-Jolain, N., Tchamitchian, M., and Tittonell, P. (2011). Facing up to the paradigm of ecological intensification in agronomy: Revisiting methods, concepts and knowledge. *European Journal of Agronomy* 34**,** 197-210.

Douglas, M.R., and Tooker, J.F. (2012). Slug (Mollusca: Agriolimacidae, Arionidae) Ecology and Management in No-Till Field Crops, With an Emphasis on the mid-Atlantic Region. *Journal of Integrated Pest Management* 3**,** C1-C9.

Evans, D. (1972). "Filed performance of glyphosate derivatives in the control of Agropyron repens and other perennial weeds", in: *Brit Weed Contr Conf Proc*).

Fao (2021). *Conservation Agriculture principles https://www.fao.org/conservation-agriculture/overview/principles-of-ca/en/, accessed on 13th December 2021* [Online]. [Accessed 2021].

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., and Snyder, P.K. (2005). Global consequences of land use. *Science* 309**,** 570-574.

Friedrich, T., Derpsch, R., and Kassam, A. (2012). Overview of the Global Spread of Conservation Agriculture. *Field Actions Science Reports* 6**,** 1-7.

Gaba, S., Bretagnolle, F., Rigaud, T., and Philippot, L. (2014). Managing biotic interactions for ecological intensification of agroecosystems. *Frontiers in Ecology and Evolution* 2**,** 29.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., and Fraser, D. (2013). Sustainable intensification in agriculture: premises and policies. *Science* 341**,** 33-34.

Giller, K.E., Andersson, J.A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., and Vanlauwe, B. (2015). Beyond conservation agriculture. *Frontiers in Plant Science* 6**,** 870.

Green, J.M. (2018). The rise and future of glyphosate and glyphosate-resistant crops. *Pest Management Science* 74**,** 1035-1039.

Grundy, A., Mead, A., Bond, W., Clark, G., and Burston, S. (2011). The impact of herbicide management on long-term changes in the diversity and species composition of weed populations. *Weed Research* 51**,** 187-200.

Hill, S.B., and Macrae, R.J. (1995). Conceptual framework for the transition from conventional to sustainable agriculture. *Journal of Sustainable Agriculture* 7**,** 81-87.

Hoss, N.E., Al-Khatib, K., Peterson, D.E., and Loughin, T.M. (2003). Efficacy of glyphosate, glufosinate, and imazethapyr on selected weed species. *Weed Science* 51**,** 110-117.

Jeuffroy, M.-H., Loyce, C., Lefeuvre, T., Valantin-Morison, M., Colnenne-David, C., Gauffreteau, A., Médiène, S., Pelzer, E., Reau, R., and Salembier, C. (2022). Design workshops for innovative cropping systems and decision-support tools: learning from 12 case studies. *European Journal of Agronomy* 139**,** 126573.

Kassam, A., and Friedrich, T. (2011). "Conservation agriculture: Principles, sustainable land management and ecosystem services", in: *Proceedings of the 40th National Convention of the Italian Agronomy Society*), 7-9.

Kassam, A., Friedrich, T., and Derpsch, R. (2019). Global spread of conservation agriculture. *International Journal of Environmental Studies* 76**,** 29-51.

Kassam, A., Friedrich, T., Shaxson, F., and Pretty, J. (2009). The spread of Conservation Agriculture: Justification, sustainability and uptake. *International Journal of Agricultural Sustainability* 7**,** 292–320.

Keene, C., Curran, W., Wallace, J., Ryan, M., Mirsky, S., Vangessel, M., and Barbercheck, M. (2017). Cover crop termination timing is critical in organic rotational no-till systems. *Agronomy Journal* 109**,** 272-282.

Knowler, D., and Bradshaw, B. (2007). Farmers' adoption of conservation agriculture: A review and synthesis of recent research. *Food Policy* 32**,** 25-48.

Lechenet, M., Bretagnolle, V., Bockstaller, C., Boissinot, F., Petit, M.-S., Petit, S., and Munier-Jolain, N. (2014). Reconciling pesticide reduction with economic and environmental sustainability in arable farming. *PlosOne* 9**,** e97922.

Lechenet, M., Dessaint, F., Py, G., Makowski, D., and Munier-Jolain, N. (2017). Reducing pesticide use while preserving crop productivity and profitability on arable farms. *Nature Plants* 3**,** 17008 https://www.nature.com/articles/nplants20178.

Lechenet, M., Makowski, D., Py, G., and Munier-Jolain, N. (2016). Profiling farming management strategies with contrasting pesticide use in France. *Agricultural Systems* 149**,** 40-53 https://doi.org/10.1016/j.agsy.2016.1008.1005.

Maes, J., and Jacobs, S. (2017). Nature-based solutions for Europe's sustainable development. *Conservation letters* 10**,** 121-124.

Menalled, U., Adeux, G., Cordeau, S., Smith, R., Mirsky, S., and Ryan, M. (2022). Cereal rye mulch biomass and crop density affect weed suppression and community assembly in no-till planted soybean. *Ecosphere* 13.

Meynard, J.-M., Cerf, M., Coquil, X., Durant, D., Le Bail, M., Lefèvre, A., Navarrete, M., Pernel, J., Périnelle, A., and Perrin, B. (2023). Unravelling the step-by-step process for farming system design to support agroecological transition. *European Journal of Agronomy* 150**,** 126948.

Mirsky, S.B., Ackroyd, V.J., Cordeau, S., Curran, W.S., Hashemi, M., Reberg-Horton, C.S., Ryan, M.R., and Spargo, J.T. (2017). Hairy vetch biomass across the Eastern United States: effects of latitude, seeding rate and date, and termination timing. *Agronomy Journal* 109**,** 1510-1519.

Mirsky, S.B., Ryan, M.R., Curran, W.S., Teasdale, J.R., Maul, J., Spargo, J.T., Moyer, J., Grantham, A.M., Weber, D., Way, T.R., and Camargo, G.G. (2012). Conservation tillage issues: Cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. *Renewable Agriculture and Food Systems* 27**,** 31-40.

Mulugeta, D., and Stoltenberg, D.E. (1997). Increased weed emergence and seed bank depletion by soil disturbance in a no-tillage system. *Weed Science* 45**,** 234-241.

Nazarko, O.M., Van Acker, R.C., and Entz, M.H. (2005). Strategies and tactics for herbicide use reduction in field crops in Canada: a review. *Canadian Journal of Plant Science* 85**,** 457-479.

Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K., and Johns, C. (2020). What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. *Frontiers in Sustainable Food Systems* 4**,** 194.

Nichols, V., Verhulst, N., Cox, R., and Govaerts, B. (2015). Weed dynamics and conservation agriculture principles: A review. *Field Crops Research* 183**,** 56-68.

Osipitan, O.A., Dille, J.A., Assefa, Y., Radicetti, E., Ayeni, A., and Knezevic, S.Z. (2019). Impact of cover crop management on level of weed suppression: A meta-analysis. *Crop Science* 59, 833-842.

Owen, M.D. (2008). Weed species shifts in glyphosate-resistant crops. *Pest Management Science: formerly Pesticide Science* 64, 377-387.

Peixoto, D.S., Silva, B.M., Oliveira, G.C.D., Moreira, S.G., Da Silva, F., and Curi, N. (2019). A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. *Soil and Tillage Research* 194, 104307.

Peixoto, D.S., Silva, L.D.C.M.D., Melo, L.B.B.D., Azevedo, R.P., Araújo, B.C.L., Carvalho, T.S.D., Moreira, S.G., Curi, N., and Silva, B.M. (2020). Occasional tillage in no-tillage systems: A global meta-analysis. *Science of the Total Environment* 745, 140887.

Petit, S., Cordeau, S., Chauvel, B., Bohan, D., Guillemin, J.-P., and Steinberg, C. (2018). Biodiversity-based options for arable weed management. A review. *Agronomy for Sustainable Development* 38, 48.

Petit, S., Deytieux, V., and Cordeau, S. (2021). Landscape-scale approaches for designing and assessing biodiversity-based agricultural systems enhancing biological pest control. *Environmental Monitoring and Assessment* 193, 75.

R4p (2023). *Update of the Herbicide Resistance maps 2023 https://www.r4p-inra.fr/en/update-of-the-herbicide-resistance-maps-2023/* [Online]. [Accessed 12/02/2024 2024].

Reau, R., Geloen, M., Laurent, A., Loyce, C., Schaub, A., and Caballero, M. (2015). "De novo design workshop: a method for co-designing innovative cropping systems", in: *5 th International Symposium for Farming Systems Design, 7-10 September 201*).

Reicosky, D.C. (2015). Conservation tillage is not conservation agriculture. *Journal of Soil and Water Conservation* 70, 103A-108A.

Rincon-Florez, V.A., Ng, C., Dang, Y.P., Schenk, P.M., and Carvalhais, L.C. (2016). Short-term impact of an occasional tillage on microbial communities in a Vertosol after 43 years of no-tillage or conventional tillage. *European Journal of Soil Biology* 74, 32-38.

Roger-Estrade, J., Colbach, N., Leterme, P., Richard, G., and Caneill, J. (2001). Modelling vertical and lateral weed seed movements during mouldboard ploughing with a skim-coulter. *Soil and Tillage Research* 63, 35-49.

Rouge, A., Adeux, G., Busset, H., Hugard, R., Martin, J., Matejicek, A., Moreau, D., Guillemin, J.-P., and Cordeau, S. (2022). Weed suppression in cover crop mixtures under contrasted levels of resource availability. *European Journal of Agronomy* 136, 126499.

Rouge, A., Adeux, G., Busset, H., Hugard, R., Martin, J., Matejicek, A., Moreau, D., Guillemin, J.-P., and Cordeau, S. (2023). Carry-over effects of cover crops on weeds and crop productivity in no-till systems. *Field Crops Research* 295, 108899.

Saffeullah, P., Nabi, N., Liaqat, S., Anjum, N.A., Siddiqi, T.O., and Umar, S. (2021). "Organic Agriculture: Principles, Current Status, and Significance," in *Microbiota and Biofertilizers.* Springer), 17-37.

Smith, R.G., Warren, N.D., and Cordeau, S. (2020). Are cover crop mixtures better at suppressing weeds than cover crop monocultures? *Weed Science* 68, 186-194.

Soltani, E., Baskin, C.C., Baskin, J.M., Soltani, A., Galeshi, S., Ghaderi-Far, F., and Zeinali, E. (2016). A quantitative analysis of seed dormancy and germination in the winter annual weed Sinapis arvensis (Brassicaceae). *Botany* 94, 289-300.

Teasdale, J.R., and Mohler, C.L. (2000). The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Science* 48, 385-392.

Thompson, K., Band, S.R., and Hodgson, J.G. (1993). Seed size and shape predict persistence in soil. *Functional Ecology* 7, 236-241.

Van Den Putte, A., Govers, G., Diels, J., Gillijns, K., and Demuzere, M. (2010). Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. *European Journal of Agronomy* 33, 231-241.

Vanbergen, A.J., Aizen, M.A., Cordeau, S., Garibaldi, L.A., Garratt, M.P.D., Kovács-Hostyánszki, A., Lecuyer, L., Ngo, H.T., Potts, S.G., Settele, J., Skrimizea, E., and Young, J.C. (2020). Transformation of agricultural landscapes in the Anthropocene: Nature’s contributions to people, agriculture and food security. *Advances in Ecological Research* 63, 193-253.

Vankeerberghen, A., and Stassart, P.M. (2016). The transition to conservation agriculture: an insularization process towards sustainability. *International Journal of Agricultural Sustainability* 14**,** 392-407.

Vereijken, P. (1997). A methodical way of prototyping integrated and ecological arable farming systems (I/EAFS) in interaction with pilot farms. *European Journal of Agronomy* 7**,** 235-250.

Watson, G. (1974). "Motivation and response in the development of minimal tillage techniques outside the United Kingdom", in: *Proceedings*).

Wortman, S.E., Francis, C.A., Bernards, M.L., Drijber, R.A., and Lindquist, J.L. (2012). Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agronomy Journal* 104**,** 1425-1435.