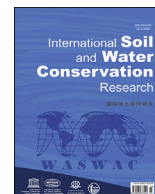




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Original Research Article

Economic comparison of conventional and conservation tillage in a long-term experiment: Is it worth shifting?

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ABSTRACT

There is considerable knowledge regarding the environmental benefits of conservation agriculture (CA). However, long-term profitability data are limited, despite their potential to drive CA adoption. This study analyses and compares the economic indicators of conservation reduced tillage (CT) widely practiced in Central Europe with those of conventional ploughing tillage (PT). This research investigated the costs and incomes under CT and assessed the impact of CT on crop yields and profitability over a 20-year period (2004–2023). The study covered 83 ha in 10 paired plots (from year 13 onwards, 76 ha in 9 paired plots), including extreme weather conditions and 6 crops. All annual data were adjusted to 2024 price levels to maintain consistency. Piecewise linear regression was applied to the data, revealing four distinct temporal phases. On the basis of profit, periods 'Transitional' (years 1–3), 'Adapted 1' (years 4–10), 'Steady' (years 11–17) and 'Adapted 2' (years 18–20) were separated. During the transitional period, profit under CT decreased by an average of 11.9% compared with PT, but subsequent periods indicated positive results. Therefore, the shift from year 7 onwards resulted in a profit increase. Over 20 years, material costs for CT plots were 1.9% higher and operating costs were 9.8% lower compared with PT. In addition, gross income increased by 2.3%, leading to a 13.0% higher profit on CT compared with PT plots, which could encourage wider adoption of CT by farmers.

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1. Introduction

The adverse effects of conventional ploughing tillage (PT) have long been acknowledged by the scientific community. To mitigate or prevent these negative impacts, several non-inversion

technologies were developed in the mid-20th century. However, these technologies were ahead of their time because machines capable of combined operations and the adequate pulling power required to operate them were not yet available. Consequently, the widespread adoption of conservation agriculture technologies had to wait until the late 20th to early 21st century (Kassam et al., 2017, 2018). In recent decades, there has been a dynamic increase in the use of conservation tillage (CT) worldwide (ranging from reduced tillage to no-till and regenerative agriculture), particularly in North and South America and Australia (Kassam et al., 2018, 2019; Kertész & Madarász, 2014). Various CT methods have been studied extensively over the last few decades, mainly focusing on soil properties,

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environmental impacts and crop yields (Blevins et al., 1983; Busari et al., 2015; Derpsch et al., 2010; Gao et al., 2019; Holland, 2004; Merten et al., 2015; Six et al., 1999). Research has consistently highlighted CT's positive effects on soil health, although findings on crop yields have been more variable. Mal et al. (2015) reported higher yields in Africa and comparable yields in America, whereas lower yields have been observed in Asia and Europe following a transition to CT. Nonetheless, notable variation exists within continents and among different crop species (Afshar et al., 2019; Etiendem & Cornelis, 2023; Ogieriakhi & Woodward, 2022; Toliver et al., 2012; Varner et al., 2011). Yields and economics are closely linked. Studying economics should be of paramount importance as it is the main concern of most farmers (Cary & Wilkinson, 1997; Ogieriakhi & Woodward, 2022). Farmers may ask themselves: What if I start? What can I expect? Will I be better or worse off with CT? Soil and environmental benefits alone cannot be expected to lead masses of farmers (apart from a few committed and innovative farmers) to adopt CT. However, it is only through them that the shift to CT is possible. Many studies have looked not only at soil and environmental parameters but also at production costs. Although the results of physico-chemical tests, perhaps less sensitive to weather conditions, can be interpreted well even over short periods, economic calculations can be significantly influenced by the yearly variability of the weather during the study period, possibly leading to erroneous conclusions. This highlights the critical importance of conducting long-term studies and analyses, which are particularly essential for economic calculations (Archer, & Reicosky, 2009; Toliver et al., 2012; Madarász et al., 2016; So et al., 2009; Cusser et al., 2020; Su et al., 2021). However, such long-term studies remain lacking. Published data often cover only a few years and/or a selected crop and mostly only one or two production cost categories (Malhi et al., 1988; Verch et al., 2009; Afshar et al., 2019; Deleon et al., 2020; Cooper et al., 2020; Iqbal et al., 2024; Nath et al., 2024). In addition, these studies are often conducted on small plots, which may be more prone to end up with misleading outcomes. Most studies agree that CT requires lower levels of inputs, especially in terms of fuel, labour and machinery costs (Deleon et al., 2020; Huggins & Reganold, 2008). However, the potential additional crop protection costs and lower yields can reduce or offset the positive economic impact of the former (Basch et al., 2008). Farmers often live under the spell of yields. If PT results in higher yields, this may be a disincentive to adopt CT, even if CT is ultimately more profitable (Ogieriakhi & Woodward, 2022). Therefore, it is particularly essential to have reliable (long-term) data on the profits that can be achieved.

Consequently, we aimed to analyse the economics of CT. Our hypothesis was that under sub-humid conditions, a shift over a 20-year period would ultimately prove beneficial. We wanted to find out how the costs of cultivation (looking separately at material and operational costs) have been affected by CT over 20 years and what impact CT has had on crop yields and, thus, profitability. We aimed to determine whether the long-term data series could distinguish distinct phases of production and profitability. However, our study focuses on long-term changes and impacts. Therefore, it is not concerned with a detailed analysis on the values of individual years (e.g. yield outliers).

2. Material and methods

2.1. Study area

The study site is located in a hilly region with slopes between 1% and 17% steepness next to the village of Dióskál in western Hungary (Fig. 1). The regional climate is warm-summer humid continental

(Köppen, 1936, pp. 1–44), with a mean annual temperature of 11 °C and mean annual precipitation of 600–700 mm. Currently, the mean annual temperature is experiencing a gradual increase, whereas the mean annual precipitation is showing a declining trend (Kocsis et al., 2024). The parent material is loess, and the soil are eroded Haplic Luvisol (Loamic, Humic) (WRB, 2022) on the convex upper part of the slopes, while thicker soil sections are typical on the lower concave slopes due to sedimentation. A more detailed description of the physical and chemical properties of the cultivated layer and the slope conditions of the experimental plots in the field is given by Madarász et al. (2016). The experimental area is representative for the central European croplands, in terms of most environmental conditions and crop rotation. The experimental field was established in 2003 to study PT and CT in the framework of an EU Life project (Bádonyi et al., 2008; Kertész et al., 2010; Madarász et al., 2016). Before the experiment, PT was applied for decades to the entire area with a maize-wheat crop rotation.

2.2. Experimental design and tillage systems

The 83 ha study area was initially divided into 10 pairs of CT and PT plots of similar sizes (~4 ha). Since 2016, we have been working on 9 pairs of plots (76 ha), and plot 1 (PT1 and CT1) was discontinued. The plot arrangement in 2003 was aligned with the needs of agro-ecological and ornithological research (Field et al., 2007). The plots are divided into two blocks: one to the west ['Dióskál 1' (D1) PT1/CT1–PT6/CT6, 51 ha] and one to the east ['Dióskál 2' (D2) PT9/CT9–PT12/CT12, 32 ha] of the road running North-South (Fig. 1). The crop rotation in the two blocks differed. As a result of these different rotations, information on the costs of two crops per year was obtained. The details of the experimental design and the slope conditions of the individual plots were previously reported in Madarász et al. (2016). Details of the tillage systems are presented in Table S1. In brief, PT consists of mouldboard ploughing (25–30 cm depth), harrowing and seedbed preparation every year (unless occasionally prevented by extremely dry weather and soil conditions). CT involves non-inversion, ploughless tillage with a reduced number of tillage operations. Throughout the initial four years of CT, shallow disking was used. However, because of persistent weed issues and the formation of a disc pan layer, it was eventually substituted with a cultivator (20–25 cm) (Madarász et al., 2016). After harvesting, the crop residues remained on both PT and CT plots. In PT plots, they were fully incorporated into the soil through ploughing, while in the CT plots, they were only partially mixed into the soil using shallow tillage. This practice ensured that minimum 30% of the soil surface remained covered by crop residues. The only difference between plot pairs within blocks was the tillage type. All other aspects (crop rotation, crop type, fertilisation and plant protection since year 5) were kept consistent. An exception was the winter of years 2/3 when cover crops were used only on the CT plots of block D1. In addition, cover crops were used on the PT and CT plots of blocks D1 and D2 in the winters of years 15/16 and 19/20. Medium deep loosening (35–40 cm) was performed in block D1 in years 10, 16 and 20 and in block D2 in years 9, and 20, and furthermore, exclusively in the PT area in years 5 and 11. Ploughing was performed annually in the D1 area, whereas in the D2 area, it was omitted in certain years. Specifically, no ploughing followed the deep loosening in years 5 and 11, while extreme drought in year 6 and excessive precipitation in year 8 prevented ploughing. Additionally, in year 4, ploughing was not carried out due to the late harvest of maize. The crop rotation over the last 20 years is detailed in Table S2 by block (D1 and D2). It should also be noted that the farmer has faced various challenges throughout the 20-year period under review. There were instances



Fig. 1. Location of the study area (red rectangle) and the experimental design. CT 1–6 and CT 9–12: conservation tillage plots; PT 1–6 and PT 9–12: ploughing tillage plots. The D1 block is marked in red, the D2 block in yellow.

when weeds were problematic (Madarász et al., 2016) and other times when extreme weather conditions led to the cancellation of ploughing (Since the beginning of meteorological measurements in 1901, the wettest year was 2010 (Year 7), while the driest year was 2011 (Year 8) (http1). These elements will not be described year by year (but are available on request) because the focus is not on the cost ratios for individual years but rather on how these elements evolve with the long-term application of CT.

2.3. Economic analysis

Data on production costs were collected in collaboration with the landowner and used to calculate the economic indicators for the two types of tillage systems. Only costs and incomes directly and effectively linked to production were considered for profitability calculations. Rental costs and public subsidies were excluded from the calculations. To ensure accurate comparisons and account for depreciation, operational costs (such as soil tillage, plant protection, fertilisation, etc.) were recorded as contract work. Operational costs were calculated based on the annual contract work table from 'South-Balaton Ltd.' (http2). Material costs (such as seeds, pesticides, fertilisers, etc.) reflect the actual expenses incurred by the farmer. Total costs comprise operational costs and material costs. The income side is derived from the gain yields and their corresponding selling prices. The same variety or hybrid was grown in both CT and PT plots in a given year. Therefore, this made no difference to crop yields and sales. There was no difference in the quality of the crop harvested from each plot that would have affected sales and the selling price. Thus, the income was determined solely using the average gain yield per hectare. Initially, gain yields were measured on-site using a weighing scale for each plot. From 2017 onwards, a yield meter built into the combine allowed the yield per plot to be determined. The average of the plot data was used to calculate the average yield per tillage system. Profit was calculated as the difference between the total costs (D1 plots + D2 plots) and income (D1 plots + D2 plots) for each tillage system. We determined profit differences for each crop and calculated an aggregate profit difference based on tillage. The general formula is as Eq. (1)

$$I = \sum_{k=1}^N \left((P_k \cdot Y_k) - (C_{gk} + C_{mk}) \right) \quad (1)$$

where I is the total income, N is the number of crops, P_k is the price per unit of the k -th crop, Y_k is the quantity sold of the k -th crop, C_{gk} is the total machinery cost associated with the k -th crop Eq. (2), and C_{mk} is the total material cost associated with the k -th crop Eq. (3).

$$C_{gk} = \sum_{i=1}^{n_k} G_{ik} \quad (2)$$

$$C_{mk} = \sum_{j=1}^{m_k} M_{jk} \quad (3)$$

where G_{ik} is the i -th machinery cost for the k -th crop, M_{jk} is the j -th material cost for the k -th crop, n_k is the number of machinery cost items for the k -th crop, and m_k is the number of material cost items for the k -th crop.

The two experimental blocks (D1 and D2) provided data on the cultivation of two crops per year, resulting in a total of 40 income data for 5 different crops. Our data cover a 20-year period (2004–2023) and include six crops: maize (12 years), winter cereals [wheat (11 years) and barley (2 years)], oilseed rape (8 years), spring barley (6 years) and sunflower (1 year). We converted the data collected each year to 2024 price levels to ensure consistency, aiming to negate the impact of inflation on the value of income and expenses. Consequently, all monetary costs and revenues were expressed in 2024 prices, first in HUF and then in EUR (Table S3). Our primary objective was to compare tillage costs while eliminating macro-economic effects. These effects are diverse but exert the same influence on the evolution of costs and revenues for both technologies, making the results methodologically comparable and allowing the quantification of differences.

2.4. Statistical analysis

Piecewise linear regression (PLR) is a statistical method that enables the modelling of distinct trends and their breakpoints within data over time. This technique allows the separate linear modelling of different segments of a dataset. The breakpoints indicate the points in time where a change in the trend occurs. Although the model provides breakpoints with decimal precision, such granularity holds little practical relevance for management purposes, where only the rounded estimates are meaningful. Nonetheless, the unrounded values are presented and used in this study because they offer greater statistical accuracy. PLR was fitted to the data (after conversion to 2024 price levels) for the following.

- The mean yield gain percentage (%) cumulated from 2004 to 2023. The mean yield gain percentage was calculated as the difference between the mean yields of PT and CT divided by the mean yield of CT.
- The gross income gain (EUR) cumulated from 2004 to 2023. The gross income gain was calculated as the difference between the gross income from PT and CT.
- The total cost gain (EUR) cumulated from 2004 to 2023. The total cost gain was calculated as the difference between the total costs of CT and PT.
- The profit gain (net income) (EUR) accumulated from 2004 to 2023. The profit gain was calculated as the difference between the profit of PT and CT.

First, the number of breakpoints was optimised (Muggeo, 2020), followed by PLR analysis. We calculated the explained variance rate (adjusted R^2) and tested its significance using a t -test. We also calculated and tested the parameter estimations using t -tests. Finally, we performed fivefold cross-validations to compare the models with different breakpoints. The analysis was performed using R (v.4.3.2, 2023; R Core Team, 2023) with the packages 'segmented' (Muggeo, 2008) and 'cv' (Fox & Monette, 2024).

3. Results and discussion

3.1. Gain yields and gross income

3.1.1. Gain yields

The 20-year data series can be divided into four distinct phases (with three breakpoints) when analysing the differences in average yield gain of CT (% compared with PT) modelled by PLR (Fig. 2(a)). The estimated breakpoints (3.3, 10.9 and 16.0), the parameter estimations of the segmented linear fit and their t -tests and 95% confidence intervals are given in Table 1A, and the observed values with the best-fitted segmented line are shown in Fig. 2(a).

The four stages based on yields are as follows.

- (1) *'Transitional' period*: During the first 3 years following the transition, a clear and significant reduction in average yields under CT cultivation was observed compared with PT cultivation with significant negative slope. This decrease reached a peak of −14.2% in the second year (this was −11% for D1 plots, and the absolute minimum for 20 years was −18.4% for D2 plots). The causes of this reduction have been previously attributed to transitional challenges, inappropriate machinery and a lack of knowledge and experience (Madarász et al., 2016). Additional issues arose, such as selecting unsuitable winter wheat varieties, resulting in *Fusarium* infection. This issue was confined to the CT plots, where the remnants of the previous year's maize stalks were left partially on the surface,

contributing to the infection. By contrast, in the PT plots, the maize stalks were ploughed in. A common characteristic of these three years was the continued use of shallow disc tillage in the CT plots.

- (2) *'Adapted 1' period*: After the 3rd year of the experiment, yield gains started to increase with a significantly high positive slope. By this time, it was possible to conclude the experience of the first years: a technology adapted to local conditions was developed, and appropriate equipment was already available (Madarász et al., 2016). This ensured that all operations could be conducted promptly and at the most optimal times, in contrast to the earlier years when such timing was not always feasible because of delays in securing rental machinery. In addition, this period was crucial for the development of the rich soil fauna characteristic of CT-tilled areas (Madarász et al., 2011; Roger-Estrade et al., 2010). This, in turn, contributed to an increase in soil organic matter, an improvement in soil structure, a reduction in soil erosion and an enhancement in infiltration capacity (Juhos et al., 2024; Madarász et al., 2021; Nugroho et al., 2023). Period 2 (based on yields) covers the 4–10 years after the shift. During this period, consistently higher average gain yields (an increase of 11.3% on average) were recorded for all crops grown in CT fields despite the occurrence of both extremely wet (year 7) and extremely dry (years 8–9) conditions. A notable change during this phase was the introduction of cultivator treatment in CT fields from the fifth year onwards in response to weed issues.
- (3) *'Steady' period*: The third phase covers years 11–16 after the shift. In this period, the previously significant yield gain of CT is reduced, and in several cases, it turned negative with an insignificant slope calculated for this interval (Fig. 2(a), Fig. 3(b) and Table 1). The fact that the slope is not significant means that it does not differ from zero statistically significantly (i.e. it is practically horizontal), which indicates the name of this period 'Steady'. On average, yield differences favoured both PT and CT. The reduction in yield gain can be partially attributed to increased 'biodiversity'. For example, in year 14, maize yields were notably affected by wild boar, which foraged exclusively in the moisture soil of CT (of D2) areas, attracted by the higher abundance of soil-dwelling worms and earthworms. Other pests also became more prevalent. In the same year, wireworms posed significant challenges in oilseed rape, with infestation levels twice as high as those observed in PT (of D1) areas. In addition, weed problems resurfaced, particularly with *Apera spica-venti* and *Lolium multiflorum*.
- (4) *'Adapted 2' period*: Period 4 encompasses the 16th–20th years following the shift to CT. After the problems of period 3 had been solved (e.g. electrification of the fence against wild animals, improved crop protection and more precise sowing techniques), CT again ensured higher yields. This is manifested with a significant positive slope at PLR. The slope was lower than that of the second period, which indicates a slower but notable increase. If the CT technology is perfectly implemented, there is a good chance that yields will return to the higher levels of period 2 later. However, in year 20, the introduction of sunflower into the rotation resulted in yields significantly lower than anticipated because of sowing errors (Table 2). The issue was traced to an inadequate closure of the drilling line, and positive yields are expected in the future, including for sunflower.

The initial yield reductions (10%–18%) observed during the first 3

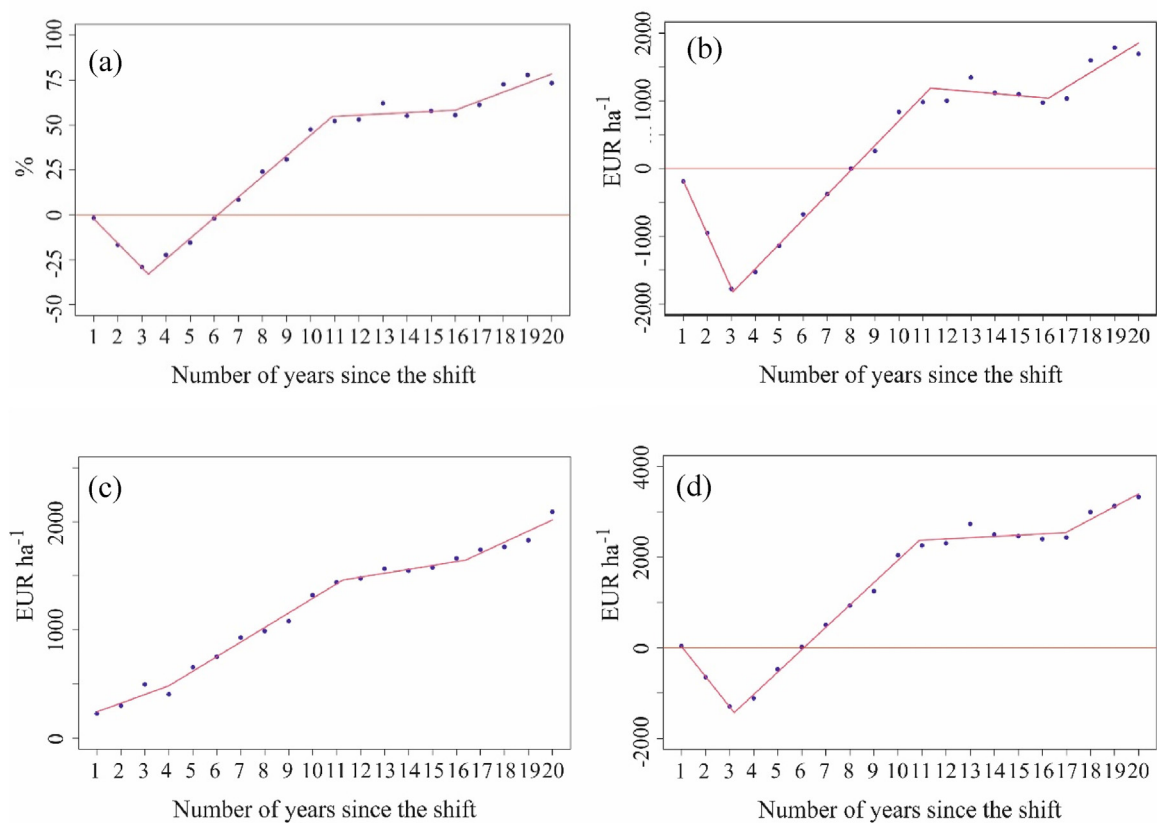


Fig. 2. Cumulated mean yield gain of CT (% compared with PT) (a), cumulated gross income gain (EUR ha⁻¹) (b), cumulated total cost gain (EUR ha⁻¹) (c) and cumulated profit (net income) gain (EUR ha⁻¹) (d) with the segmented linear fit (adjusted R² = 0.98, p < 0.001) (year 1 was assigned to 2004).

Table 1
The estimated breakpoints and the parameter estimations of the segmented linear fit on the cumulated mean yield gain (%) (A), the cumulated gross income gain (EUR ha⁻¹) (B), the cumulated total cost gain (EUR ha⁻¹) (C) and the cumulated profit gain (EUR ha⁻¹) (D) together with their t-tests, 95% confidence interval lower (CIL) and upper (CIU) endpoints.

A: cumulated mean yield gain [%] Adjusted R ² = 0.99; p < 0.001						B: cumulated gross income gain [EUR ha ⁻¹] Adjusted R ² = 0.98; p < 0.001					
	Estimated values	StError	t	CIL	CIU		Estimated values	StError	t	CIL	CIU
Breakpoints	3.3	0.20	16.50***	2.84	3.69		3.1	0.15	20.67***	2.75	3.39
	10.9	0.39	27.95***	10.05	11.76		11.3	0.41	27.56***	10.42	12.21
	16.0	1.11	14.41***	13.59	18.41		16.2	0.78	20.77***	14.53	17.94
C: cumulated total cost gain [EUR ha ⁻¹] Adjusted R ² = 0.99; p < 0.001						D: cumulated profit gain [EUR ha ⁻¹] Adjusted R ² = 0.98; p < 0.001					
	Estimated values	StError	t	CIL	CIU		Estimated values	StError	t	CIL	CIU
Breakpoints	4.0	1.89	2.12 ⁺ bb	-0.13	8.13		3.2	0.16	20.00***	2.84	3.54
	11.3	0.74	15.23***	9.64	12.89		10.9	0.34	32.06***	10.16	11.63
	16.4	1.29	12.70***	13.58	19.18		17.0	0.70	24.29***	16.96	18.48
Slope						Slope					
Period 1	80.45	43.66	1.84 ⁺ vb	-14.68	175.58		-666.32	100.03	-6.66***	-884.26	-448.38
Period 2	134.52	9.53	14.12***	113.76	155.28		493.87	26.73	18.47***	435.62	552.11
Period 3	35.95	19.53	1.84 ⁺ vb	-6.60	78.49		27.37	33.82	0.81nsb	-46.31	101.05
Period 4	102.45	27.62	3.71***v	42.28	162.62		281.88	63.26	4.46***	144.04	419.72

ns: not significant ***significant at p < 0.001; **p < 0.01; *p < 0.05; + p < 0.1.

years were particularly pronounced for both maize and wheat, especially in the second and third years. [Achankeg & Cornelis \(2023\)](#) also highlighted maize's underperformance, attributing it to reduced soil looseness, which impedes root development. However, these losses were quickly offset by the gains achieved during the adapted period so that by year 6, cumulative yields had already

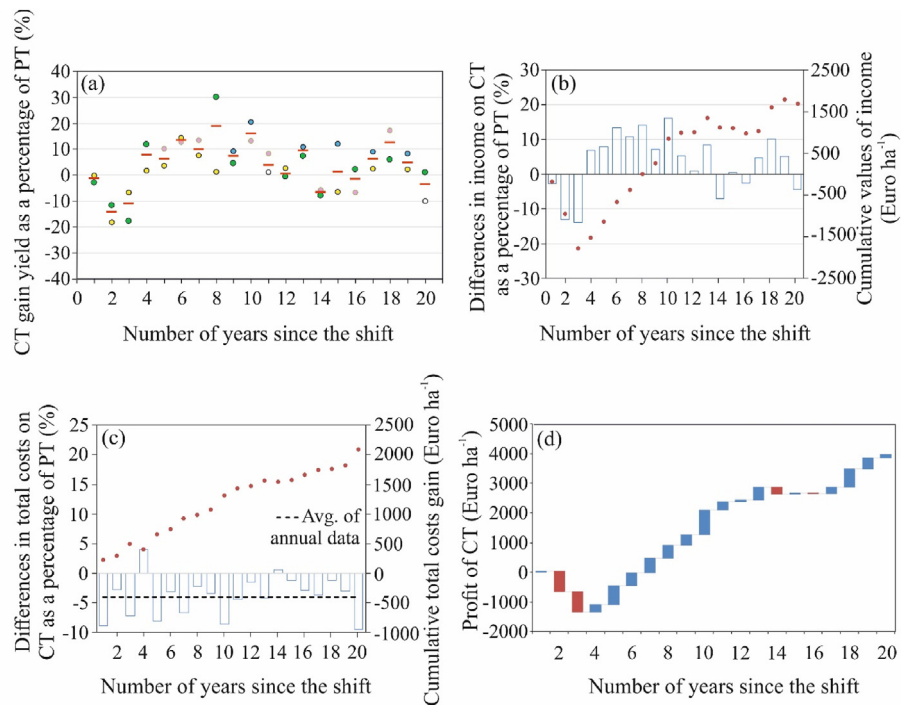


Fig. 3. Comparison of average annual gain yield differences and the yield difference between the two crops grown (a), gross income (b), total costs (c) and profit (d) per hectare for conservation tillage (CT) versus conventional ploughing tillage (PT) over 20 years following the shift, with cumulative values expressed in EUR per hectare (b, c, d). On diagram (a): yellow dots, winter cereals; green dots, maize; pink dots, oilseed rape; blue dots, spring barley; white dot, sunflower; red lines, average of two crops.

Table 2
Average yield gain (positive values) and loss (negative values) of conservation tillage plots for each crop, expressed as the percentage based on conventional ploughed tillage plots during the experimental periods.

	First (Transitional) period, 1–3 years (%)	Adapted1, Steady and Adapted 2 periods, 4–20 years (%)	Entire studied period 1–20 years (%)
Winter cereals	−9.4 (n = 3)	+2.7 (n = 10)	+0.3 (n = 13)
Maize	−10.3 (n = 3)	+4.6 (n = 9)	+0.04 (n = 12)
Rape		+7.6 (n = 8)	+7.6 (n = 8)
Spring barley		+11.4 (n = 6)	+11.4 (n = 6)
Sunflower		−10.0 (n = 1)	−10.0 (n = 1)

surpassed those of the PT areas. Over the full 20-year period, the farmer harvested on average 3.9% more from the CT areas despite the initial significant decrease. [Tebrügge & Böhrnsen \(1997\)](#) investigated the effects of no-till in their long-term studies conducted in Germany (1981–1997) and observed a more pronounced yield reduction during the initial 2 years compared with conventional tillage, followed by a gradual increase in yields thereafter. Similar findings were reported by [So et al. \(2009\)](#) in Australia on loamy soil, where they observed a 12.8% yield reduction during the first 4 years by no-till, followed by a 28.1% yield surplus during the subsequent 10 years, corresponding to our Adapted 1 phase. However, a meta-analysis of European studies conducted by [Achankeng & Cornelis \(2023\)](#) concluded that no-, ridge- and strip-till practices were associated with an average yield reduction of 5% compared with PT.

Yield differences by crop are summarised in [Table 2](#). The data indicate that although CT resulted in modest yield increases for winter cereals and maize (2.7% and 4.6%, respectively), it produced substantial yield gains for oilseed rape and spring barley (7.6% and 11.4%, respectively). However, sunflower is an outlier. Because it was only grown in one year, with significant sowing errors, no definitive conclusions can be drawn from its results.

3.1.2. Gross income

Gross income is derived from crop sales, making gain yields the

primary factor influencing gross income levels. Although yield gain became positive from the fourth year onwards, the initial lower yields and the subsequent reduced gross income were not offset in the gross income until the eighth year ([Fig. 3\(b\)](#)), which can be explained by the absolute value of the significant positive slope of the second period that is approximately half as high as the absolute value of the significant negative slope of the first period (c.f. the time of reaching the value zero in year 8 in [Fig. 2\(b\)](#)).

It is essential to highlight that there were considerable variations in the selling prices of the same crop across different years. Even after accounting for inflation and fluctuations in exchange rates, price differences of 1.8–3.0 times were observed ([Fig. 4](#)). These variations are often a critical factor in determining profitability and underscore the susceptibility of farmers to global market dynamics. For instance, the sharp increase in Chinese oilseed rape imports in 2021 triggered a significant increase in oilseed rape prices, which subsequently returned to more typical levels in the following years ([http3, Forbs, 2021](#)).

Gross income data are closely linked to yields. Therefore, it is unsurprising that the PLR model–estimated parameters mirrored the yield analysis results ([Fig. 2\(a\)](#) and (b)). PLR also identified three optimal breakpoints, confirming the stages described earlier with a third period of an insignificant slope that was followed by a period of a significant positive slope. Again, the significant increase in the

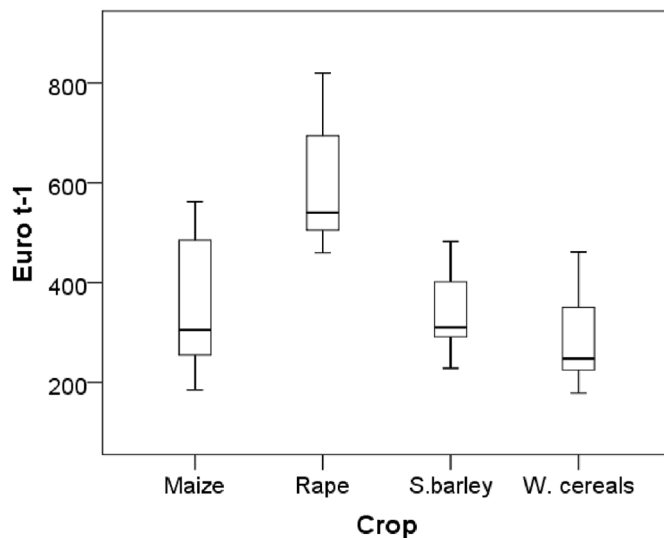


Fig. 4. Distribution of crop selling prices for the study area in 2004–2023 (maize $n = 12$; rape $n = 8$; spring barley $n = 6$; winter cereals: winter wheat $n = 11$ and winter barley $n = 2$).

fourth period was slower than that in the second period. The estimated breakpoints, the parameter estimations of the segmented linear fit and their t-tests and 95% confidence intervals are given in Table 1, and the observed values with the best-fitted segmented line are shown in Fig. 2(b).

3.2. Total (operation and material) costs

3.2.1. Operational costs

In reduced tillage systems, the primary reduction in operating costs stems from the elimination of ploughing and harrowing. Over the 20-year period, this reduction averaged 9.8%, which translated into an average saving of €129 per hectare per year for the studied fields. During the initial 4 years following the transition, the farmer used shallow (disc) tillage, which was significantly less costly than ploughing, resulting in a 15.5% cost saving. From year 5 onwards, shallow (disc) tillage was replaced with a loosener and cultivator, which increased the operating costs of CT. Consequently, the cost savings diminished, with the differences between tillage methods narrowing, leading to an approximate saving of 8.3%. Variations between years can be attributed to the relative costs of unploughing machinery compared with ploughing and additional factors such as the need for enhanced crop protection or the use of cover crops on CT plots (year 2). The largest difference in operating costs was observed in year 20, with a 25.7% reduction when medium deep loosening was applied to CT plots in both study blocks (D1 and D2), and the PT plots underwent loosening and ploughing. This scenario reflects the maximum savings in machinery costs. Meanwhile, Afshar et al. (2019) reported a 26.8% reduction in operational costs over a 3-year trial, and Verch et al. (2009) documented a similar 22.0% reduction over a 4-year period. Notably, the reduced tillage in CT systems results in lower CO₂ emissions (Kern & Johnson, 1993; Leake, 2000; West & Marland, 2002). Combined with the carbon sequestration potential of CT soils (Angers et al., 1997; González-Sánchez et al., 2012; Piazza et al., 2020), this contributes to a significant reduction in CO₂ emissions. Moreover, fewer tillage operations and passes across the field reduce trampling and soil compaction, alongside lowering the man-hours per hectare and the overall labour demand in CT cultivation (Huggins & Reganold, 2008).

3.2.2. Material costs

Regarding material costs, the first four years—rather than just the first three—stand out as distinct from the subsequent period (Table 3). Weed problems in the first 4 years required extra crop protection on the CT plots. Moreover, the use of cover crops exclusively on the D1 CT plots in the winter of year 2 led to an average annual increase of 9.6% in CT material costs. However, additional crop protection was applied only where CT technology was necessitated. From year 5 onwards, these issues were resolved with the benefit of increased expertise and the use of appropriate machinery (the shift to using a cultivator instead of a disc). As a result, crop protection measures for the CT and PT fields became comparable, leading to similar material costs. Consequently, material costs were only 1.9% higher over the entire 20-year period.

3.2.3. Total costs

For the total costs, the use of CT resulted in lower costs, except for two years (years 4 and 14). Over 20 years, this represents a cost saving of 4.0% in favour of CT (on average, 104.5 Euro year⁻¹ ha⁻¹ gain for the fields studied) (Fig. 3(c)). Verch et al. (2009) investigated the total costs of reduced tillage in a 4-year trial in Germany and found a much larger cost reduction of 11.6%. The PLR analysis on the cumulative total cost gain (EUR ha⁻¹) also resulted in three breakpoints (Fig. 2(c)). The estimated breakpoints were at 4.0, 11.3 and 16.4 years according to the model. The model aligns well with the breakpoints identified for gross income, although the slopes of the fitted line show variation and could even be described as smoothed. The parameter estimates of the segmented linear fit, along with their corresponding t-tests and 95% confidence intervals, are presented in Table 1. The technological challenges outlined earlier are mirrored in certain phases of the total cost gain. Following the transition period (years 1–3) (e.g. higher crop protection expenditure with an insignificant slope), the total cost gain increased in period 2 (Adapted 1) because the technology became better suited and adapted to the conditions, as indicated by the significant positive slope of the fitted lines (Fig. 2(c)). In period 3 (Steady), the slope of the total cost gain line decreased again and did not show a significantly different trend from a zero-slope one, reflecting the issues discussed in Section 3.1. Addressing these problems in period 3 led to a renewed increase in cost savings in period 4. This was represented again by a significant positive slope that was lower than that in the second phase, indicating a slower but pronounced increase (Adapted 2).

3.3. Profitability analysis

Over the 20-year duration of the experiment, the material costs on CT plots were 1.9% higher and operating costs were 9.8% lower as averages. In addition, gross income increased by 2.3%. Consequently, the profit on CT plots was 13.0% higher than that on PT plots, translating to an average profit of 199.1 Euro year⁻¹ ha⁻¹. It is essential to note that the farmer had a negative profit in two of the three years following the transition, leading to a profit loss of 11.9%. However, in the next 17 years, PT cultivation was more profitable in only two times (Fig. 3(d)). Because of the initial losses, the farmer was able to realise a real profit surplus from year 7 onwards. Examining the period after the transition separately (a total of 17 years), CT outperformed PT with a 27.6% higher profit. Despite this overall success, it is essential to note that not all crops were profitable every year. For example, oil seed rape grown on D1 plots in year 12 and wheat on D1 plots in year 15 resulted in losses under CT. Nevertheless, these losses were compensated by additional income from other crops in the other block (D2, winter wheat and spring barley, respectively), leading to an overall positive income for those years (Table 4). Deleon et al. (2020) examined years 5–6 of

Table 3

Material costs of conservation tillage (CT) plots as a percentage of conventional ploughing tillage (PT) and differences in material costs in Euro ha⁻¹ in the study area (2004–2023).

Years	1. 2004	2. 2005	3. 2006	4. 2007	5. 2008	6. 2009	7. 2010	8. 2011	9. 2012	10. 2013
CT/PT rate	8.5	12.9	−0.6	17.4	0.0	0.0	0.0	0.0	0.0	0.0
CT-PT (Euro ha ⁻¹)	95.5	167.0	−8.5	184.4	0.0	0.0	0.0	0.0	0.0	0.0
Years	11. 2014	12. 2015	13. 2016	14. 2017	15. 2018	16. 2019	17. 2020	18. 2021	19. 2022	20. 2023
CT/PT rate	0.0	0.0	0.0	0.4	0.0	1.0	0.0	0.5	−0.3	2.0
CT-PT (Euro ha ⁻¹)	0.0	0.0	0.0	5.6	0.5	14	0.1	6.0	−3.4	33.1

Table 4

Average profitability gain (positive values) or loss (negative values) of conservation tillage expressed as the percentage compared with conventional ploughing tillage in the study area (2004–2023) for maize, rape, spring barley, sunflower and winter cereals.

	1–3 years, Transitional period, (%)	4–20 years, Adapted 1, Steady and Adapted 2 periods, (%)	1–20 years, Entire studied period, (%)
Winter cereals	16.1 (n = 3)	18.0 (n = 10)	17.8 (n = 13)
Maize	−13.0 (n = 3)	19.7 (n = 9)	−0.7 (n = 12)
Rape		53.0 (n = 8)	53.0 (n = 8)
Spring Barley		32.0 (n = 6)	32.0 (n = 6)
Sunflower		4.0 (n = 1)	4.0 (n = 1)
All	−11.9 (n = 6)	27.6 (n = 34)	12.9 (n = 40)

an experiment in Colorado and reported a 22% increase in profits from minimum tillage for maize and barley, which aligns closely with our findings. However, if we look only at the 5–6 years of our experiment when winter wheat and oilseed rape were sown, the results showed that the profit in favour of CT was 85%(!) in these two years alone. This also showed the importance of long-term analysis.

Of the five crops grown, the most relevant profit difference was observed for oilseed rape (53%), followed by spring barley (32%) (Table 4). Despite the challenges that hindered production during the transitional period, winter cereal profits remained stable, achieving a balanced performance that is essential to emphasise. Notably, the adaptation of technology did not result in a notable increase in profitability for winter cereals. The impact of the shift, particularly in terms of weed pressure, was most pronounced in maize. This crop experienced a substantial reduction in yields, leading to a relevant decrease in profit despite lower expenditure (−13.0%). However, following the transition period, maize provided a comparable additional profit (19.7%) to winter wheat (18.0%). Nevertheless, because of the initial decrease, there was still a slight income loss in the 20th year (−0.7%). PLR also found three optimal breakpoints for profit in the data series (Fig. 2(d)). The estimated breakpoints, the parameter estimations of the segmented linear fit and their t-tests and 95% confidence intervals are given in Table 1. The four periods already set up for yields in the case of profit differences based on the PLR are as follows.

1. 'Transitional' or declining period (years 1–3): despite significant cost savings, the decrease in yields resulted in a corresponding decrease in profit (−11.9%) with a significant negative slope that described the process.
2. 'Adapted 1' period or growth phase (years 4–11): during this 8-year phase, a substantial income gain in favour of CT cultivation was observed (58.9%) with a highly positive slope of its trend. However, the initial profit loss was not fully offset until year 6, with CT becoming consistently profitable from year 7 onwards (c.f. the time of reaching the value zero in year 6 in Fig. 2(d)).
3. 'Steady' period (years 11–17): the issues encountered during this period—previously discussed under yields, such as weed

infestation, wireworm problems and wildlife damage—also affected profitability, leading to occasional low or even negative profit in two instances (Fig. 3(d)), which could be detected in the insignificant slope of this period.

4. 'Adapted 2' period (years 18–20): after identifying and effectively managing these challenges, profit differences returned to their previous high levels from year 18 onwards (Fig. 2(d), Fig. 3(d)), with a significant positive slope though lower than in the second period (Adapted 1) pointing out a slower but still remarkable increase (Table 1).

4. Conclusion

On the basis of the results, the answer to the question in the title is clearly yes. The average profit surplus over the 20-year period was 13.0%, with the potential for further increase as the impact of negative values in the early years diminishes. This profit surplus is primarily attributed to a 9.8% reduction in operating costs and a 2.3% increase in gross income, slightly mitigated by a 1.9% increase in material costs. In support with our initial hypothesis, we concluded that a CT system has gain yield and profit advantages over PT for the long term and can be divided into four distinct periods using PLR (Transitional, Adapted 1, Steady and Adapted 2). The notable yield losses observed during the first three years (transitional period) may understandably deter farmers. However, it is crucial to consider and commit to CT cultivation for the long term, where substantial profit surpluses can be realised. Our study also highlights that short-term studies may yield results that are inconsistent with long-term realities, as argued by Cusser et al. (2020). In the ca. 80-ha farm that we examined, profitability was achieved by year 7. Naturally, this timeframe depends on factors such as farm size, geographical location, climate, soil type, crop type and market prices, and these factors are a limitation of this study. However, it underscores that immediate profits should not be expected and that the worst course of action would be to abandon CT after a few years and revert to ploughing. The 'steady state' yield losses identified in our study also indicate that CT cultivation requires on-going attention and cannot be conducted on a routine basis, even after 10–15 years. The authors emphasise that

the focus of CT technology should not be limited solely to yields and profits, although these are undeniably crucial considerations from a farmer's perspective. The well-documented positive environmental impacts of CT (Holland, 2004; Li et al., 2019) should be underscored, even in scenarios where net production remains unchanged. Moreover, our calculations indicate that even if CT produced the same yield as PT after the initial decrease, a profit margin of 3.4% could still be realised because of significant cost reductions. This suggests that the profit achievable with PT (under current climatic conditions) could still be realised with CT technology, even with slightly lower gain yields. A lack of understanding of economic outcomes poses an on-going risk, particularly when altering cropping patterns in pursuit of optimal approaches (Ghasemi-Mobtaker et al., 2022). Although the PT system remains financially sustainable at present, its associated costs are likely to increase in the future. This is evidenced by the recent sharp increase in fuel prices across Europe and the substantial surge in fertiliser prices driven by the war in Ukraine. In addition, the COVID-19 pandemic has caused severe disruptions to global supply chains, which is a risk that is expected to grow, potentially leading to further price increases. However, these issues are likely to be mitigated by implementing CT, reducing operational costs, potentially lowering fertiliser requirements in the long term and improving soil health. In crises, this approach could even enhance the safety of food supply. CT offers clear economic benefits for farmers in the framework that we have outlined and, considering its environmental impacts, would also be advantageous for society as a whole. Consequently, a bridging subsidy from responsible policymakers could be a cost-effective investment with notable returns for the entire community.

CRediT authorship contribution statement

Balázs Madarász: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Éva Zsuzsanna Járás:** Data curation. **Gergely Jakab:** Writing – original draft, Conceptualization. **Zoltán Szalai:** Supervision, Methodology. **Márta Ladányi:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.iswcr.2025.02.012>.

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