## How a decade of different tillage intensity influences yield response to seasonal weather variations

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## Synopsis

A 10 year study of crop establishment systems showed that ploughing gave the most stable yields whilst direct drilling was benefical in dry years.

## Highlights

* Ploughing provided the greatest yield stability across all crops and seasons.
* Direct drilling can preserve soil moisture which resulted in higher yields than ploughing in drier years.
* Seasonal variability in wheat yield was partly explained by cultivation and temperature variables.
* Spring wheat was more sensitive to temperature variations than winter wheat.

## Abstract

Variability in weather conditions represents a growing challenge to crop yield stability and performance. This long-term field experiment aimed to evaluate how weather conditions affect arable yields under contrasting cultivation practices: plough-based tillage (P), minimum tillage (MT) and direct drill (DD), over a 10-year period. Our results showed that ploughing provided the greatest yield stability in all crops across the seasons. Although DD produced lower yields in the first 4-years, DD can preserve soil moisture making more efficient use of the available precipitation resulting in similar or higher yields than plough based systems in drier and warmer years. This is especially important as we observed an upward trend in the seasonal maximum temperatures (TMax). For wheat crops, our results showed that yield variability was in part explained by cultivations and temperature variables, with spring wheat being more sensitive to variations in weather conditions in comparison to winter crops. When mean seasonal temperatures were <12.3°C, spring wheat had lower yields under DD compared to MT and P. For winter wheat, yields were lower when the TMax in February was <9.9°C regardless of the cultivation system. This study can conclude that cultivation systems can affect arable yields, but weather conditions can have both positively and negatively impact crop yields depending on the tillage systems. Climatic variables measured during different crop growth stages were better predictors of yield variability than those averaged over the entire growing season. These results highlight the importance of crop management for optimising production in response to weather variability.

## Keywords

Reduce tillage; Wheat yield; Cereals; Weather; Temperature; No tillage

## Introduction

### Interactions among weather and cultivation practices.

Climate change has already caused a global decrease in cereal yields ranging from -0.3 MT to -5.0 MT (Ray et al., 2019). More specifically, yield losses in eastern and northern Europe are widespread for maize (-24.5%), barley (-9.1%), and wheat (-2.1%) (Ray et al., 2019). Similarly, Vogel et al. (2019) reported that maize and spring wheat are highly sensitive to climate variations and extreme climatic events. To continue feeding a growing population while ensuring resilience toward climate change, agricultural systems must promote soil health and a sustainable increase in productivity and efficiency (Godfray and Garnett, 2014). Seasonal temperature increases have been shown to affect crop development causing losses in yields (Rial-Lovera et al., 2017; Rezaei et al., 2018) but this negative effect has been exacerbated when higher temperatures are accompanied by lower precipitation (Lesk et al, 2021; Zhang and Huang, 2011) or extreme weather events (van der Velde et al., 2012). Reduced tillage (RT) systems, such as direct drill (DD) and minimum tillage (MT), have been studied and promoted to sustain crop productivity and resilience under extreme weather conditions (Dicks et al., 2019; Liu and Basso, 2020; Rial-Lovera et al., 2017; Tilman et al., 2011). Residue retention under RT systems has been shown to enhance crop system adaptation to climate change by increasing soil water retention (Çelik et al., 2018; Rial-Lovera et al., 2016a). These systems can also improve soil organic carbon (SOC) content, create more soil macropores and promote earthworm activity (Blanco-Canqui and Ruis, 2018; Giannitsopoulos et al., 2019; Liu and Basso, 2020); increase soil water holding capacity and soil organic matter (SOM) improving the stability and water infiltration in the aggregates which in turn reduces topsoil erosion and water runoff (Soane et al., 2012). Regardless of these benefits, RT systems have not been fully adopted with only 12.5% of the global cropping area under RT within conservation agriculture (Kassam et al., 2018).

Reasons for low adoption rates of RT have been linked to lower crop yields and the variability of performance under different climate conditions and other management practices (Pittelkow et al., 2015). RT systems can result in increased soil compaction and a reduction in soil aeration due to less soil mixing (Blanco-Canqui and Wortmann, 2020; Çelik et al., 2018). The accumulation of crop residues within the topsoil can also result in cooler soils, leading to slower mineralisation of nitrogen (N) affecting its nitrogen availability in early spring (Rial-Lovera et al., 2016a). In addition, RT systems can lead to higher weed pressure resulting from less soil disturbance and build-up of weed seeds in the topsoil layers (Armengot et al., 2016; Cordeau et al., 2020; Hofmeijer et al., 2019; Vijaya Bhaskar et al.; 2013a) thus requiring greater weed chemical control than in ploughed-based tillage systems (P) (Fonteyne et al., 2020; Rial-Lovera et al., 2016b). However, this increase in weed pressure tends to be mostly accentuated during the first years of RT (Hernández Plaza et al., 2015; Hofmeijer et al., 2019).

Crop and soil type and weather conditions can also largely explain the variability in crop yields under RT vs P (Baiamonte et al., 2019; Pittelkow et al., 2015; Samson et al., 2019; Su et al., 2021). For instance, Jalli et al. (2021) reported that direct drilled spring wheat yielded up to 30% more in a diversified crop rotation when compared to DD monoculture. This supports results found by Marini et al. (2020) reporting that growing diverse crop species in a rotation led to higher grain yields in both winter and spring cereals in years with higher temperatures and scant precipitations. Overall, RT systems, especially DD, have performed better under rainfed conditions in dry climates due to their ability to retain more soil moisture (Blanchy et al., 2020; Su et al., 2021; Vanderlinden et al., 2021).

The interconnections between grain yield, tillage management and changes in weather conditions as a result of climate change still require further research. Climate change and the increase in extreme weather events will bring more challenges for UK cereal production unless new adaptation practices are implemented (Rial-Lovera et al., 2017; Wheeler and Lobley, 2021). Long-term field experiments are therefore needed to further understand the potential effects that cultivation practices have on crop yields as a function of changing weather conditions.

This study evaluated how weather conditions affect arable crop yields under contrasting cultivation systems. More specifically, it aimed to i) identify the most influential factors in determining inter-annual crop yield variations; ii) determine the comparative response of cultivation systems, plough-based tillage (P), minimum tillage (MT) and no-till (DD), over a ten-year growing period, and iii) explore the relationship between local periodic yields under contrasted cultivation systems and precipitation and temperature patterns in an arable cropping system in the United Kingdom.

## Materials and methods

*Experimental site*

The study was conducted on a 10-year field experiment that began in October 2010 at the Royal Agricultural University’s Harnhill Manor Farm (51°42′N, 01°59′W; 135 m a.s.l.), Cirencester, UK. The soil is Evesham soil series (SSEW 1983) with a clay texture (pH 6.9 and 4.7% organic matter). During the experimental period 2010-2020, the mean annual temperature and total annual rainfall were 10.4°C and 829.7 mm, respectively (Figure 1).

Figure 1. Total annual rainfall (mm) (bars) and mean annual temperature (°C) (line) during the experimental years 2010-2020

*Experimental design*

The experiment followed a complete randomised block design with three cultivation treatments replicated in six blocks (90 x 100 m2), conventional plough-based tillage (P), minimum tillage (MT) and no-till (DD). Each plot had a size of (33.3 m x 100 m). Cultivation systems specifications are shown in Table 1.

*Table 1. Cultivation treatments specifications*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Cropping season** | **Experimental year** | **PT** | **MT** | **DD** |
| 2010/11 | 1 | Five furrows Kverneland reversible plough (20cm) + Kuhn power harrow combination seed drill (8cm) | 2 passes of ST bar attached to Simba Xpress (25 + 12cm) + Vaderstad Rapid-A system disc combination seed drill (8cm) | 1 pass of ST bar attached to Simba Xpress (25 + 12cm) + Eco-Dyn integrated seed drill (8 cm) |
| 2012 | 2 |
| 2013 | 3 |
| 2014 | 4 |
| 2015 | 5 | Topdown (30 cm) + Moore Unidrill (8 cm) | Moore Unidrill (8 cm) |
| 2015/16 | 6 |
| 2016/17 | 7 | Vaderstad Swift (20cm) + Moore Unidrill (8 cm) | Claydon Hybrid drill (8 cm) |
| 2017/18 | 8 | Topdown (30 cm) + Moore Unidrill (8 cm) |
| 2018/19 | 9 | Vaderstad Swift (20 cm) + Moore Unidrill (8 cm) | Moore Unidrill (8 cm) |
| 2019/20 | 10 | Five furrows Kverneland reversible plough (20cm) + Horsch Joker + Horsch sprinter drill (8cm) | Horsch Joker (25 cm) + Horsch sprinter drill (8cm) | Horsch sprinter drill (8cm) |

The experimental years cover ten cropping seasons from 2010/11 to 2019/20 with winter and spring wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.) and winter oilseed rape (*Brassica napus* L.) (Table 2). Sowing dates for the winter cereal crops ranged from the end of September until the beginning of November, while spring cereals were sown between March and April. Oilseed rape was sown at the end of August and harvested in July (Table 2). During the first three seasons of the study, 2010-13, the trial followed an organic management regime after which, in 2014, a conventional management was adopted (Table 2). However, individual cultivation treatment plots remained constant throughout the years. As fertilisation was not investigated in this experiment, all plots, from 2014 onwards, received the same amount of nitrogen (N), phosphorus (P) and potassium (K), adapted to the specific requirement of each crop under conventional management according to AHDB Nutrient Management Guide RB209 (AHDB, 2020). Herbicides and fungicides were also applied to the whole experiment area under conventional management.

*Table 2. Outline of farming systems and crop details*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Cropping season** | **Farming system** | **Crop** | **Variety** | **Seed rate (seed m-2)** | **Sowing date** | **Harvest date** |
| 2010/11 | Organic | Winter wheat | Claire | 410 | 05/11/2010 | 25/08/2011 |
| 2012 | Spring wheat | Paragon | 420 | 14/03/2012 | 22/08/2012 |
| 2013 | Conventional | Spring wheat | Paragon | 480 | 10/04/2013 | 27/08/2013 |
| 2014 | Spring wheat | Paragon | 480 | 18/04/2014 | 31/08/2014 |
| 2015 | Spring wheat | Tybalt | 520 | 21/04/2015 | 16/08/2015 |
| 2015/16 | Winter wheat | Revelation | 190 | 04/10/2015 | 17/08/2016 |
| 2016/17 | Winter barley | KWS Infinity | 225 | 06/10/2016 | 14/07/2017 |
| 2017/18 | Winter oilseed rape | Veritas | 65 | 26/08/2017 | 17/07/2018 |
| 2018/19 | Winter wheat | Santiago | 400 | 22/10/2018 | 14/08/2019 |
| 2019/20 | Winter barley | California | 450 | 23/10/2019 | 29/07/2020 |

### Data collection

#### **Climatic parameters**

Climatic data was collected from the Royal Agricultural University’s meteorological station in Cirencester (51° 42' 33.6'' N 1° 59' 40.7'' W), 3 miles away from the trial site. Climatic variables were measured at daily intervals for maxima (TMax), minima (TMin) and average temperatures (TMean) (°C), and total rainfall (Rain) (mm) across the study years. This higher resolution of the climatic data enabled a more precise assessment of how cultivation systems impacted crop yields under various climatic conditions.

To determine the most critical weather conditions influencing crop yields under different cultivations, an analysis of factors influencing crops was conducted using seasonal meteorological and agronomic data. For winter crops, this analysis included monthly (maxima, minima and mean) temperatures and monthly total rainfall covering from October until the end of the growing season (August), including the period when cultivation systems were conducted. For spring crops, monthly temperatures and rainfall patterns were considered from the first cultivations in March through harvest in August.

Volumetric soil water content (VWC) at 20-22 cm depth was measured in the June 2018- harvest 2020 cropping season using soil sensors from Soil Scout Monitoring service in one of the six replicate blocks. The value were recorded at midnight on the 15th of the month to represent the monthly soil moisture content.

#### **Plant sampling**

Crop yields were determined by hand-harvesting using a 0.25 m2 quadrat replicated 4 times for each plot, recovering all above-ground plant material for analysis. Plant materials were dried at 105°C overnight and dry matter (DM) was recorded. For cereals, ears were threshed by hand and the amount of grain weighed to obtain grain yield, and subsequently corrected to 15% grain moisture content. Oilseed rape yield was obtained using a plot combine in the field taking the average yield of a 6m strip replicated 4 times.

#### **Data analysis**

* *Trend test*

The non-parametric Mann-Kendall trend test (Kendall, 1948; Mann, 1945) was used to identify trends in time (2010-2020) for the annual TMean, TMin and TMax (°C) and total rain (mm) in the study site. The test was carried out using the “MKTREND” macro (EPA, 2006) in MiniTab.

* *Univariance statistical analysis*

An initial assessment of variance components was conducted to determine the primary factors affecting yields. Variance decomposition was estimated for year, cultivation and the interaction with crop yields. The responses of each crop were assessed separately. A mixed linear procedure was used in SPSS (IBM Corp, 2019) with cultivation systems as subject, cultivation and year as fixed effects and blocks as random effects. Year was included as a ﬁxed repeated measure to account for the cumulative eﬀects of treatments over time. The restricted maximum likelihood (REML) method was used to compute estimates and the Kenward-Roger method was used to calculate the degrees of freedom. Homogeneity of variance was veriﬁed through the analysis of residuals. The results of these statistical tests were declared signiﬁcant at P<0.05. When results showed a significant response, Fisher’s test was used for multiple comparisons of treatment means, at 5% probability. Part of the crop yields in 2010-2014 were previously published by Rial-Lovera et al. (2016a) and Vijaya Bhaskar et al. (2013b). These data were included in our statistical analyses since they represent the starting points of the experiment.

* *Multivariate statistical analysis*

Generally, early season conditions around planting and crop establishment, and late-season conditions around late vegetative and early reproductive growth have been demonstrated as most critical for determining crop yields (Barber et al., 2017). However, this paper analysed a series of meteorological and agronomic factors to determine the most critical weather conditions influencing crop yields under different cultivations. For this, the focus was on both winter and spring wheat as these crops were the most frequent in the experiment. Analyses included monthly TMean, TMin and TMax (°C) and rain (mm) covering the crop growing seasons (as stated in Table 2), as well as cultivation systems. Climatic variables also included TMax and Heat Stress Unit accumulation (HSU) during critical growing points, such as early booting (Critical 1, GS41-45) and early anthesis (Critical 2, GS61-65) were analysed as suggested by Barber et al. (2017). HSU was computed based on a 22°C threshold as , where TMax is the daily maximum temperature and the summation was accumulated daily over the critical period of n days, but only for days when TMax exceeded the threshold. HSU was evaluated only at critical periods 1 & 2 as stated above.

All climatic and agronomic variables were de-trended when they exhibited a significant linear trend (P<0.05) across the experimental period. De-trended data was the deviation of the original data from the predicted value of the linear trend. The Pearson correlation among these variables was determined and the multiple regression of these variables on yield was computed using a stepwise selection process with P<0.01 as the selection criterion for entry and retention in the model. To assess the relative importance of variables selected for each model, standardised regression coefficients were used.

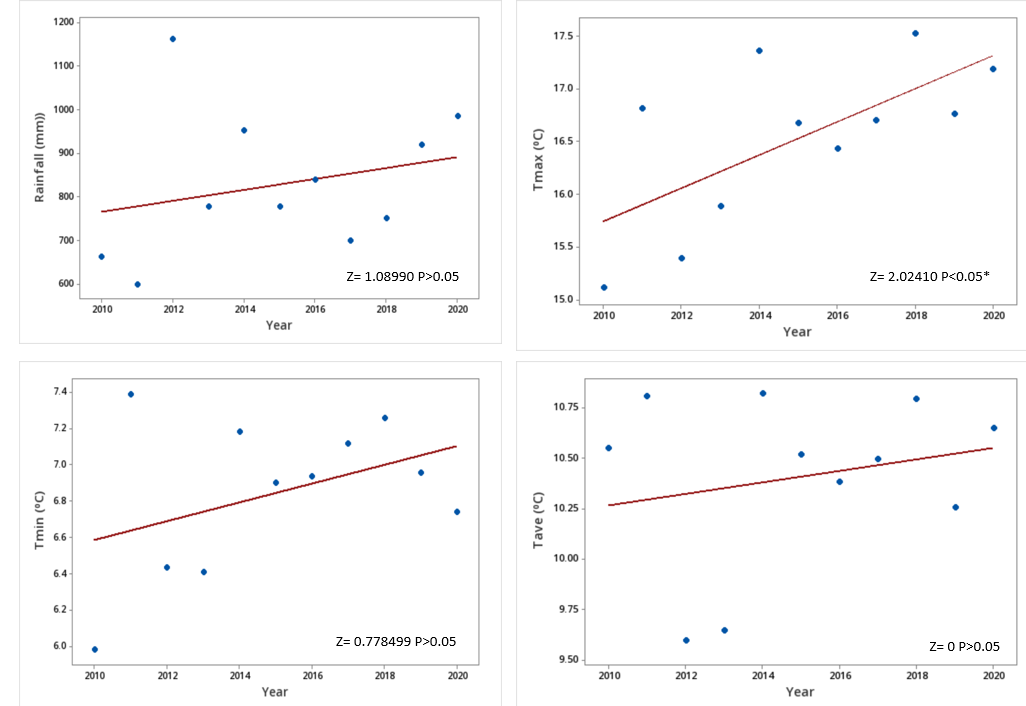
To find a better predictor for the combination of variables, the variables included in the stepwise criteria were also used in a basic regression tree model (Kuhn and Johnson, 2013) using crop yields as the response variable and all the above-mentioned variables as predictors. The regression tree model consists of one or more nested if-then statements for the predictors that partition the data. Within these partitions, a model is used to predict the outcome (Kuhn and Johnson, 2013).

## Results

### Temporal variations in climate variables

During the 10 years of the experiment, the Mann-Kendall trend test showed a significant upward trend for TMax (z= 2.02410, P<0.05) and no significant (P>0.05) trends for rainfall, TMean and TMin (Figure 2). Moreover, noteworthy year-to-year climatic variability was observed revealing singular years, for example, warm and dry years in 2011 and 2018, and a cold and wet season in 2012.

*Figure 2. Temporal evolution of annual climate variables (Rainfall, TMax, TMin and Tave) during the study period 2010-2020 in the study site.*



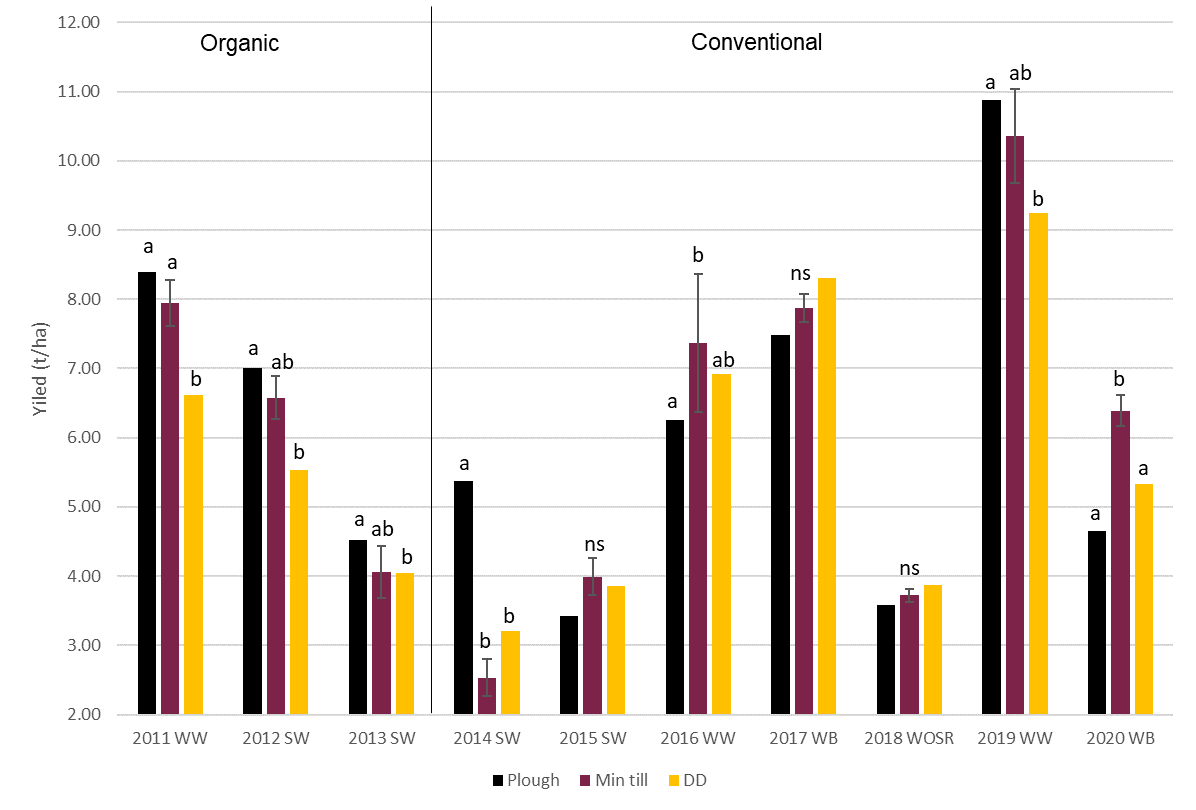
*Asterisks indicate the significance (P<0.05) of temporal trends according to the Mann-Kendall test.*

### Cultivation systems effects on crop yields

Crop yields were significantly affected by year (P<0.001), tillage system (P<0.01) and year x tillage interaction (P<0.001). The first winter wheat crop in 2011 showed significantly higher yields with both MT and P compared to DD (Figure 3). Similar results were observed in 2012 and 2013 with significantly lower spring wheat yields under DD in comparison to plough-based systems. Differences between non-inversion tillage treatments were reduced in the next season with 2014 showing lower spring wheat yields under DD and MT than those under P. The last spring wheat crop showed no significant differences between tillage systems in 2015. However, winter wheat in 2016 produced a lower yield under P in comparison to non-inversion tillage systems. Differences were then reduced, with no significant differences between cultivations in winter barley in 2017 and winter oilseed rape in 2018. In 2019, winter wheat showed the highest yield for this experiment, highlighting again significantly higher yields under plough based systems than under DD (Figure 4). The last cropping season in 2020 showed significant yield differences for winter barley, with MT outperforming DD and P.

Overall, it is suggested that MT performance can be compared to P in most seasons and crops used in this experiment. Yet, when comparing yields under DD with P, DD yields showed an increase after four years following the establishment of the experiment. This resulted in higher or similar yields than those found under plough based systems regardless of the crop type. However, this trend appears to change when winter cereal crops are introduced into the rotation following a brassica break crop.

Figure 3. Mean spring crop (2012-2015) and winter crop (2011, 2016-2020) yields (t ha-1) as influenced by tillage systems and year interaction.



Means with different letters within the same year are significantly different at the P<0.05 confidence level. ns = no significant differences. Bars represent S.E. Vertical line corresponds to the start of conventional management from 2014-2020 following organic management (2011-2013). P, Conventional plough-based tillage; MT, Minimum tillage; DD, Direct drill; WW, Winter wheat; SW, Spring wheat; WB, Winter barley; WOSR, Winter oilseed rape.

### Cultivation systems on soil moisture

Soil moisture content was significantly influenced by the sampling date (P<0.05) as well as the cultivation system (P<0.05) at various points during the sampling period. The results are inconsistent with periods where PT and MT behave similarly and other points where DD and MT have significantly greater or lesser soil moisture percentage than PT. there are also many sampling points where there is no significant difference in the soil moisture content between the different cultivation systems. These soil moisture results seem to be influenced by the date of cultivation but also the seasonal weather effects.

*Figure 4. The impact of cultivation systems on volumetric soil moisture content (%) from June 2018 to August 2020*

### Weather conditions effects on crop yields

Multiple regression of the climatic variables, cultivation systems and wheat yields were carried out with stepwise selection criteria and standardised regression coefficients (Table 3 and 4). Several climatic and management variables were identified that explained a large portion of the inter-annual variability of yield data in this experiment, with many climatic variables showing a strong correlation.

For winter wheat, TMax and HSU during the critical growing period 1 (GS41-45), and TMax in February showed a positive correlation with yields (correlation coefficients ranging from 0.440 to 0.498) (Table 3). TMin in October, January and May, as well as rainfall in January and February, resulted in negative correlations with yields (correlation coefficients ranging from -0.451 to -0.483). While cultivation systems resulted in a weak positive correlation with yields (correlation coefficient 0.273), this factor was included in the regression model following the stepwise criteria. The optimum multiple regression model for winter wheat explained 32.2% (R2=0.322, P<0.001) of the yield variability, with tillage and TMax in February explaining a proportion of these (standardised coefficients of 0.498 and 0.273 respectively) (Table 3).

For spring wheat, temperatures across the season generally showed stronger correlations with yields compared to rainfall factors, with TMean showing the strongest positive correlation coefficient at 0.525 and TMax and TMin in August causing the strongest negative correlation with yields (correlation coefficients ranging from -0.483 to -0.504) (Table 4). The optimum multiple regression model for spring wheat explained 44.3% (R2= 0.443, P<0.001) of the yield variability. This revealed that cultivation systems and the seasonal TMean can largely explain the variability in spring wheat (standardised coefficient of 0.408 and 0.531) (Table 4).

*Table 3. Pearson’s correlation and standardised multiple regression coefficients for winter crop yields and the related climatic variables and cultivation systems in 2010/11, 2015/16 and 2018/19 cropping seasons*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Factor** | **Correlation coefficienta** | **Standardised multiple regression coefficientsb** | **Factor** | **Correlation coefficienta** | | **Standardised multiple regression coefficientsb** | |
| Cultivations | **0.273\*\*** | **0.273\*\*\*** | TMin Jan | **-0.451\*\*** |  | |
| cTMax | **0.180\*** |  | TMin Feb | -0.004 |  | |
| cTMin | 0.130 |  | TMin Mar | **0.373\*\*** |  | |
| cTMean | **0.161\*** |  | TMin Apr | -0.003 |  | |
| TMax Critical 1 | **0.440\*\*** |  | TMin May | **-0.483\*\*** |  | |
| TMax Critical 2 | **-0.218\*\*** |  | TMin Jun | -0.004 |  | |
| HSU Critical 1 | **0.465\*\*** |  | TMin Jul | 0.152 |  | |
| HSU Critical 2 | **-0.263\*\*** |  | TMin Aug | **-0.227\*\*** |  | |
| TMax Oct | **0.229\*\*** |  | Seasonal Rain | -0.077 |  | |
| TMax Nov | -0.022 |  | Rain Critical 1 | **0.175\*** |  | |
| TMax Dec | -0.004 |  | Rain Critical 2 | **0.360\*\*** |  | |
| TMax Jan | **-0.214\*\*** |  | Rain Oct | -0.110 |  | |
| TMax Feb | **0.498\*\*** | **0.4998\*\*\*** | Rain Nov | -0.058 |  | |
| TMax Mar | **0.377\*\*** |  | Rain Dec | 0.080 |  | |
| TMax Apr | 0.006 |  | Rain Jan | **-0.466\*\*** |  | |
| TMax May | 0.078 |  | Rain Feb | **-0.457\*\*** |  | |
| TMax Jun | **-0.166\*** |  | Rain Mar | -0.091 |  | |
| TMax Jul | **0.267\*\*** |  | Rain Apr | 0.030 |  | |
| TMax Aug | -0.034 |  | Rain May | **-0.340\*\*** |  | |
| TMin Oct | **-0.463\*\*** |  | Rain Jun | **0.209\*\*** |  | |
| TMin Nov | -0.039 |  | Rain Jul | **0.225\*\*** |  | |
| TMin Dec | -0.031 |  | Rain Aug | **0.393\*\*** |  | |

Orange and blue grids represent negative and positive correlations, respectively*.* aDependent variable: Yield. bMultiple standardised regression coefficients are shown for factors entered and retained in the model according to a stepwise selection procedure at P<0.01. cMean values cover the variable across the crop growing season. Bold numbers represent significant correlations. \*\*\*P<0.001 level (2-tailed). \*\*P<0.01 level (2-tailed). \*P<0.05 level (2-tailed). Missing values indicate that the factor was excluded from the model. HSU, Heat Stress Unit accumulation; Critical 1, Critical growing point at GS41-45; Critical 2, Critical growing point at GS61-65.

*Table 4. Pearson’s correlation and standardised multiple regression coefficients for spring crop yields and the related climatic variables and cultivation systems over 2012-2015 spring cropping seasons*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Factor** | **Correlation coefficienta** | **Standardised multiple regression coefficientsb** | **Factor** | **Correlation coefficienta** | **Standardised multiple regression coefficientsb** |
| Cultivations | **0.400\*\*** | **0.408\*\*\*** | TMin Apr | **0.431\*\*** |  |
| cTMax | **0.512\*\*** |  | TMin May | **0.355\*\*** |  |
| cTMin | **0.330\*\*** |  | TMin Jun | 0.118 |  |
| cTMean | **0.525\*\*** | **0.531\*\*\*** | TMin Jul | **-0.175\*\*** |  |
| TMax Critical 1 | **0.430\*\*** |  | TMin Aug | **-0.483\*\*** |  |
| TMax Critical 2 | **0.449\*\*** |  | Rain Mar | **-0.235\*\*** |  |
| HSU Critical 1 | **0.346\*\*** |  | Rain Apr | -0.078 |  |
| HSU Critical 2 | **0.400\*\*** |  | Rain May | **0.282\*\*** |  |
| TMax Mar | **0.261\*\*** |  | Rain Jun | **-0.153\*** |  |
| TMax Apr | **0.412\*\*** |  | Rain Jul | 0.004 |  |
| TMax May | **0.336\*\*** |  | Rain Aug | **0.191\*\*** |  |
| TMax Jun | **0.435\*\*** |  | Seasonal Rain | -0.054 |  |
| TMax Jul | -0.002 |  | Rain Critical 1 | -0.091 |  |
| TMax Aug | **-0.504\*\*** |  | Rain Critical 2 | **-0.170\*\*** |  |
| TMin Mar | **0.209\*\*** |  |  |  |  |

Orange and blue grids represent negative and positive correlations, respectively*.* aDependent variable: Yield. bMultiple standardised regression coefficients are shown for factors entered and retained in the model according to a stepwise selection procedure at P<0.01. cMean values cover the variable across the crop growing season. Bold numbers represent significant correlations. \*\*\*P<0.001 level (2-tailed). \*\*P<0.01 level (2-tailed). \*P<0.05 level (2-tailed). Missing values indicate that the factor was excluded from the model. HSU, Heat Stress Unit accumulation; Critical 1, Critical growing point at GS41-45; Critical 2, Critical growing point at GS61-65.

Although N fertilisation and weed cover are known to have a major role in determining and affecting crop yields, they were not included as variables in these analyses. All cultivation systems received the same amount of fertiliser so this factor would not be expected to have strong explanatory power in differentiating yields. Weed cover, however, can be expected to have an influential effect, as suggested by Teasdale and Cavigelli (2017). Unfortunately, this experiment did not look at weed biomass across all seasons, but an indication of such effects could be seen from 2011 until 2014 as reported by Rial-Lovera et al. (2016a) and Vijaya Bhaskar et al. (2013b).

* 1. **Cultivations and weather conditions interactions**

A regression tree analysis based on the factors used for the stepwise criteria model was conducted to investigate how the interaction of weather conditions and cultivation management characteristics were associated with winter and spring wheat yield (Figure 5 & 6). For winter wheat, the primary splitting node (node 1) shows that TMax< 9.9°C in February resulted in substantially lower yields, with a prediction level of 88.9%, while TMax> 9.9°C in February will increase yields (Figure 5).

Figure 5. Winter wheat decision tree

For spring wheat, the primary splitting node suggests that TMean< 12.3°C could result in lower yields (Node 1, Figure 6). Under such circumstances, DD results in lower yields (Node 3) than MT (Node 5) and then P (Node 6). Therefore, it is expected that under a scenario of TMean<12.3°C, P systems will outperform RT for spring wheat yield.

Figure 6. Spring wheat decision tree

## Discussion

### Cultivation systems effects on crop yields

Cultivation systems affected crop yields in different ways across the seasons. DD tended to reduce winter and spring wheat yields in the first four years after implementation but resulted in similar or significantly higher crop yields than with P afterwards until the last season recorded. Berner et al. (2008) and Godwin et al. (2022) also found lower wheat yields in the first years of RT. However*,* Xu et al. (2019)reported higher wheat yields under DD during the first years, while Shakoor et al. (2021) found no differences between tillage systems in a global meta-analysis.

The organic management followed during the first three seasons of this study influenced the performance of RT practices. As found by Hofmeijer et al. (2019) and Vijaya Bhaskar et al. (2013a), higher weed pressure and slower N mineralisation under organic RT could have reduced yields in comparison to P. Berner et al. (2008) also found that N mineralisation under RT systems is not asynchronous with the crop needs resulting in lower yields. Nevertheless, when N fertilisation is not a limiting factor, RT can perform similarly to P, as reported by Maltas et al. (2013). Rial-Lovera et al. (2016a) and Vijaya Bhaskar et al. (2013) reported the first four years of this experiment. Both papers explained that although from 2014 onwards weeds were controlled by pre-cultivation herbicides and mineral N fertilisation, the potential build-up of weed cover in 2014 following organic management could have explained lower yields under MT and DD than those under P (Rial-Lovera et al. 2016a; Vijaya Bhaskar et al. 2013b). Jalli et al. (2021) have also reported a greater occurrence of weeds in RT systems compared to P. Continuous chemical control of weeds in the following seasons could have reduced the negative impacts under MT and DD systems promoting greater crop yields than P as reported by others (de Cárcer et al., 2019).

It is also hypothesised that the increase in yield performance under DD and MT after four years of establishment is a result of the gradual improvement of soil conditions over time in this study clay soil. This corroborates other studies (Rebetzke et al., 2014; Samson et al., 2019; Vanderlinden et al., 2021) highlighting the benefits of non-inversion tillage on soil properties, especially those with minimal soil disturbance, gradually improving yields and thereby helping the system become climate-resilient (Lal, 2020) as demonstrated in the volumetric water content. However, differences in cultivation systems were shifted in the last season of this study. Mild weather conditions across the UK in 2019 resulted in the highest wheat yields in the last 25 years (DEFRA, 2019). Those conditions in combination with the effects of a preceding brassica as a break crop (Sieling and Christen, 2015) could have explained why the highest yield found in this study was in 2019, regardless of the cultivation system used. The long-term lack of soil disturbance under DD could have also resulted in higher soil compaction potentially reducing yields after eight years, while conditions under MT and P promoted higher yields in 2019, as found by Bogunovic et al. (2018) and Skaalsveen et al. (2019).

In 2020, MT favoured barley yields under wet and cold conditions which could be related to a better soil structure allowing better soil water infiltration in winter months and and higher soil moisture content during the summer months in comparison to the P system, as found by Piazza et al. (2020). The highest yield of the preceding wheat crop in 2019, could have also led to more unincorporated straw with lower decomposition rates in DD resulting in lower barley yields than MT in 2020. However, improved soil conditions and higher soil moisture content later the in the season under DD could have resulted in similar yields to P. The results agree with other studies reporting similar long-term yields between plough-based systems and non-inversion tillage (Büchi et al., 2018; de Cárcer et al., 2019; Pittelkow et al., 2015).

Considering climate variability, crop yield stability has become increasingly important, as unexpected climatic conditions will occur more often (Rial-Lovera et al., 2017). However, it is difficult to strongly suggest a cultivation system that can promote yield stability as the ability of each cultivation system depends on the crop considered (Xu et al., 2019). In this study, it can be suggested that ploughing could promote yield stability in the face of climate uncertainty for both cereals and oilseed rape. This contrasts with Xu et al. (2019) reporting the greatest yield variation in plough-based systems. Nevertheless, given the importance of water use efficiency and the upward trend observed for TMax in this study area, DD could offer more efficient use of the available precipitation for production, as also reported by others (Baiamonte et al., 2019; Franchini et al., 2012; Rial-Lovera et al., 2016a).

### 4.2. Interaction effects of cultivation systems and weather conditions on crop yields

Inter-annual crop yield variability is affected by many factors, including agronomic practices, the influence of pests and diseases and weather conditions from year to year. Although according to Ray et al. (2015) a third of global crop yield variability could be explained by climatic variation, climatic impacts on crop yield need to be evaluated together with other factors such as agricultural management practices and crop physiology.

Results have shown that the weather variables and cultivation systems considered in this study explain between 44.3% and 32.2% of the variance of wheat yields. This study further shows that temperatures across the seasons have a stronger association with crop yield variability than rainfall-related variables, including those such as total rainfall. This is in agreement with results shown by Vogel et al. (2019) and Li et al. (2019) who reported that temperature stress impacts grain yields and yield stability in wheat. Barber et al. (2017) highlighted that the fertility of wheat is highly susceptible to heat stress during early booting and early anthesis with the severity of the impact determined by genotypes. In this study, however, heat stress (above 20°C) and TMax at critical periods such as early booting and anthesis, seem to have a positive relationship with yields, especially on winter sown. However, those parameters have less explanatory power on both winter and spring wheat yields as they were excluded by our multiple regression model.

Overall, our results suggest that spring crops are more sensitive to variations in climatic conditions in comparison to winter crops, as also reported by Vogel et al. (2019). Likewise, Fronzek et al. (2018) reported that spring wheat has a greater sensitivity to temperature changes than to precipitation. Mean temperature across the seasons seems to have created a greater impact on spring crops with increases in average temperatures resulting in higher yields, perhaps due to an acceleration of the crop development as temperatures increased. This supports the findings of Ye et al. (2021) reporting that climate warming can increase spring wheat yields in cool areas. Our results also suggest that under a climatic scenario of colder seasons, with mean temperatures lower than 12.3°C, plough-based systems can outperform reduced cultivation systems for spring wheat production. The presence of crop residues on the soil surface and potential compaction on the topsoil layer can result in colder soils under RT which in turn can lower yields (Rial-Lovera et al., 2016a). Shen et al. (2018) also suggest that the insulation effect created by soil residues can reduce the advantage of DD systems in colder environments.

For winter wheat, our results suggest that higher maximum temperatures in February, which occur in winter wheat crops at the foundation stage, seem to explain in large the variation in yield causing a positive effect as TMax increases (with a predictor of TMax ≥ 9.9°C). Increases in temperatures during tillering stage could have accelerated crop development promoting a higher tiller & shoot numbers, therefore promoting higher yields. Higher temperatures at pre-anthesis have also been shown to significantly shorten the length of winter wheat growth resulting in higher yields (Tian et al., 2014). However, such results on wheat have been inconsistent as phenologies of different cultivars also play an important role (Rezaei et al., 2018). For example, Lorenzo et al. (2015) reported that increases in temperature at tillering can reduce the relative tiller production rate in winter wheat under controlled conditions, resulting in lower yields. It is also worth commenting that rainfall in January and February showed a negative correlation with yields, although these factors seem to have less explanatory power as were therefore excluded from the multiple regression model. Similarly, cultivation effects although shown to have significantly affected winter wheat yields, seem to have less exploratory power than temperatures. This supports the findings of (Urruty, et al., 2017) who found that under average weather conditions, winter wheat yield increases with the intensity of the management practice.

Both winter and spring wheat yields were influenced by a complex combination of climatic conditions across the growing season and the cultivation systems used. The range of different components demonstrates the complexity of changing climatic conditions and the challenges of responding to these changes. However, evaluating agronomic practices that can reduce wheat sensitivity to changes in climate and improve yield robustness to unfavourable weather conditions, can be of interest for future research.

## Conclusions

Our long-term experiment shows that although plough-based tillage can promote yield stability across various crops, reduced cultivations have the potential to produce similar or higher yields as plough-based systems over a long-term period. This study also provides an insight into the weather parameters influencing crop yields under different cultivation systems. When considering wheat crops, both spring and winter sown, showed higher variability to temperature variables than rainfall. Our study also demonstrated that spring wheat is more sensitive to variations in climatic conditions in comparison to winter crops and that some weather parameters can enhance the performance of cultivation systems. For instance, RT systems can result in lower spring wheat yields in cold seasons, but this was not seen in winter wheat. It can also be concluded that climatic variables measured during different growth development stages were better predictors of yield variability than those averaged over the entire growing season. Although our study highlights the importance of crop management for optimising production in response to weather variability, larger datasets are needed to fully understand the variability of weather patterns and their effects on yields.

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Fully ethical approval was given from the RAU Ethics Committee

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