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The impact of crop establishment system on winter wheat performance as assessed by replicated trials and multiple on-farm case studies in Ireland's Atlantic-influenced climate

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Abstract

Crop establishment system choice is crucial for growers, with various options differing in tillage type, depth and intensity. In Ireland, plough-based establishment dominates, but interest in and adoption of non-inversion systems is growing. These systems have proven successful in drier climates, where they evolved, but their performance under wetter Atlantic-influenced conditions is less studied. Limited research indicates challenges such as increased grass weed pressure, inconsistent yields, poorer crop establishment and reduced suitability for spring cropping. Additionally, the suitability of conventional replicated trials for extrapolating performance to farm level is frequently questioned for systems-type research. This research combines two complementary studies: a replicated field trial and detailed on-farm studies. The performance of wheat grown following a break crop in plough, min-till and direct drill systems was evaluated using both methods over three seasons. In the replicated trial, where management and input use were consistent across treatments, variation was recorded in plant densities and growth with only minor effects on yield. In contrast, the on-farm study, where management and input use varied between systems, showed no variation in plant densities and growth but did reveal significant yield differences. These were associated with input use and establishment system. The on-farm study provided valuable insight into the range of performance of these systems in commercial settings. However, it was less effective at isolating which specific components were responsible for the observed performance differences between systems.

Introduction

The choice of crop establishment system can directly impact on plant density, which is an early determinant of crop yield potential (Wade *et al.*, 2006). Establishment systems can also influence later plant growth, soil structure, soil fauna, greenhouse gas emissions, soil C storage, weed population density and distribution, soil moisture status and machinery work rates and costs (Abdalla *et al.*, 2010; Bekele, 2020; Cook *et al.*, 2006; Coulibaly *et al.*, 2022; Forristal and Murphy, 2009; Nunes *et al.*, 2020; Šarauskis *et al.*, 2012; Smith *et al.*, 2005). Crop establishment systems are frequently presented as a limited number of discrete systems such as plough, min-till and direct drill; however, there is a continuum of systems incorporating soil cultivation and sowing operations that vary in tillage type, depth and intensity (Davies and Finney, 2002). Establishment systems can be broadly divided into inversion and non-inversion systems. Inversion utilizes a mouldboard plough that inverts the soil, typically to a depth of 200–250 mm, followed by secondary tillage either prior to or in combination with sowing (Tebrügge and Düring, 1999). Non-inversion systems may mechanically cultivate the soil but do not invert it. The depth and intensity of tillage in non-inversion systems vary considerably (Tebrügge and Düring, 1999) with three sub-categories: minimum tillage (min-till), strip till and direct drilling normally identified. Min-till includes soil cultivation, but the type, depth and level of disturbance can vary, with reports in Ireland, for example, indicating depths varying from 75 mm to 200 mm being used (Jameson, McDonnell and Forristal, 2024). Strip-till, a subdivision of min-till, involves cultivation of strips of soil and simultaneous seeding within the cultivated strip, leaving relatively undisturbed soil between the seeded rows (Pöhlitz *et al.*, 2018). Direct drilling (also referred to as No-tillage or Zero-till) systems place seed directly into the soil with very little disturbance (Derpsch *et al.*, 2014).

In Ireland, the most important cereal crops are spring barley (116,400 ha), winter barley (67,500 ha) and winter wheat (56,200 ha) (CSO, 2021). The climate is Atlantic influenced (Jameson *et al.*, 2024; Peel *et al.*, 2007), which, in combination with a cropland history dominated by mixed grassland/spring cropping, gives Ireland a very high yield potential for cereals (Forristal and Grant, 2011) with Ireland having the second highest rainfed average cereal yield globally in 2022 (FAO, 2024). Prior to 2000, plough-based crop establishment was almost universally used, but in recent years, there has been an increase in the interest and use of non-inversion systems to establish crops. Growers have turned to these systems in response to reduced labour availability and increasing crop establishment costs and a desire to retain more soil carbon, improve their sustainability and increase work rates (Forristal and Murphy, 2009).

Crop establishment systems research in drier climates frequently suggests that there are benefits associated with non-inversion systems relating to improved soil moisture retention, comparable or improved yields, lower establishment costs and improved soil carbon retention (Alvarez and Steinbach, 2009; Derpsch *et al.*, 2010; Kassam *et al.*, 2009; Soane *et al.*, 2012; Triplett Jr. and Dick, 2008; Zarea, 2011). However, limited Irish research has indicated some concerns around the suitability of these systems in wetter climates, such as increases in critical grass weeds and herbicide-resistance development risk (Alwarnaidu Vijayarajan *et al.*, 2022; Alwarnaidu Vijayarajan *et al.*, 2021), inconsistent crop yields (Brennan *et al.*, 2014), poorer crop establishment (Brennan *et al.*, 2014; Byrne *et al.*, 2022) and reduced suitability for spring cropping (Brennan *et al.*, 2015). For winter cereals, as autumn progresses, there is generally a risk of poorer establishment as a result of wet weather, especially for non-inversion systems, and many growers using these systems sow earlier when weather conditions are more favourable to reduce this risk (Jameson *et al.*, 2024). However, in a climate already conducive to considerable grass weed pressure, earlier sowing usually exacerbates grass weed issues (Moss, 2017), effectively negating integrated weed management approaches, questioning the suitability of these systems for this climate. Currently, results from studies conducted in different climates and grower anecdotes are contributing to growers' decision to adopt non-inversion systems (Jameson *et al.*, 2024). There are clear gaps in knowledge that need to be addressed before the role of non-inversion systems in an Atlantic climate can be determined.

Crop establishment systems, in addition to incorporating variations in tillage practice, can include differences in residue management, rotation, cover-cropping and traffic management. The multifaceted nature of these systems lends them to being considered as complex from an innovation adoption viewpoint (Alskaf *et al.*, 2019). Researching agricultural systems using replicated field experiments is challenging, as plot size can be limiting and some factors involved in these systems can be difficult to replicate at a small plot scale (Wainwright *et al.*, 2000). Furthermore, the contribution to any performance differences of the component elements of a system may be difficult to determine. Growers and advisors at dissemination meetings and as part of stakeholder groups indicate a strong preference for evaluations that apply the crop establishment elements similar to what occurs in commercial fields with larger implements, sequential cultivation passes at different angles to the first pass, forward speeds in excess of 10 km/h and wide turning areas. This results in very large experimental areas being required for replicated experiments with multiple treatments. Additionally, to determine the impacts of the individual components of a system, which may include management differences such as sowing date, weed control, etc., experimental designs become larger, more complex and difficult to implement. While farm studies as an alternative to controlled experiments may give growers more confidence, they have analysis challenges usually due to the lack of replication at individual locations, single treatment level per site and variations in management, soils and meteorological conditions between sites. On-farm research study types vary, with un-replicated split farm studies (Cooper *et al.*, 2020), tramline trials (Kindred *et al.*, 2018), un-replicated large observational studies (Alesso *et al.*, 2019), un-replicated multiple on-farm detailed case studies (Alwarnaidu Vijayarajan *et al.*, 2022) and simple case studies (Bechini and Castoldi, 2009) used. There are challenges with some on-farm research methods; for example, split farm studies and tramline trials require growers to implement management changes/treatments to areas within farms or fields, which can be a participant deterrent. Larger observational studies, multiple on-farm detailed case studies and simple case studies overcome this issue. However, the numbers of experimental units needed in larger observational studies can be difficult to achieve as the resources needed to collect data on a large number of farms can be prohibitive. Simple case studies are practical and feasible to implement but usually only include a single or a small number of farms, making statistically valid comparisons difficult. Multiple detailed studies of a relatively low number of farms operating the systems of interest would be feasible and could facilitate detailed measurement and subsequent analysis, but variations in grower management and site characteristics remain a challenge. However, such study types have not been evaluated. There is very little knowledge concerning the role of on-farm research methods, particularly in comparison with conventional replicated small plot trials.

The objectives of the research described in this paper were:

- To assess alternative crop establishment systems in an Atlantic-influenced climate by monitoring the performance of winter wheat crops grown following a break crop.
- To assess the utility of an on-farm research model incorporating multiple detailed case studies of a number of farms operating different crop establishment systems compared with a replicated small plot experiment assessing the same systems.

This research should help growers to make more informed decisions about crop establishment system adoption and operation, while assessing alternative evaluation methodology for systems.

Materials and methods

The research reported here was conducted on crops of first wheat, that is, crops grown following a break crop, grown with three different crop establishment systems using two different research methods: a replicated trial and multiple on-farm case studies, over three growing seasons.

Replicated trial

Site description

The replicated experiment was conducted during the 2021 (year 1), 2022 (year 2) and 2023 (year 3) growing seasons on winter wheat (*T. aestivum L. em Thell.*) crops grown after winter winter oilseed rape (*Brassica napus L. var. napus*) at the Teagasc Crops Research Centre Knockbeg site (52°86_87 N, −6°94_14 W, 55m a.s.l), County Carlow, Ireland. The soil type is a Haplic Luvisol (humic epidystric) and is a medium textured clay loam of the Mortarstown series (Brennan *et al.*, 2014; Conry, 1987) (Table 1). Mean long-term (1980–2010) annual rainfall and temperature are 840.2 mm and 9.8 °C, respectively (Coonan *et al.*, 2024a; Coonan *et al.*, 2024b). The experiment was located on an existing trial site with a

Table 1. Soil characteristics of the replicated trial experimental site (Knockbeg site)[a]

Soil texture analysis[b]	Depth (cm) 0–30	30–70	70–150	150+
Coarse sand % (2–0.5 mm)	10	7	9	29
Fine sand % (0.5–0.053 mm)	34	30	38	46
Silt % (53–2 μm)	34	43	17	15
Clay % (<2 μm)	22	20	39	9
Soil chemical analysis				
pH	6.5			
OM %	4.7			
Phosphorus (mg L^{-1})	4.25			
Potassium (mg L^{-1})	106			
Magnesium (mg L^{-1})	148			

Notes: [a]Soil texture class – Clay Loam (UK/ADAS Classification). World reference base classification: Haplic Luvisol (humic epidystric); OM, organic matter.
[b]Adapted from Brennan *et al.* (2014).

long history of establishment system studies. The site was annually cropped since 1992, and a replicated trial with establishment system treatments was established in 2001 to compare plough and min-till establishment. In 2014, the treatments were altered to include plough, min-till and strip till (with strip till and min-till on previously min-till plots) with sub-plots of rotational crops. Direct drilling was substituted for strip till at the start of the reported experiment (2021).

Treatments and experimental design

The study was part of a larger field trial that assessed the impact of crop establishment system and rotation in combination on the performance of a range of crops (full trial layout shown in Supplementary Figure 1). The crop establishment systems plough, shallow plough, min-till and direct drill were the main plot treatments on 30 m × 30 m plots. These plots were replicated four times in a randomized block design. All five individual crops of a 5-year rotation – winter oilseed rape (WOSR), winter wheat (WW1), winter oats (WO), winter wheat (WW2) and winter barley (WB), along with a fixed continuous wheat treatment (WW3) – were grown as sub-plots (30 m × 5 m) within each main plot. This study used the winter wheat grown after winter oilseed rape (WW1) in each of the plough, min-till and direct drill crop establishment treatments.

The plough plots were ploughed in mid-September in year 1 and in early October in years 2 and 3, to a depth of 225 mm. Secondary cultivation and sowing were carried with a combined cultivator and drill unit, using a 2.5 m rotary power harrow with vertical tines, working to a depth of 75 mm and a cereal box-type drill fitted to the harrow with seed coulters spaced at 125 mm (Amazone D9; Amazonen-Werke H. Dreyer SE & Co. KG, Germany). The plots were sown on the 14th, 11th and 10th of October, respectively, for years 1, 2 and 3. The min-till plots were cultivated with a tine-type stubble cultivator (Horsch Terrano FX; Horsch Maschinen GmbH, Germany) to a depth of 75–100 mm in the second half of August or the first days of September and consolidated with a ring roller as part of a stale seedbed process. New weed growth was sprayed with glyphosate three to five weeks later. Sowing was on the same date as the plough plots using a cultivator drill with disc coulters (Vaderstad Rapid; Vaderstad AB, Sweden). The direct drill plots were sown with a double disc direct drill using commercial coulter units (Weaving GD; E F Weaving Ltd., UK) on the same day as the plough and min-till plots. For all treatments, sowing depth was 30–40 mm, and straw from the previous crop was removed.

Crop management

The crops were managed according to normal commercial practice, based on Teagasc guidelines (Collins and Phelan, 2020), with all crop establishment treatments receiving the same management inputs. Wheat (cv. Graham) grown following a crop of WOSR was sown at 367, 360 and 360 seeds m^2 on the respective sowing years. Fertilizer nitrogen (N) was applied at a total of 210 kg N/ha in three applications: at Zadoks decimal growth stage (GS) 25 (0.4 of the total N), GS 31 (0.4 of the total N) and GS 37–39 (0.2 of the total N). Phosphorus and potassium were applied in accordance with soil test results. Disease control consisted of a three-spray programme, with fungicides applied when leaf 3 was fully emerged (BBCH 32–33), when the flag leaf was fully emerged (BBCH 39) and at the start of flowering (BBCH 61) (Lancashire *et al.*, 1991). For all systems, weed control consisted of application of residual herbicides (e.g. flufenacet and diflufenican) early post-emergence (late October/early November) for broad-leaved and grass weed control. This was supplemented by spring application of mesosulfuron-methyl and propoxycarbazone-sodium targeting *Bromus* species and pinoxaden targeting *Avena fatua*. An insecticide (lambda-cyhalothrin) was applied to all treatments in October/November for aphid control to prevent barley yellow dwarf virus (BYDV) infection.

Data collection

Following crop emergence, plant population density was determined each year by counting plants present along a predetermined length of crop row in six locations within each plot. The area sampled differed by treatment based on drill row spacing; row spacing was 125 mm for plough and min-till treatments and 166 mm for the direct drill treatment. For plough and min-till treatments, four 1 m lengths of a crop row were counted, resulting in area sampled being 0.125 m^2. For the direct drill system, three 0.75 m lengths of a crop row were counted, resulting in area sampled being 0.1245m^2. As an indicator of crop growth and biomass development, the fraction of photosynthetically active radiation intercepted (FIPAR) by the crop was determined at growth stages 21–25, 30, 32 and 37. FIPAR was determined by measuring photosynthetically active radiation, both above and below the crop canopy, using a Sunscan Canopy Analysis System (Delta-T Devices, Cambridge, UK) (Gower *et al.*, 1999).

$$FIPAR = 1 - \left(\frac{PARBelowCanopy}{PARAboveCanopy}\right)$$

At crop maturity, samples of a given area (outlined above for establishment counts) were hand harvested (clipped at ground level and secured in hessian bag) from which ears per m^2, grains per ear and harvest index were subsequently determined. Plots were harvested using a Deutz–Fahr plot combine (SDF Group, Treviglio, Italy) fitted with a Harvestmaster weighing system (Juniper Systems & Harvestmaster Inc., USA) with harvest dates of the 16th, 8th and 4th of August for the 3 years, respectively. Plot yields were recorded and adjusted to 15% moisture content with samples taken for grain quality analysis.

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Statistical analysis

Data analysis was carried out using R, version 4.1.0 (R Core Team, 2024). Linear mixed effects models were fitted using plant population density, FIPAR and grain yield data for the 3 years with the 'lmer' function from the 'lme4' package (Bates *et al.*, 2015). The models included system and year and interaction of system and year as fixed effects. Random effects were included to account for variation associated with the interaction between year and block, and a nested random effect was included to account for variation among treatment plots within each block (block and column location taken into account). The significance of fixed effects and interactions (*P* values) was calculated using type III sums of squares with the 'Anova' function from the 'car' package (Fox and Weisberg, 2018). Where significant effects were detected, estimated marginal means were obtained using the emmeans package (Lenth, 2025), and pairwise comparisons were performed using the least significant difference (LSD) method. The same analysis method was also carried out on the same data at an individual year level with system included as a fixed effect and block and column location included as random effects.

To ensure the validity of the linear mixed effects models used in this study, key statistical assumptions were assessed. An analysis of residuals was performed to evaluate normality, homogeneity of variances and independence. Normality of residuals was evaluated visually using quantile-quantile (Q-Q) plots. Model residuals were visually inspected through residuals versus fitted values plots to confirm homogeneity of variances. The assumption of independence of residuals was checked by examining residual plots for patterns that might indicate temporal or spatial autocorrelation.

On-farm field scale case studies

Field selection and experimental design

To determine the impact of crop establishment system on 'first' wheat crops (i.e. those grown subsequent to a break crop) grown on farms, growers using plough, min-till and direct drill systems with a suitable cropping sequence, were recruited from the networks of Teagasc (Irish state-funded research and farm advisory organization) advisors and commercial crop advisors/consultants. Study fields were located within a 65 km radius of Teagasc Oak Park research centre, Carlow, Ireland, which is in the main cereal growing area of Ireland (Figure 1). Twenty-one growers participated each year; seven using each crop establishment system (plough-based, min-till and direct drill). This study was conducted during the same growing seasons as the replicated trial: 2020/2021, 2021/2022 and 2022/2023. A different field was monitored each year with each grower due to rotation constraints, giving a total of 63 monitored fields over the three years. If a grower didn't have the target crop available, a new grower was subbed in. Soil texture and rotation sequence information is given in Table 2. All fields were managed under their respective crop establishment system for a minimum of 5 years for plough and min-till and 3 years for direct drill in advance of the reported study. The minimum number of years was reduced for direct drilling compared to other systems as there were very few growers in Ireland with a history of direct drilling that was greater than 3 years at the time of the study. The study fields also had combinable crops (cereals, oilseeds and grain legumes) grown for a minimum of 10 years prior to the experimental period. The mean field size was 11.86 ha (range: 2.06–50.40 ha). Plough-based establishment on farms was very similar to that implemented in the replicated trial. However, cultivation depth for min-till growers ranged from 50–150 mm, and most direct drill growers used a very shallow (~20–30 mm) stubble cultivation/straw harrow operation to encourage germination of weed seeds and volunteers before glyphosate application in advance of planting.

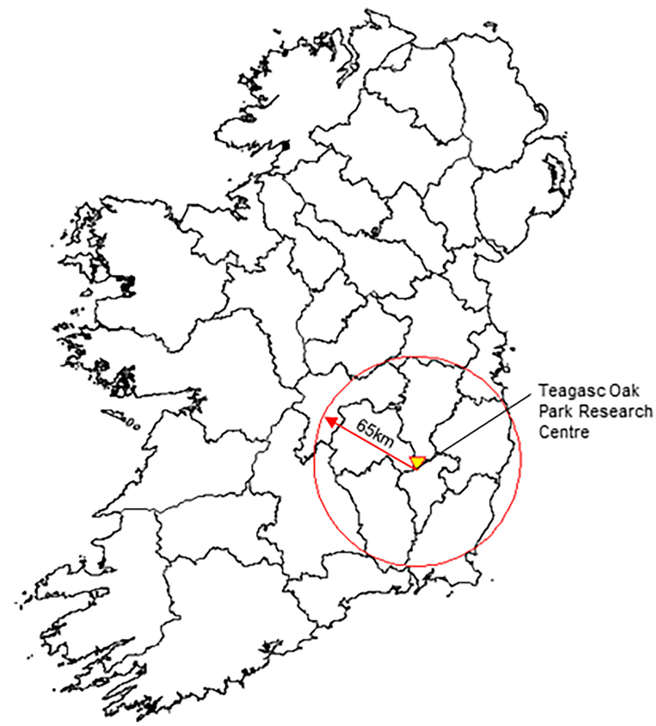

Figure 1. Study site area: all sites were within the marked area.

Data collection, establishment and growth

At the start of each year, 10 positions within each study field were selected using a 'W' pattern, with all points adjacent to crop tramlines and located subsequently by their satellite-determined co-ordinates and a field marker. Crop information was collected at these positions throughout the growing season. Field headlands were avoided due to variability in both management and crop performance associated with these areas. Following crop emergence (autumn), plant population density was determined by counting plants present along a predetermined length of crop row at each of the 10 points in each field; the length of row sampled depended on the row spacing of the drill used to establish that field. The FIPAR by the crop was determined at each of the 10 points at growth stage 21–25, 30, 32 and 37 as outlined previously where data collection methodology of the replicated trial is described.

Yield estimation in growers' fields

As it was not feasible to use a plot combine to assess yields in each of the 21 fields due to the crop ripening in a short time period at crop maturity across all the locations, a detailed manual yield estimation technique was used, which allowed a wider sampling time window. The technique developed by Ward *et al.* (2020) was adapted to account for differences in row widths, meaning a predetermined number of row lengths, adopted for the row width of the drill, were harvested to give a precise sample size in the range: 0.25–0.3 m^2. Whole crop samples were harvested from the sample positions. The samples were dried in a glasshouse, weighed, heads removed and threshed (Saatmeister Kurt Pelz, Maschinenbau, Germany) and the resulting grain cleaned (Laboratory seed

Table 2. Soil texture analysis and preceding crops for on-farm fields

Soil texture analysis[a]	No of fields with soil texture classification/preceding crop			
	Total ($n = 63$)	Plough ($n = 21$)	Min-till ($n = 21$)	Direct drill ($n = 21$)
Clay loam	52	18	17	17
Sand silt loam	3	3	0	0
Sandy clay loam	2	0	2	0
Sandy loam	6	0	2	4
Preceding crop				
Oilseed rape	23	6	13	4
Faba beans	16	2	6	8
Peas	13	4	0	9
Oats[b]	10	8	2	0
Maize	1	1	0	0

[a]Soil texture based on UK soil texture classifications (Natural England, 2008).
bOats is considered a break crop in Ireland as it is not susceptible to the same take-all (*Gaeumannomyces graminis*) disease strain as wheat or barley, conferring a disease break to the following wheat or barley crop.

winnower, type 4111.10.00, Seed Processing Holland, Enkhuizen, the Netherlands). All yield components were weighed and dry matters determined. This technique generated a yield figure (t/ha) for each of the in-field sample points. These yield estimates tend to be higher than total field yield estimates as headland areas are avoided and no allowance for uncropped tramlines is made (Ward *et al.*, 2020). Harvest parameters including ears per m^2, grains per ear and harvest index were determined.

Crop management

As this study was carried out in commercial fields, crop management and husbandry practices varied both within and among crop establishment system groups. To account for potential effects on crop performance these variations in crop management and husbandry practices may have had, detailed records of all management actions, including input types and quantities, application rates and timings and all machinery operations were obtained from growers.

Statistical analysis

Comparisons between the different crop establishment system groups must be considered carefully, due to the limited number within each group, variations in management practice and site differences.

To determine if plant establishment was more variable in certain systems, the coefficient of variation of the plant density figures from the ten positions within each study field was used. The coefficient of variations of the different systems were then compared by carrying out an analysis of variance using the 'aov' function from the 'stats' package (R Core Team, 2024). Analysis of variance was also carried out on FIPAR and yield component (harvest index, ears/m^2, grain/ear, thousand-grain weight [TGW], HL weight and protein) data to determine if there were significant differences between the different systems. For these analyses of variance, for the all-years data, system, year and the interaction of systems and year were included as effects. When significant effects were found, a post hoc Tukey multiple comparison of means was used (TukeyHSD function from the 'stats' package, R Core Team, 2024). Analyses of variance were also carried out on the data at an individual year basis with system only included as an effect. Prior to conducting the analysis of variances, the data were examined to ensure compliance with the key assumptions of normality, homogeneity of variances and independence. Normality of residuals was evaluated visually using quantile-quantile (Q-Q) plots. Homogeneity of variances was assessed by visual inspection of residuals versus fitted values plots, and independence of residuals was verified by examining residual plots for patterns that might indicate temporal or spatial autocorrelation.

To determine the factors that may impact on crop yield, a linear mixed effects model was fitted using 3 years data as described previously for the replicated trial. System, year and the interaction of system and year were included as fixed effects. Nitrogen application rates and fungicide expenditures were grouped into bands of 10 units (e.g. kg N/ha for nitrogen, €/ha for fungicides), with growers assigned to categories based on their respective input levels. These groupings were included as random effects along with soil texture (its effect was allowed to vary by year). As previously described, p-values were computed for the final model, and where significance was detected, pairwise comparisons were carried out using the LSD method. The same analysis method was also carried out on the same data at an individual year level with system included as a fixed effect and nitrogen application rate, grower fungicide spend and soil texture included as random effects. Prior to conducting the linear mixed effects model analysis, the data were evaluated to ensure that key assumptions were met as previously described.

A nitrogen application rate per hectare for each grower was established by calculating the nitrogen supplied by chemical and organic fertilizers. These nitrogen application rates were then adjusted based on the amount of nitrogen that was estimated to have been supplied by the preceding crop (e.g. legume or oilseed rape vs oats) type based on the guidelines in the Teagasc Winter Wheat Guide (Lynch *et al.*, 2016). A fungicide spend per hectare for each grower was established by multiplying the fungicide product rates used by growers by the recommended retail prices for these products.

With growers free to manage their crops as they normally would, there were inevitable differences in management between growers. If these differences were associated with establishment system, then they could be confounding the results. Therefore, key yield influencing inputs, in this case nitrogen application rate and

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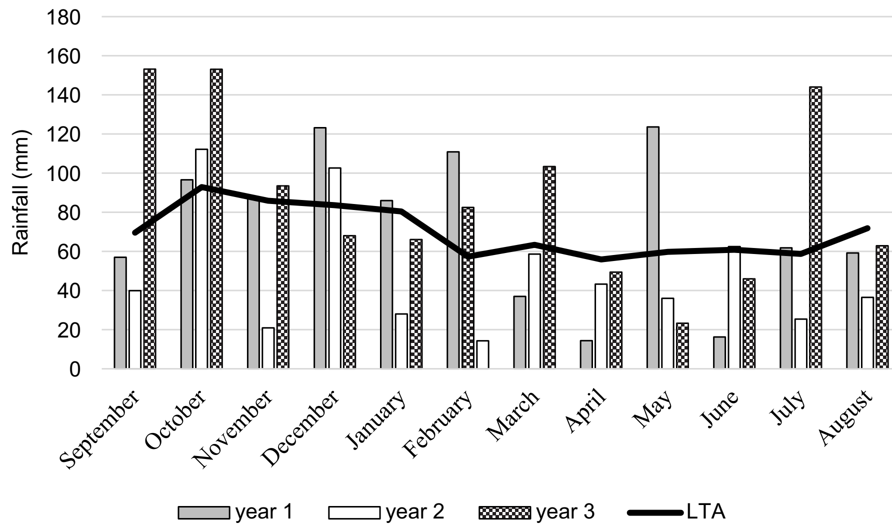

Figure 2. Monthly rainfall amounts for each month in the experimental period in comparison with long-term average (LTA – 1980–2010).

grower fungicide spend, were tested to see if they were confounded with crop establishment system as failing to identify confounders can bias results and attribute effects to system that are actually due to other factors. To robustly assess potential confounding, we employed several complementary methods to test whether input application rates were confounded with system. The Kruskal–Wallis test (kruskal.test function) was used to test for associations between crop establishment system and input levels; kruskal.test function is from the 'stats' package (R Core Team, 2024), and associations of nitrogen application rate and grower fungicide spend with the system would indicate possible confounding. Spearman correlations (cor.test function) were used to test whether nitrogen rate and fungicide spend were correlated with yield; correlations of these factors with yield would indicate possible confounding, and cor.test function used is from the 'stats' package (R Core Team, 2024). A linear fixed effects model was fitted using the lm function (Lenth, 2025) with nitrogen application rate and grower fungicide spend as fixed effects to test whether these effects were significant predictors of yield; effect significance was calculated using type III sums of squares as previously described. These factors being significant predictors of yield would indicated possible confounding. Another approach was to fit 2 linear fixed effects models, one including system, year, the interaction of system and year, nitrogen application rate and grower fungicide spend as fixed effects and another that included system, year, the interaction of system and year as fixed effects, these models were then compared to assess how the estimated effect of system changes when nitrogen application rate and grower fungicide spend were included. A change by more than 10% in the estimated effect of system would indicate possible confounding. This multifaceted approach is consistent with recommendations in the literature to confirm confounding from multiple perspectives (Mickey and Greenland, 1989; Maldonado and Greenland, 1993; Brookhart *et al.*, 2006).

Results

Weather conditions

Cumulative rainfall within growing seasons (September to August) during the study varied considerably; year 1 and 3 were above average, while year 2 was below average. December, February and May of year 1, October and December of year 2 and September, October, March and July of year 3 were marked by heavy rainfall (Figure 2). In year 3, this heavy rainfall occurred in September and October, which is during the establishment period of winter cereals. Mean annual rainfall for the Republic of Ireland was 1202.6 mm (Coonan *et al.*, 2024a).

Monthly mean air temperatures were close to average during the growing season (March to harvest) in year 1 with the exception of July, which was 2.1 °C above average while in year 2, May, July and August were each 1.6°C above average and in year 3, May and June were 2.1 °C and 2.9 °C above average, respectively (Figure 3). Mean annual temperature for the Republic of Ireland was 9.1 °C (Coonan *et al.*, 2024b).

Replicated trial

Plant population density and light interception

The effects of crop establishment system on plant population density are presented in Table 3. In years 1 and in the all-years analysis, the direct drill system had significantly lower plant population densities than the plough-based and min-till systems, indicating poorer crop establishment, as all plots were sown with the same seeding rate. In year 3, direct drill system had significantly lower plant population densities than the min-till system which had significantly lower densities than the plough-based system. The effects of crop establishment system on growth, as measured by light intercepted, are presented in Table 3. When all years were considered, the direct drill system was intercepting significantly less light at growth stages 30 and 32 than the plough-based and min-till systems, indicating less biomass accumulation at these stages. For individual years, the direct drill system was intercepting significantly less light than the other systems at growth stages 21–25 (year 1), 30 (in years 1 and 2), 32 (in years 1 and 3) and 37 (in year 3).

Grain yield and yield components

The effects of crop establishment system on grain yield and yield components are presented in Table 4. In year 2, the direct drill system produced a significantly lower grain yield than the plough-based system but not the min-till system, and in year 1, there was also a trend that direct drill yields were lower but not significantly so. The direct drill system had significantly lower number of ears per m^2 in year 3 and in the all-years analysis as establishment system was shown to significantly impact on ear numbers. Min-till had a significantly higher number of grains per

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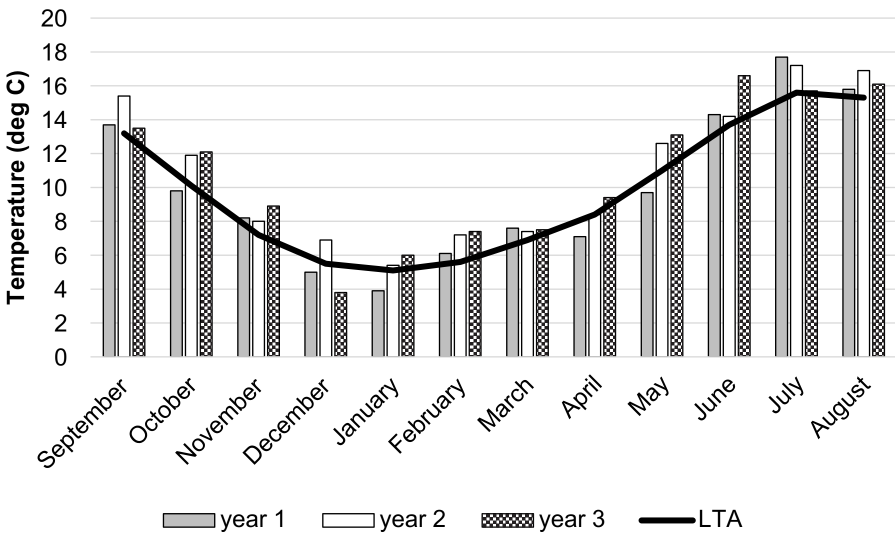

Figure 3. Mean monthly air temperatures for each month of the experimental period in comparison to the long-term averages (LTA – 1980–2010).

Table 3. Plant population density and fraction of photosynthetically active radiation intercepted (FIPAR) over three growing seasons in the replicated trial

	Plant density (plants/m^2)	FIPAR GS 21–25	FIPAR GS 30	FIPAR GS 32	FIPAR GS 37
Year 1					
Plough	329[a]	0.37[ab]	0.56[a]	0.83[ab]	0.86
Min-till	323[a]	0.43[b]	0.60[a]	0.86[b]	0.89
Direct drill	277[b]	0.33[a]	0.43[b]	0.77[a]	0.84
P	< 0.001	< 0.001	< 0.001	< 0.01	0.223
Year 2					
Plough	331	0.43	0.77[a]	0.90	0.85
Min-till	342	0.47	0.80[a]	0.91	0.86
Direct drill	286	0.33	0.66[b]	0.92	0.91
P	0.059	0.681	< 0.001	0.825	0.115
Year 3					
Plough	285[b]	0.39	[1]—	0.90[a]	0.91[a]
Min-till	310[c]	0.39	—	0.90[a]	0.90[a]
Direct drill	217[a]	0.30	—	0.81[b]	0.86[b]
P	< 0.001	0.337	—	< 0.001	< 0.001
All years					
Plough	315[a]	0.40	0.67[a]	0.88[a]	0.87
Min-till	325[a]	0.43	0.70[a]	0.89[a]	0.88
Direct drill	260[b]	0.32	0.54[b]	0.83[b]	0.87
***P* (system)**	< 0.01	0.189	< 0.001	< 0.01	0.123
***P* (year)**	< 0.01	0.759	< 0.001	< 0.05	< 0.05
***P* (system × year)**	0.311	0.779	0.906	< 0.05	< 0.001

[1]Data from growth stage 30 missing due to an instrument data logging malfunction. Pr>F values are from analysis of variance.

ear in year 2 than the plough-based system, and the direct drill system had a significantly higher number of grains per ear in year 3 (Table 4). There was no significant difference in TGW or protein levels between systems in any of the study years. Year also had a significant impact on some parameters, with grain yield, TGW, HL weight and protein levels varying significantly with year.

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Table 4. Grain yield and yield components of three establishment systems over three growing seasons in replicated trial

	Grain yield (t/ha)	HI	Ears/m²	Grain/ear	TGW (g)	HL weight	Protein (%)
Year 1							
Plough	12.71	0.53[ab]	604[a]	38.90[a]	51.32	81.90	8.63
Min-till	12.76	0.51[a]	705[b]	36.92[a]	50.65	82.40	8.87
Direct drill	12.32	0.54[b]	605[a]	43.77[b]	50.69	82.02	9.05
P	0.091	< 0.05	< 0.001	< 0.001	0.495	0.495	0.149
Year 2							
Plough	13.68[a]	0.50	614[b]	35.79[a]	52.55	82.55[a]	9.28
Min-till	12.70[ab]	0.50	648[a]	44.62[b]	50.15	82.16[a]	9.62
Direct drill	12.39[b]	0.49	641[ab]	39.82[a]	51.00	80.69[b]	9.18
P	< 0.001	0.563	< 0.001	< 0.001	0.091	< 0.001	0.245
Year 3							
Plough	11.14	0.52	665[a]	40.28[a]	41.8	78.88[a]	11.48[a]
Min-till	11.80	0.49	690[a]	39.94[a]	43.2	79.32[b]	11.70[a]
Direct drill	10.96	0.49	479[b]	52.63[b]	44	78.90[a]	11.70[a]
P	0.353	0.569	< 0.001	< 0.001	0.240	< 0.001	< 0.05
All years							
Plough	12.51	0.52	655[a]	40.53	47.9	81.25[a]	9.83
Min-till	12.42	0.50	663[a]	38.58	47.7	80.87[a]	10.01
Direct drill	11.89	0.51	566[b]	44.92	48.1	80.99[a]	9.98
***P* (system)**	0.603	0.623	< 0.05	0.057	0.976	< 0.001	0.139
***P* (year)**	< 0.01	0.631	0.078	0.532	< 0.001	< 0.001	< 0.001
***P* (system × year)**	0.126	0.521	< 0.001	< 0.01	0.097	< 0.001	0.076

HI, harvest index; proportion of grain to straw dry matter; TGW, thousand-grain weight at 85% dry matter; HL weight, hectolitre weight at 80% dry matter. Pr>F values are from an analysis of variance.

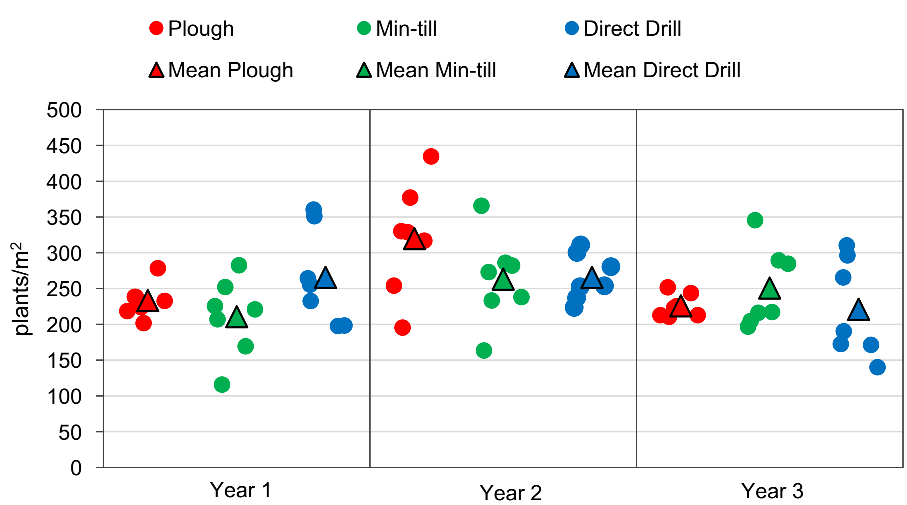

Figure 4. Jitter plot of plant population densities for individual fields ($n = 63$) in the on-farm study for each of the study years.

On-farm field scale case studies

Plant population density and light interception

There was a large range in plant population densities both within and across systems in the on-farm study in all study years with the range of individual farm values within their system shown graphically in Figure 4 and the system means (7 farms in each) shown in Table 5.

The plant population density between the individual farms ranged from 116 to 435 plants per m², with high variation evident within each of the establishment system groupings. There was no difference in plant populations that could be attributable to crop establishment systems as indicated by *P* value > 0.05 for each of the individual years, or all years combined. There was a significant year effect on the plant populations. The coefficients of variation of the

Table 5. Plant population density and fraction of photosynthetically active radiation intercepted (FIPAR) for on-farm study

	Plant density (plants/m²)	Plant density (CV)	Seeding rate (kg/ha)	Planting date (days)[1]	FIPAR GS 21–25	FIPAR GS 30	FIPAR GS 32	FIPAR GS 37
Year 1								
Plough	233	0.160	165.67	16.43	0.38	0.57	0.78	0.93
Min-till	211	0.171	163.83	10.43	0.41	0.60	0.73	0.88
Direct drill	266	0.142	183.90	9.14	0.40	0.54	0.76	0.90
P	0.161	0.794	—	—	0.938	0.722	0.5	0.102
Year 2								
Plough	320	0.157	162.35	19.57	0.39	0.63	0.82	0.81
Min-till	263	0.148	166.26	10.57	0.45	0.69	0.75	0.78
Direct drill	265	0.143	174.43	13.57	0.36	0.62	0.79	0.80
P	0.171	0.738	—	—	0.636	0.457	0.409	0.886
Year 3								
Plough	226	0.150	157.08	15.71	0.33	0.55	0.80	0.85
Min-till	251	0.188	170.29	9.00	0.33	0.60	0.83	0.84
Direct drill	221	0.194	180.43	12.14	0.43	0.51	0.77	0.84
P	0.527	0.181	—	—	0.289	0.338	0.243	0.992
All years								
Plough	260	0.156	161.70	17.24	0.37	0.58	0.60	0.86
Min-till	242	0.169	166.79	10.00	0.40	0.63	0.77	0.83
Direct drill	251	0.160	179.59	11.62	0.39	0.56	0.77	0.85
***P* (system)**	0.57024	0.737	—	—	0.650	0.1390	0.376	0.6240
***P* (year)**	< 0.01	0.252	—	—	0.705	< 0.05	0.226	< 0.05
***P* (system × year)**	0.09360	0.354	—	—	0.422	0.9879	0.413	0.8222

[1]Planting date is given in the form of days after first crop in study planted; with first crop planted being day 1, first crops were planted on 25/09/2020, 23/09/2021 and 26/09/2022 in years 1, 2 and 3, respectively.
CV, coefficient of variation.

ten measured plant density values in each field were used as an assessment of crop establishment variability. There was no significant difference in variability of crop establishment between systems (Table 5). Plough-based growers planted their crops later than min-till growers and direct drill growers on average over the 3 years (Table 5). Also, the seed rate used by direct drill growers was higher than that used by the other groups.

Using light interception as an indicator of canopy development and crop growth, there was an expected trend in increasing interception as the plants progressed through their growth stages (Table 5 and Figure 5) and there were differences between years at certain growth stages, however there was no significant difference in light intercepted by the different establishment systems at any of the growth stages in any of the study years or in the all-years analysis.

Grain yield and yield components

The effects of system on grain yield and yield components are presented in Table 6. The distribution of the individual farm yield data points is presented by establishment system in Figure 6.

The establishment system used significantly impacted on grain yield in years 1 and 3, with direct drill yields lower than the other systems in year 1 only. In year 3, while the impact of system was significant, post hoc testing could not show systems to be significantly different to one another. There was also a trend in the all-years analysis that system impacted on grain yield, with direct drill fields having numerically lower yields; however, this was not significant (Tables 6 and 7).

Confounding analysis on the data from all years confirmed that nitrogen rate and fungicide spend were confounded with establishment system. The Kruskal–Wallis test confirmed that nitrogen rate and fungicide spend varied significantly between systems ($p < 0.001$). Spearman correlation analysis showed significant correlations between these variables and yield ($p < 0.01$), and in a linear model with nitrogen rate and fungicide spend as explanatory variables and yield as the dependent variable, fungicide spend was a significant predictor of yield ($p < 0.01$), while nitrogen rate showed a weaker effect ($p = 0.071$). Furthermore, models with and without these covariates showed a mean change of 18.37% in system effects, exceeding the 10% threshold for confounding, highlighting the impact of input differences on observed yield variation. Confounding analysis on individual years' data followed the same trend as above, confirming confounding of nitrogen rate and fungicide spend with establishment system on an individual year basis but with year 2 showing slightly weaker support for confounding than the other years. The

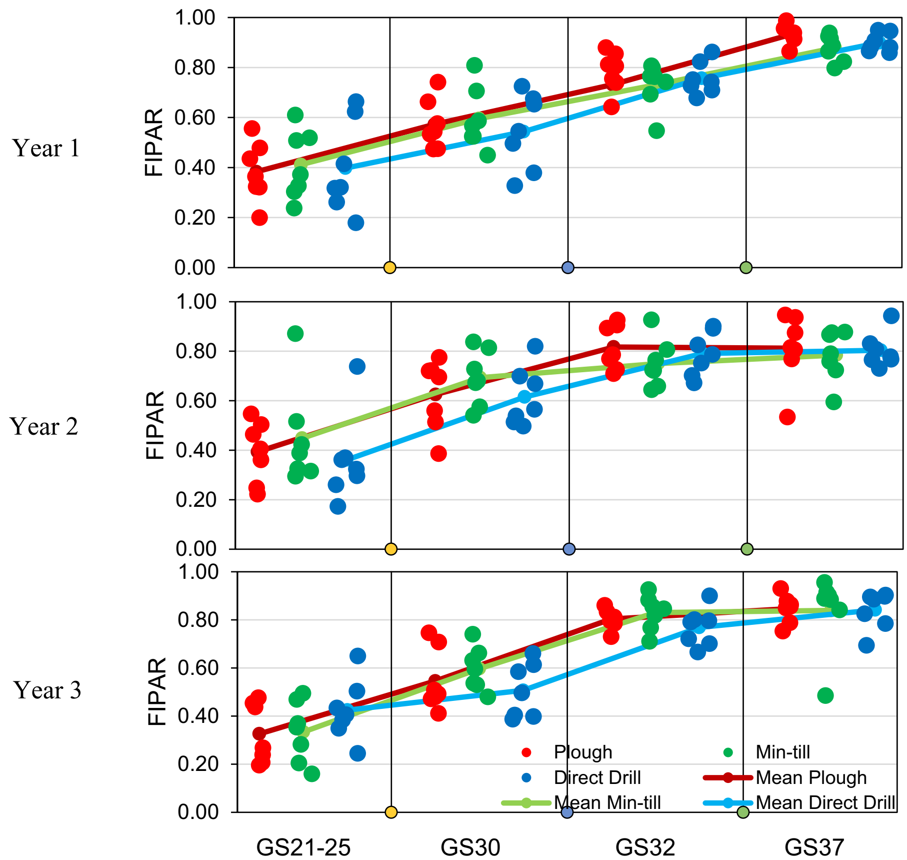

Figure 5. Light intercepted for individual fields in on-farm study for each of the study years.
Notes: FIPAR – fraction of photosynthetically active radiation intercepted.

Table 6. Grain yield and yield components for on-farm study

	Grain yield (t/ha)	HI	**Ears/m²**	Grain/ear	TGW (g)	HL weight (kg/HL)	Protein (%)
Year 1							
Plough	12.73[a]	0.51	637	46.80	43.25[b]	82.90	9.35
Min-till	12.53[ab]	0.52	560	47.33	47.59[a]	81.86	8.52
Direct drill	10.97[b]	0.49	585	45.50	41.72[b]	82.27	8.14
P	< 0.01	0.068	0.103	0.83	< 0.05	0.451	0.061
Year 2							
Plough	12.33	0.48	616	43.66	46.09	85.29	8.90
Min-till	13.04	0.50	560	49.31	47.68	85.26	8.47
Direct drill	11.40	0.49	572	43.18	46.62	83.96	8.02
P	0.224	0.559	0.429	0.050	0.749	0.429	0.262
Year 3							
Plough	11.82[a]	53.24	620[a]	48.99	39.58	77.82	8.86
Min-till	12.49[a]	51.86	683[a]	43.06	42.68	80.53	9.26
Direct drill	9.79[a]	48.77	523[b]	46.78	40.30	79.61	8.82
P	< 0.05	0.126	< 0.01	0.167	0.384	0.274	0.641
All years							
Plough	12.29	50.81[ab]	624[a]	46.48	42.95[b]	82.01	9.01
Min-till	12.69	51.32[a]	601[ab]	46.57	45.98[a]	82.55	8.75
Direct drill	10.72	48.80[b]	560[b]	45.16	42.88[b]	81.93	8.32
P (system)	0.069	< 0.05	< 0.05	0.640	< 0.05	0.648	0.071
P (year)	0.745	< 0.05	0.278	0.767	< 0.001	< 0.001	0.245
P (system × year)	0.816	0.117	< 0.05	0.066	0.575	0.204	0.383

HI, harvest index; TGW, thousand-grain weight at 85% dry matter; HL weight, hectolitre weight at 80% dry matter.

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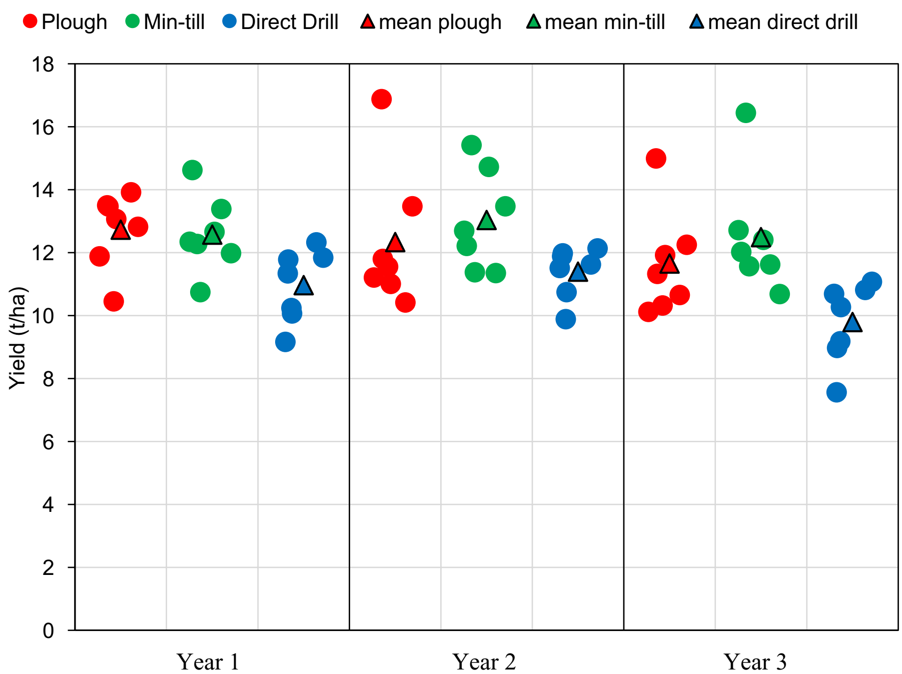

Figure 6. Jitter plot of grower grain yields in the on-farm study.

Table 7. Grower fungicide spend and nitrogen application rates in on-farm study for study years

Effect	Year 1	Year 2	Year 3	All years
Fungicide spend (ha)				
Plough	€192.21[a]	€181.59	€232.07[a]	€201.96[a]
Min-till	€123.35[b]	€175.61	€187.33[ab]	€162.10[b]
Direct drill	€136.74[ab]	€116.28	€113.98[b]	€122.33[c]
P (system)	< 0.05	0.095	< 0.01	< 0.001
Nitrogen application rate (kg/ha)				
Plough	246.26[a]	231.29	241.24[a]	239.60[a]
Min-till	245.05[ab]	229.11	247.54[a]	240.57[a]
Direct drill	208.93[b]	203.23	205.35[b]	205.83[b]
P (system)	< 0.05	0.058	< 0.05	< 0.001

Notes: P values from Kruskal–Wallis – to test for association between system and potential confounder.

fungicide spend and nitrogen rate per group are displayed in Table 7.

The treatments with numerically lower yields had lower ear numbers and little compensation by increases in either grains per ear or TGW. Crops from direct drill fields had significantly lower harvest indices than min-tilled fields (Table 6). System also significantly affected harvest indices, with the direct drill fields having lower harvest indices in the all-years analysis, and direct-drilled fields also had significantly lower ear counts than the other systems in year 3 and significantly lower ear counts than the plough-based but not the min-tilled fields in the all-years analysis. For TGW, system had a significant effect in year 1 and in the all-years analysis with direct-drilled and plough-based fields having significantly lower TGW than min-tilled fields, following the trends observed with treatment yields.

Discussion

Results from both the replicated trial and the on-farm studies are considered together in this section. The limited number in each establishment system group in the on-farm studies, coupled with the large differences in site, soil and particularly crop management practices, requires a degree of caution to be exerted when interpreting differences observed in the farm data. The replicated trials allow fair and useful comparisons to be made and, having been carried out in the same seasons, provide a useful basis for interpretation of the results of the on-farm study.

While there were considerable differences in weather across the three study years, of most interest was the above average rainfall in September in year 2 and in both September and October in year 3. This was associated with lower plant population densities in direct drill in the replicated trial in year 3. Year 3 also had lower yields across all systems. To give an indication of the frequency of the occurrence of such weather events, in an earlier replicated trial on the same site, above average post sowing rainfall in one out of three study seasons led to lower grain yields but also a difference between crop establishment systems (Brennan *et al.*, 2014), where min-till had lower plant population densities and subsequent lower yields. Furthermore, from the period 2005–2023 (19 years) at the replicated trial site, there were 3 years where October and 4 years where November rainfall was over 50% higher than the long-term average rainfall for these respective months. However, weather was not the only factor impacting establishment as the direct drill plant population density, was also significantly lower in year 1 perhaps due to less favourable seedbed conditions reported in uncultivated soils such as reduced soil to seed contact as a result of surface residues in the seed slot (Sprague, 1986), increased soil strength resulting in restricted root growth and vigour of emergence (Ball and O'Sullivan, 1982) and lower soil temperatures and slower soil warming as a result of increased soil moisture (Alvarez and Steinbach, 2009); resulting in slower seedling emergence (Blake *et al.*, 2003).

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In the replicated trial, the plant densities recorded with the plough-based and min-till systems were higher than the direct drill system throughout the experiment, suggesting that these systems produced more suitable conditions for crop establishment in this region. Despite the differences in plant densities in years 1 and 3, there was no statistical difference in grain yields, indicating that adequate plant densities were still achieved to maintain yield potential in winter wheat. The lower grain yield recorded for the direct drill system in year 2 compared to the plough-based but not the min-till systems was not accompanied by a significant difference in establishment or light interception at flag leaf emergence. Considering light interception, in the replicated trial, while the low growth height at GS 21–25 makes measurement of crop canopy differences using light absorption difficult, there were differences in at least one of the later three growth stages measured with direct-drilled crop absorbing less light at all stages where differences were significant. The reduction in light absorbed by the direct-drilled crop at the earlier growth stages may be associated with poorer establishment where less plant numbers result in slower canopy development but this may also be compounded by some of the conditions that cause poorer establishment such as increased soil strength, lower soil temperature and slower soil warming; which have been shown to result in slower early season growth in direct-drilled crops (Alvarez and Steinbach, 2009; Ball and O'Sullivan, 1982; Blake *et al.*, 2003). Slower growth in the direct drill system was confined to early in the season in years 1 and 2; however, in year 3, the direct drill system was still intercepting significantly less light at flag leaf emergence, but while this was associated with numerically lower grain yields, this was only a trend and not statistically significant. In year 1, reduced plant densities in the direct drill system were compensated for by increased tillering as evidenced by similar ear numbers at harvest; this is similar to findings from Brennan *et al.* (2014) and Wade *et al.* (2006). However, in year 3, the direct drill system had significantly lower ear numbers but compensated by producing a significantly higher number of grains per ear. Despite this compensatory production of an increased number of grains per ear, yields were numerically lower than the other systems but not significantly so.

In the on-farm study, there was no statistical difference in plant densities or canopy development between the systems, in contrast to the replicated trial. Those using direct drill systems on farms used higher seed rates and earlier sowing dates to counteract the risk of poorer establishment. While sowing earlier has benefits from an establishment point of view, it may bring some other challenges, as it can increase grass weed (Moss, 2017; Andrew and Storkey, 2017; Cook *et al.*, 2006), disease (Hardwick *et al.*, 2001; Polley and Thomas, 1991; Fitt *et al.*, 2011) and pest (Kennedy and Connery, 2001; Foster *et al.*, 2004; Mc Namara *et al.*, 2020) pressures which may result in more pressure on chemical control measures, increasing the risk of pesticide resistance development and yield impacting infestations. This is likely to be more challenging in wetter Atlantic-influenced climates, where delayed sowing of winter crops is suggested as a good integrated control measure for grassweeds (Alwarnaidu Vijayarajan *et al.*, 2020; Byrne *et al.*, 2018), barley yellow dwarf virus (Walsh *et al.*, 2022) and foliar diseases (Kildea *et al.*, 2021). Plough-based growers sowed later, following current advice and best practice. In contrast, min-till and direct drill growers chose to sow earlier to mitigate the risk of poor establishment due to adverse weather, which becomes more likely with later sowing dates. Anecdotally, growers believe crop establishment is more variable in non-inversion systems; however, there was no significant difference found in variability of establishment between systems using the coefficients of variations of the plant population densities recorded at 10 positions in each field.

In the on-farm study, results varied with year. In year 1, crops in the direct drill fields yielded significantly lower than those in the plough-based fields; in year 2, there was numerical differences in grain yields between the systems, but these differences were not statistically significant, and in year 3, there was a significant system effect on yield detected. However, despite the numerical differences in yields, post hoc testing could not differentiate between systems. Again, in the all-years data analysis, there were large numerical differences in yields with direct drill mean yields appearing to be substantially lower than the other systems; however, this was only a trend and did not reach significance. Since individual growers were free to apply different management strategies, the possibility of confounding was suspected. In observational studies, external variables not accounted for in the experimental design can influence both the independent factors and the observed outcomes; this dual influence may bias the estimated treatment effects, ultimately obscuring the true relationship between the variables (Greenland, 1989). In field trials, variability in management practices can confound treatment effects, with factors such as nitrogen application and fungicide use having previously been shown to independently influence yield (Olesen *et al.*, 2003; Lollato *et al.*, 2022; Koua *et al.*, 2021). Our observations, which show that these variables are significantly associated with yield, agree with previous findings. This study also, through the detection of variables which were confounded the factor of interest; establishment system; demonstrates that this on-farm study methodology is unsuitable for isolating the performance of each establishment system, as key input levels were not controlled. The treatment effects of system on yield and yield components in the on-farm study are likely to be at least partly masked by the influence of the confounding variables, nitrogen rate and fungicide spend. This reinforces the importance of using controlled experiments to accurately assess system performance.

Differences in nitrogen and fungicide use by growers suggest that they may have been anticipating a lower yield from the use of non-inversion, specifically direct drill systems (Table 7). Another theory is that these non-inversion growers may have been using the establishment cost savings associated with these non-inversion systems as part of a larger effort to reduce their overall production costs. Having similar spends on fungicides and use of nitrogen between groups, or similar degrees of variation in spend and use among groups, may have overcome this challenge. However, this was not possible to achieve as this was an observational study. Given that similar yields were achieved by all systems in the replicated trial, where input levels were similar across all systems, the reduced use of inputs by growers may have had a negative impact on direct drill yields on the study farms. Furthermore, the reduced spend on nitrogen and fungicides in the direct drill fields in the on-farm study coupled with lower crop establishment costs may partially or fully compensate for the numerically lower yields observed in these fields, warranting further exploration in an economic analysis.

The characteristics of this study, which combined a replicated field trial with an on-farm study, across three seasons, allowed unique knowledge to be gathered. The replicated trial results showed that in two of the three years, there was no significant difference in first wheat yields between the three establishment systems, but there was a difference in 1 year, indicating the importance of season (and weather) and confirming the need for long-term studies in this area. The replicated trial also contributed significantly to the explanation of the on-farm study results. The differences in yield between systems recorded in the on-farm study cannot be solely attributed to the crop establishment system, as growers, perhaps anticipating yield differences, had altered their management, which was also a significant factor in explaining the yield differences. In both studies, there was a tendency for direct drilling to have some negative impacts on first wheat performance, indicating the need for climate–specific studies on a range of crop species and spring-sown crops, which may not have the same capacity as wheat to compensate for establishment challenges. While the on-farm studies indicated the range of management and crop performance found on farms, the scale and format of this study did not allow the factors that influence yield to be definitively determined, indicating that multi-factor, controlled, replicated trials are necessary to quantify the effects of different factors and their interaction. The utility of on-farm studies, as used in this trial, may best be limited to the determination of the factors that need to be studied in controlled experimentation. In this study, sowing date, seeding rate, disease control strategy and nitrogen fertilizer use were identified as being of interest when comparing establishment systems. Without these detailed studies, growers will not know how best to manage crops established with different systems. Before promoting the adoption of a crop establishment system in Ireland, further research is needed to assess how crop establishment systems affect the crop, economic and environmental performance of all major arable crops. Any recommendation must then consider the benefits and trade-offs of adopting a given system within the context of Irish cropping systems.

Conclusions

This study combined a replicated trial and on-farm study, showing that the effects of establishment systems on wheat yield are strongly influenced by season and management and that replicated controlled trials are essential to accurately estimate these effects. Future research should quantify establishment system impacts across crops, sowing seasons and environments to inform future management approaches in Irish cropping systems.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0021859625100245.

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Author contribution. Conceptualization: J.J., P.D.F and K.M.; data curation: J.J. and P.D.F; formal analysis: J.J., P.D.F and K.M.; funding acquisition: P.D.F and K.M.; investigation: J.J., P.D.F and K.M.; methodology: J.J., P.D.F and K.M.; project administration: J.J., P.D.F and K.M.; supervision: P.D.F and K.M.; visualization: J.J., P.D.F and K.M.; writing – original draft: J.J.; writing – review and editing: J.J., P.D.F and K.M.

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Competing interests. The authors declare there are no conflicts of interest.

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