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The impact of variation in grain number and individual grain weight on winter wheat yield in the high yield potential environment of Ireland

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ABSTRACT

Previous studies from regions that produce high proportions of global winter wheat have highlighted that difference in sink size influences the majority of variations in winter wheat yield. However, the potential for source limitation due to environmental differences in regions that consistently produce a large sink capacity (i.e. > 20,000 grains/m^2), such as Ireland, have not been widely studied. The aim of this study was to characterise the variation in growth pattern and yield components that contribute to variations in grain yield in regions of high yield potential, and to identify the periods of development that are most likely to influence yield in these regions. Monitor crops of winter wheat were grown at three sites with contrasting latitudes on the island of Ireland, during three growing seasons (2013–2015). Crops were assessed regularly for measurements of crop growth and development, including biomass accumulation, canopy development and light interception. Grain yield ranged between 10.7–15.8 t/ha at 15% moisture content, with a grand mean of 12.7 t/ha. Results indicated that variations in grains/m^2 had a larger effect on winter wheat yield than variations in individual grain weight. Variability in grains/m^2 was influenced by changes in spikes/m^2 more than the number of grains/spike. While spikes/m^2 at harvest was significantly related to the number of shoots/m^2 at GS59, no significant relationship was observed between the shoots/m^2 at the time of maximum tillers/plant and spikes/m^2 at harvest. Furthermore, a significantly negative linear relationship was observed between shoots/m^2 at the time of maximum tillers/plant and grains/spike. Therefore, high rates of tillering were not beneficial to yield formation in the majority of crops monitored. A strong effect of individual grain weight was observed at one site of the nine evaluated in the study, indicating that a partial source limitation of yield is possible in certain Irish environmental conditions. However, variations in grain yield of crops of winter wheat grown at different locations in Ireland in different seasons were primarily driven by variations in grain number, and therefore were generally sink-limited.

1. Introduction

The pressure to maximise yields in Irish wheat production systems has increased recently, due to increased demand for grain caused by the large predicted increases in population by 2050 (Alexandrator and Briunsma, 2012), and the small profit margins available above high inputs costs required to protect crops against disease and weeds, especially during periods of low grain prices (O'Donovan, 2016). Despite substantial increases in the national average wheat yield from the 1960's through to the late 1990's, this trend has slowed substantially in the last decade (Fischer and Edmeades, 2010; CSO, 2016).

The limiting factors causing this plateauing of yield can result from either a limitation of the sink size available to store yield during grain filling or a limitation of the source available to produce assimilate for grain filling (Fischer, 1985). As the determination of sink size and potential source generally occurs at different periods of crop development with only a small degree of overlap (Slafer et al., 2014), the identification of which factor has a greater influence on the variation in yield for a certain region is important for targeting efforts in breeding, the development of new technologies and crop management, and to achieve a greater proportion of yield potential.

During the past 30 years, many studies have investigated which factors limit the yield of cereal crops through alterations in the sink:source ratio, either through the manual reduction in sink size (Slafer and Savin, 1994; Acreche and Slafer, 2006; Calderini et al., 2006; Zhang et al., 2010; González et al., 2014), alterations in the

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potential radiation interception (Fischer, 1985; Savin and Slafer, 1991; Beed et al., 2007; Ahmadi et al., 2009; Serrago et al., 2013; Asseng et al., 2017), the analysis of contrasting genotypes (Abbate et al., 1998; Shearman et al., 2005; Acreche and Slafer, 2009) or the analysis of crops grown in different environments (Bingham et al., 2007; Peltonen-Sainio et al., 2007; Kennedy et al., 2017). As summarised by Borrás et al. (2004) and Slafer et al. (2014), the majority of previous studies have indicated a major sink limitation (generally through grain number per m^2) of winter wheat yield for the majority of global cereal crops, with reductions in the radiation source available per unit of sink post-anthesis adequately compensated for by a utilisation of potential assimilates stored in the stem (Gent, 1994; Ehdaie et al., 2008; Serrago et al., 2013). Studies by Calderini et al. (2001), Xie et al. (2016) and Asseng et al. (2017) have highlighted a strong relationship between crop growth during the pre-anthesis period of spike development and a crops' sink size, with unfavourable conditions potentially reducing grain number through increased shoot mortality (Sparkes et al., 2006) and a reduced fruiting efficiency for grain on the spike (González et al., 2011; Gonzalez-Navarro et al., 2016).

However, many previous studies have also observed a source-sink "co-limitation" of yield, indicating a partial effect of a low source availability-high sink capacity environment on crop yield (Calderini et al., 2006; Peltonen-Sainio et al., 2007; Acreche and Slafer, 2009; Serrago et al., 2013; González et al., 2014). Winter wheat yields in Ireland are generally amongst the highest globally, facilitated by a climate that provides abundant rainfall without temperature extremes that allow for slow development and a long duration to capture resources (Burke et al., 2011). However, the Irish climate is also characterised by variability in the incidence of radiation during summer months due to cloud cover (Sweeney, 2014), and thus, the natural occurrence of a high sink-low source environment post-anthesis is plausible. Furthermore, it is important to determine the typical variation of winter wheat yield in a high yielding climate like Ireland, as Slafer et al. (2014) reported that while large changes in yield are mostly due to grains/m^2, small changes may be due to either grains/m^2 or individual grain weight. A field evaluation of the potential source or sink limitations of high-yielding winter wheat, based solely on site and seasonal variations in climate, without manual alterations of source or sink capacity has not previously been published, to the authors' knowledge.

Despite this, previous physiological studies conducted for winter (Bingham et al., 2007) and spring barley (Kennedy et al., 2017) in the UK and Ireland, respectively, have indicated a strong sink limitation for these crops despite relatively high sink capacities when compared to other international regions. These articles highlighted the importance of pre-anthesis growth to obtaining a high yield, and therefore identified a critical period in development during which crop management should be optimised. However, the greater potential for creating sinks and yield in crops of winter wheat, compared to barley, (Ugarte et al., 2007) likely results in a lesser source: sink ratio and a greater potential for source limitation. Furthermore, little information is available on the growing dynamics of wheat grown at different latitudes across the island of Ireland, as the climatic conditions can differ with region (Holden and Brereton, 2004), and thus, crop development and growth may differ somewhat.

The aim of this study was to characterise the variation in growth pattern and the yield components that contribute to variations in grain yield at contrasting sites with high yield potential environments for wheat, and to identify the periods of development that are most likely to influence yield in these regions.

2. Materials and methods

The methodology described below is based on previous work on the growth and development of barley in the UK (Bingham et al., 2007) and Ireland (Kennedy et al., 2017).

2.1. Experimental design

The experiments were located at three sites across the island of Ireland between 2012 and 2015, Crossnacreevy, Co. Down (54°33′N, 5°51′W; sowing dates: 8 November 2012, 29 October 2013, 4 December 2014), Oak Park, Co. Carlow (52°51′N, 6°54′W; sowing dates: 25 October 2012, 14 October 2013, 14 October 2014) and Killeagh, Co. Cork (51°56′N, 8°1′W; sowing dates: 23 October 2012, 15 October 2013, 6 November 2014), that represented the range in latitude of the typical wheat growing regions on the island. At Oak Park and Killeagh, each experiment consisted of six 2.5 × 24 m plots per site, which were arranged into three blocks of two plots, each containing one plot designated to observations/non-destructive analysis and the other to analysis that required destructive analysis throughout the season. At Crossnacreevy, the experiments each comprised three rows of eight plots, each 2.0 × 18 m, bordered by two plots, alternate plots being designated to observations/non-destructive analysis/harvest and to destructive analysis throughout the season. The variety sown in each experiment (*Triticum aestivum* L. cv. JB Diego, Senova, Cambridge, UK) was selected due to its commercial popularity and high-yielding performance in recommended list trials. Varieties were sown into continuous arable fields with good soil conditions following inversion ploughing and harrowing. Seeding rates were selected to achieve a target plant population of 260–280 plants/m^2. Crops were treated with a three spray fungicide program to minimise disease incidence, and all other crop management, including herbicides, insecticides and nutrient management, were applied at rates to minimise crop stress and facilitate a high yielding crop. Specifically, inorganic nitrogen applications where applied in three splits (0.3:0.4:0.3 at GS25/30, GS30/31 and GS37, respectively) at the Oak Park and Killeagh sites, and two splits (0.5:0.5, GS30 and GS37, respectively) at Crossnacreevy in all three years. The total rates applied were 200, 180 and 200 kg N/ha at Oak Park and 200, 180 and 220 kg N/ha at Killeagh for 2013, 2014 and 2015, respectively, while 220 kg N/ha was applied at Crossnacreevy for each year. Other nutrients (P, K and S) were applied at rates that would be non-limiting to crop growth and development, as described by Wall and Plunkett (2016). All sites had been in continuous tillage crop production for at least ten years. Protection against disease, weeds and pests was successful at all sites. Lodging assessments were conducted every three days during the grain filling period, however no significant amounts of lodging was observed in any of the experiments.

Weather data, including indices of temperature, radiation and rainfall, were obtained using the instruments and standards described by Fitzgerald and Fitzgerald (2004) from weather stations within 2 km of the experiments at Crossnacreevy (Skye MiniMet Automatic Weather Station, 2013-14 and courtesy of Agrii, Cheltenham, UK, 2014-15) and Oak Park (courtesy of Met Éireann, Dublin, Ireland), with weather data for the Killeagh site obtained from Roches Point, Co. Cork, 15 km south-west of the experimental site (courtesy of Met Éireann). Thermal time (°C days) was calculated using a base value of 0 °C by the method reported (method 1) by McMaster and Wilhelm (1997). Photosynthetically active radiation (PAR) was estimated as 0.5 the value of solar radiation (MJ/m^2), similar to Bingham et al. (2007). Meteorological data were summarised for three periods during each growing season and presented in Table 1.

2.2. Growth stage assessment and leaf/tiller emergence

Soon after crop emergence, 10 plants were selected at random and tagged in each observation plot. In addition, a tag was placed on the most recent emerged leaf and the number of leaves present was recorded. Observations were conducted on a monthly basis from emergence until GS30, with assessments of growth stage (Zadoks et al., 1974) conducted in addition to a count of the newly emerged leaves on the main stem since the previous observation, and the total number of tillers. Subsequent to GS30 crops were assessed on a weekly