Changing times: Opportunities for altering winter wheat phenology

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Social Impact Statement
Climate change presents challenges to agricultural production systems. Wheat is a significant crop in the United Kingdom, occupying 40% of arable land area. Increased temperatures and drought risk are predicted to lead to future productivity losses. Plant breeders and researchers are working to develop more resilient wheat varieties although are often driven by different motivating factors compared to farmers. Here, we report on a dialog with agronomists working with farmers in wheat-producing regions throughout the UK to gain greater understanding of the farm-level importance of wheat flowering time and maturity along with the future opportunities and risks presented by earlier flowering varieties.

Summary
Optimized environmental adaptation is the cornerstone of regional crop breeding. Recent and predicted future instability for long-standing adaptive response presents new challenges to selective breeding. Wheat is a long day plant, requiring extended daylength to initiate flowering, a response controlled by the Photoperiod-1 (Ppd-1) gene. Mutations conferring photoperiod insensitivity arose during domestication, allowing rapid flowering in both short and long days and extending wheat's adaptive range. In the United Kingdom, wheat production is dominated by photoperiod-sensitive winter varieties which have a relatively narrow window of flowering time. Changing seasonal conditions alongside mounting logistics pressure as a result of loss of effective agrochemicals and increasing seasonal weather fluctuations mean that greater flexibility in varietal flowering time is likely required to sustain UK wheat productivity. In this Opinion piece, we present findings from a recent dialog with UK agronomists on the demand and likely potential for greater flowering time range in winter wheat varieties. This provides important insight connecting farmer priorities and demands with ongoing genetic research and breeding. Our findings highlight the farm-level importance of wheat phenology and provide recommendations for future research and plant breeding.

KEYWORDS
adaptation, climate change, crop production, drought, plant breeding
INTRODUCTION

Understanding the sensitivity of production systems to fluctuating seasonal conditions is increasingly important with global warming of up to 4°C above current temperatures predicted by the end of the century (IPCC, 2013). In the United Kingdom, hot summers such as recently experienced are predicted to have a 50% occurrence by mid-century (UKCP18, 2019). On a seasonal basis, greater frequency and severity of adverse weather events will present a significant challenge to maintaining the UK’s current level of wheat productivity as is evident from early indications of severely reduced wheat yields in 2020 (National Farmers Union, 2020). Examples of adverse conditions caused by climate change that may affect wheat productivity in the UK include drought stress, water logging, and adverse conditions at sowing and harvesting (Harkness et al., 2020; Trnka et al., 2014). Given that 40% of UK arable land area is cropped to wheat (DEFRA, 2018), this is likely to have a major impact on both primary production and food supply.

Such impacts on wheat production were observed in the UK in 2012 which was dominated by significant deviation from typical climatic patterns (Kendon et al., 2013), recording the second driest January to March period since 1953 (for England and Wales; Parry et al., 2013) followed by the wettest 9-month period in 250 years (Kendon et al., 2013; Parry et al., 2013). This had serious implications for winter wheat productivity due to the combination of early season moisture deficit, low sunlight levels during grain fill, and elevated disease pressure associated with high rainfall levels leading to 2012 UK wheat yields suffering a 14% reduction compared to the previous year (DEFRA, 2012).

Flowering time marks the transition from vegetative to reproductive growth and its timing relative to local environmental conditions is the major determinant of grain yield in wheat (Cieśla et al., 2007; Flohr et al., 2017; Jung & Muller, 2009). Varieties should ideally flower at an appropriate time not only to maximize radiation intake by photosynthetic tissues, but also to avoid key developmental stages intercepting with adverse abiotic and biotic stresses (Bentley et al., 2013). However, there has been little investigation to date of the interaction between flowering time, ambient temperature, and drought response despite the published predictions of global warming. Wheat is a long-day species with floral initiation accelerated by exposure to lengthening days. At present, regional adaptive response is largely achieved through designed combinations of major genes, namely Vernalization (Vrn-1) and Photoperiod-1 (Ppd-1), which control the transition to flowering in response to environmental cues. Reliance on known genetic combinations to adapt wheat to climate change is an escape strategy: for example, photoperiod-insensitive varieties (possessing mutant Ppd-1a allele/s) are favored in Mediterranean environments where early flowering avoids late summer heat and drought stress (Worland, 1996; Bennett et al., 2012), thereby minimizing yield penalty.

Variation in the major Ppd-1 and Vrn-1 genes aided the worldwide spread of wheat cultivation and the expansion of cultivation into new areas. Olmstead and Rhode (2011) describe the progression of wheat cultivation in North America showing shifts across the climatic features of latitude, longitude, annual and average January and July temperature, and annual precipitation. The development of the early flowering Canadian cultivar ‘Marquis’ was attributed as a contributing factor in the settlement of western Canada (Morrison, 2008). The result of a cross between ‘Red Fife’ and the very early variety ‘Hard Red Calcutta’ (believed to have been a Himalayan variety sent to foundation Canadian wheat breeder William Saunders by Lord Dufferin, a former viceroy of India; Morrison, 2008), the variety had superior milling quality. Its distinctive earliness, being 6–10 days earlier maturing than the conventional varieties of the time, went on to dominate Canadian wheat production (Olmstead & Rhode, 2011). ‘Marquis’, along with the early breeding and selection programs in other parts of North America introduced greater environmental adaptation, supporting expansion in wheat production area to match the climatic conditions of the regions (Olmstead & Rhode, 2011). Similarly, in Asia, the Mediterranean and North Africa the introduction of photoperiod insensitive alleles into improved cultivars translated into enhanced adaptation and higher yield potentials (Ortiz Ferrera et al., 1998), while in Europe photoperiod response was differentially selected between southern and northern production environments with early flowering varieties giving a 33% yield increase (compared to late flowering lines) in southern Europe (Worland et al., 1996; Worland et al., 1998). In China, Yang et al. (2009) demonstrated that photoperiod-sensitive landraces have narrower environmental ranges compared to improved photoperiod-insensitive cultivars suggesting that plasticity in flowering time enables greater environmental adaptation.

Flowering time has clearly facilitated regional adaptation of wheat and allowed it to become a successful and important crop. Flowering time is thus a critical consideration in the adaptation of wheat to predicted climate change. Although much can be learnt from historical patterns and drivers of wheat area expansion, future adaptation needs must also be forecast well in advance given the substantial time lag in the breeding and release of new cultivars. Hamer et al. (2020) estimated that adaptive requirements should be considered at least 10 years ahead of varietal release. Based on climate model predictions, wheat yields will suffer climate change-related declines below current production in most regions in the absence of either varietal or infrastructure (e.g. irrigation) interventions (Tanaka et al., 2015). The magnitude of climate change effects on wheat will be cultivar dependent, necessitating practical solutions to tailor selective breeding to changing regional patterns (Trnka et al., 2014). These intervention needs and outcomes can be modeled via so-called “adaptation pathways” but the availability and field-based performance of theoretical future varieties within the required intervention timescales is unknown (Tanaka et al., 2015). Hunt et al. (2019) simulated and empirically tested early sowing combined with slower-developing wheat genotypes in Australia. This demonstrated clear and quantifiable potential to increase yields under climate change scenarios and therefore offers a clear route to impact for manipulation of wheat phenology (Hunt et al., 2019).
Winter wheat is both the dominant cereal and main arable winter crop grown in the UK. Spring wheat, which lacks a vernalization requirement and is sown in late winter or early spring (Figure 1), is also grown but represents a much smaller proportion of the total amount of wheat grown in the UK. Winter wheat varieties in the UK are photoperiod sensitive, most possessing the photoperiod-sensitive allele of Ppd-D1, and therefore are typically later flowering than varieties in other regions of northern Europe (Bentley et al., 2014). Considering the predicted effects of climate change in the UK, breeding varieties that flower earlier and thus pursue an escape strategy like that found in southern parts of Europe, seems a logical way forward.

Here we report on a recent consultation with UK-based agronomists across major wheat producing regions conducted to assess demand for earlier flowering varieties, and to understand associated risks. We define early flowering as a range of variation that is 5–10 days earlier than current UK winter wheat varieties. In this Opinion, we share the findings which indicate that earlier flowering time in UK winter wheat is desirable given more fluctuating seasonal conditions, and that it can mitigate drought stress, contribute to improving the logistics of on-farm crop management, and avoid pest and pathogen damage. We also highlight where additional research is needed, particularly in understanding the physiological link between flowering and maturity date, understanding frost risks, and providing new genetic controllers of adaptive response.

2 | HARVESTING VIEWS ON ALTERING WHEAT PHENOLOGY

In order to understand producer perspectives on the opportunities and potential risks associated with altering winter wheat phenology in UK-registered varieties, we consulted agronomists working...
directly with farmers across the UK’s main wheat-growing regions. In total, we spoke to 14 agronomists, including five from the NIAB regional agronomists’ team, four from the NIAB-TAG consulting team, and five from Velcourt Ltd., a farm management and advisory business. Interviewees were selected in order to be representative of regions across the UK and roughly proportionate to the volume of wheat production in these regions (Figure 2). As only a very small proportion of the UK wheat crop is grown in the North-West of England, Wales and Northern Ireland (1.2%, 1%, and 0.4%, respectively; DEFRA, 2019), no agronomists from these regions were consulted.

A set of informal questions was posed to each of the 14 agronomists in phone conversations held between 10 March and 20 April 2020 including the overall desirability of earlier flowering varieties, associated advantages and disadvantages, extent of current water availability constraints faced by farmers, and views on the use of spring wheat. Additionally, interviewees were encouraged to follow other relevant topics that arose during the resulting conversations. The consultation did not take the form of a formal designed survey but was conducted to ascertain views on future phenology-based research and breeding opportunities.

3 | MAJOR POTENTIAL BENEFITS OF EARLIER FLOWERING TIME

Across the consultation, a consistent set of opportunities were identified by all the respondents surveyed. These include the provision of a greater range of flowering times to spread seasonal risks, mitigate drought stress, and improve on-farm logistics. All these potential benefits are discussed in more detail below, along with a perspective on likely yield and overall productivity impacts.
3.1 | Winter wheat varieties with earlier flowering time are desirable given more fluctuating seasonal conditions

Overall, there was a very positive response toward having a greater range of varietal flowering times in winter wheat. While all agronomists acknowledged that the demand for early flowering varieties will differ depending on the region due to climate and, within regions, on soil type, they highlighted that there is currently a poor choice of early flowering varieties and an overabundance of later flowering varieties on the Agriculture and Horticulture Development Board (AHDB) Recommended List (RL; AHDB, 2020b). A number of agronomists shared recollections of early flowering varieties (e.g., ‘Soissons’, ‘Grafton’, and ‘Cordiale’) that are no longer on the RL but are still grown by a small number of their clients. This suggests that early flowering time varieties have been successful in the UK, which is also reflected in the area of certified seed currently produced. In 2019, 14% of certified UK seed weight (NIAB TAG, 2020) was produced from varieties that at some stage have been classified as early ripening on the RL, showing that there is clearly a demand for early flowering varieties.

We examined the claim that there is currently a poor choice of early flowering varieties recommended on the RL for winter wheat. We used data obtained from the winter wheat RL over the range of 2010/2011 to 2019/2020 (https://ahdb.org.uk/rlarchive), and for each year, we standardized the ripening of each variety to a reference variety, ‘JB Diego’, which was present in all years (Figure 3a). We used ripening (equivalent to maturity) as a proxy for flowering time because ripening and flowering time are highly correlated (Figure 4). ‘JB Diego’ is classified as an “early to mature” variety (Senova Limited, 2017); therefore, we classified any varieties having equal or earlier ripening as “early ripening/maturing” and any varieties having later ripening as “late ripening/maturing.” We acknowledge that the differences between varieties that are “early” and “late” and are close to the reference do not differ from one another substantially, but we use this classification as a simple illustrative way to show the smaller proportion of “early” varieties especially in more recent years. There was a significant difference in days to ripening across the 10 years tested (p < .001) with a clear decrease in variance of days to ripening (Table S1). Analysis of the AHDB RL thus gives some insight into the changing phenology profile of UK wheat varieties, supporting the assertions made by the agronomists.

3.2 | Improving the logistics of crop management is likely possible with earlier flowering varieties

The most commonly acknowledged benefit of early varieties among agronomists was that related to farm and crop management. Farming practices have become more compact with a narrower time window for practical operations placing higher demands on machinery and labor during key cropping activities. Treatment timings, such as ear wash sprays, can be very tight and, at harvest time, there is an upper limit on combine harvesting and significant potential loss in grain quality due to delays in harvesting. Drilling (sowing) is a key pressure point and the drill window is contracting in most regions in the UK in order to drill as much of the crop as late as possible to reduce disease risk and control black-grass growth (summarized in Figure 1). This was exacerbated in the most recent drill season (autumn 2019) by a very wet autumn that further limited feasible drilling days, thereby reducing both wheat and winter barley (−17% and −23% compared to the previous year; AHDB, 2020b). Harkness et al. (2020) also recently showed (via modeling) that the probability of extremely wet conditions early in the growing season is likely to substantially increase...
as a function of predicted rainfall increase (during winter and early spring) which suggests that what was experienced in 2019 will become more common. A later, contracted sowing time period also creates pressure in later stages of the cropping season because it reduces variability in developmental growth stages. This is illustrated in Figure 3b, where we used winter wheat RL data from the years 2010/2011 to 2020/2021 to examine the variance in the amount of time to start of stem extension (GS31) depending on which month the varieties were sown. For each month, the time to GS31 data was combined for all stated years and all varieties tested in those years, and the data was plotted according to month sown. Although there was no statistically significant difference in time to GS31 by month of sowing, for early sowing (September), the earliest and latest varieties to GS31 had a range of 19.7 days (variance = 12.19), which decreased substantially to 9.3 days (variance = 4.58) for later sowing in November.

Having access to varieties with earlier flowering and maturity date and combining these in a portfolio with varieties with later developmental timings, was seen by agronomists as a highly desirable strategy to better manage and spread out key stages in the wheat crop. The benefits of this would be, for instance, providing better assurance that harvest can be carried out when the grain is at harvest maturity, and increasing capacity across the farm. Alternatively, employing only earlier flowering and maturing varieties may open up opportunities for catch and cover crops that may not be currently possible with later maturation times. Catch crops (generally legume and brassica species mixtures) are grown for a short period from late summer and provide soil health and ecosystem service functions. Cover crops are also designed to return soil health benefits and can include legume, brassica, grass and cereals individually or in mixtures that are generally grown for a longer period between arable crops to improve soil organic matter (AHDB, 2015). This is seen as particularly advantageous in the north of the UK (north of Yorkshire and the Humber) where crops take longer to develop due to cooler temperatures, and early flowering varieties thus provide an assurance that the grain can be harvested before precipitation as well as provide for a catch and cover crop.

3.3 | Earlier flowering time can mitigate drought stress

Drought stress is already seen to be a problem in some regions of the UK, particularly on sandy and gravelly soil types. These soil types have a high sand/gravel to clay ratio and do not hold water very well, thereby enhancing any effects of low precipitation. Almost all the agronomists consulted reported that they had worked with farmers that had seen evidence of drought stress, or yield loss due to low water availability and all predict this to continue to be a problem going forward. They could thus see the advantages of wheat with earlier flowering time used to mitigate risk of drought stress. However, there was also some skepticism that forward weather predictions are currently accurate enough to base future cropping decisions on. Rather, it is more likely that earlier flowering varieties could be used as part of a variety portfolio with different flowering types used to spread risk across the farm and to give some assurance of productivity across the farm business. The use of different varieties across the farm is a strategy that is already used in the cultivation of wheat in the UK. The agronomists we spoke to also saw the potential for earlier flowering varieties to open areas for wheat cultivation that are not currently cultivated due to poor soils. For instance, in South-East Anglia on sandy or gravelly soils, farmers tend not to grow wheat at all (on land that is informally characterized as “not being a wheat soil”) and will rather grow barley which matures earlier. Therefore, earlier flowering varieties could be employed with success on intermediate soil types as a strategy to increase the area available for wheat cultivation.

Reports in literature based on climate projections suggest that heat stress rather than drought stress will impact UK wheat production in the future (Senapati et al., 2019; Harkness et al., 2020) although Harkness et al. (2020) predict drought impacts on southern and eastern production which typically receive less rainfall. Flohr et al. (2017) reported that the optimal flowering period for wheat is primarily driven by water supply and demand with heat and temperature having secondary effects. This is in agreement with the comprehensive review of Bodner et al. (2015) reporting drought as the major determinant of crop productivity losses. Heat stress events vary significantly in temporal duration and are more likely to be mitigated or compensated for by the tillering ability of the crop (Balla
et al., 2019), by the use of staggered sowing dates or adoption of variety portfolios with variable flowering times to change timing of coincidence of anthesis (the most sensitive stage; Balla et al., 2019) with stress events. Therefore, we would argue that from a logistics and infrastructure perspective it will be far more difficult for farmers to mitigate future drought (e.g., enabling use of supplementary irrigation) compared to heat stress (staggering planting dates or using flowering time varietal profiles).

3.4 | Yield will determine uptake of early flowering varieties and greater understanding of the physiological link between flowering, maturity, and the consequences for yield formation is required

An overriding consideration in varietal choice is yield and the circumstances in which farmers are willing to accept potential yield penalties (discussed further in Section 5). Several of the agronomists we consulted pointed out that flowering time per se is not a major consideration for farmers. Maturity date is of much greater relevance because this determines when harvesting occurs, a major pressure point in the cropping of wheat (Figure 1), and because maturity date is implicitly linked with expectations of yield (with later maturing being assumed to result in a higher yield). Many agronomists also questioned whether early flowering is always equivalent to an earlier maturation time. Using data generated over 2 years (2010 and 2011) for a 376-variety European winter wheat panel (TriticaceaeGenome panel; Bentley et al., 2014), we can demonstrate a clear correlation (Figure 4) between flowering time (assessed as a weighted mean of ear emergence using Zadok’s growth stage 55 across 6 northern European trial environments; Zadoks et al., 1974) and maturity assessed as an average field-based score across three dates (method described and data available in Ladejobi et al. (2019)). Therefore, in these discussions, earlier flowering time was assumed to mean earlier maturation time and a shorter grain fill period, thus leading to the assumption of a yield penalty compared to later maturing varieties, as has been demonstrated in previous investigations of Ppd-1 (Worland, 1996; Bentley et al., 2013). Overall, it was agreed that for growers the variety could not be seen to suffer from too much of a yield penalty.

Some agronomists discussed the yield advantage that a variety might have if it was early flowering but retained a similar maturation period to later flowering varieties. The major barrier to implementing this manipulation in wheat breeding remains a lack of knowledge relating to the independence of stages of development and their subsequent influence on yield. It has been proposed that photoperiod sensitivity at different developmental phases is at least partially independent (Gonzalez et al. 2005), raising potential for genetic manipulation. Some authors have shown patterns of development differing between photoperiod sensitive and insensitive types (Dyck et al. 2004; Gonzalez et al. 2005; Worland, 1996), while others have reported specific stages (e.g., stem elongation; Tanio and Kato, 2007) to be unaffected by either photoperiod, or genotype.

In a recent simulation study, Harkness et al. (2020) simulated future flowering and maturity times for UK wheat showing 10–11 to 12–14 day acceleration in anthesis (equivalent to flowering: Zadoks GS61) under mid- and high-range greenhouse gas emission scenarios with a corresponding acceleration in maturity across these scenarios (13–15 and 16–19 days, respectively). The authors attribute this acceleration to faster thermal time accumulation but it is yet to be experimentally determined if all varieties respond in an identical manner, or if linear relationships will be maintained between flowering time and maturity. Langer et al. (2014) reported a strong effect of temperature on flowering time showing that all assessed genotypes responded similarly to the different temperature regimes. Given the projection of more rapid thermal time accumulation and in order to reliably use escape strategies under future climatic uncertainty, trade-offs to physiologically based plant processes and productivity across environments need to be accurately characterized. While future wheat ideotypes can be designed and simulated in silico based on climate model predictions (Semenov & Stratonovitch, 2013), it is essential that empirical testing be used to determine if it is feasible to decouple flowering and maturation, and what the downstream production impacts of this would be.

4 | FURTHER CONSIDERATIONS AND RISKS

In addition to the overriding opportunities discussed above, the agronomists we spoke to raised additional considerations for earlier flowering varieties, including risks associated with pests and pathogens, and frost damage. In addition, we solicited views on dramatically altering phenology to move from winter to spring wheat cultivation although there was little support for this at present.

4.1 | Early flowering could reduce the risks of pest and pathogen damage

One potential benefit of earlier flowering is reduced risk of some diseases and pests that affect wheat at flowering, particularly those that infect later in the season. Two in particular were mentioned by agronomists—the ergot fungus, *Claviceps purpurea*, and orange wheat blossom midge (OWBM; *Sitodiplosis mosellana*). Ergot infects the ear at flowering with risk tending to be higher when the weather is wetter and warmer (Gordon et al., 2015). Timing of flowering is therefore likely to be a major determinant of infection if it co-occurs with these seasonal conditions that favor pathogen dispersal and infection. Wheat does show differential varietal resistance to ergot; however the cause of the variation remains largely uncharacterized (Menzies, 2004; Willis, 1953). Gordon et al. (2015) showed that ergot resistance in UK winter wheat is conferred by at least four quantitative trait loci (QTL), two
of which are co-located with the major height reducing, DELL A en-
coding Rht genes (Rht-B1 and Rht-D1; Peng et al., 1999) with shorter
lines with either the Rht-B1b or Rht-D1b semi-dwarfing allele hav-
ing significantly lower levels of infection (Gordon et al., 2015). In
addition to their role in stem elongation, gibberellins are known to
control floral development (Cheng et al., 2004); so it is possible that
there are pleiotropic interactions between height and flowering
time which determine ergot response. Gordon et al. (2015) ob-
served higher levels of ergot infection (total and average sclerotia
weight) in ‘Rialto’, ‘Solstice’, and ‘Xi-19’ compared to ‘Robigus’ and
‘Glasgow’. Field flowering time data collected over 2 years (2010
and 2011) as part of the assessment of the TriticaceGenome panel
described in Bentley et al., (2014) at NIAB, Cambridge shows that
‘Robigus’ and ‘Glasgow’ are slightly earlier flowering than the other
three varieties (by an average of 1.5–3 days in 2010; 2–4 days in
2011). This suggests there may be a link between phenology and
susceptibility to the ergot pathogen and that shifting flowering
early may help to reduce this risk.

For orange wheat blossom midge (OWBM; Sitodiplosis mosel-
lana), which feeds on developing grains, there is a precise window
of 10 days in which infection risk is extremely high. Currently, this
coincides with flowering of many UK winter wheat varieties that
do not carry the Sm1 antibiosis resistance gene (Kassa et al., 2016).
Shifting flowering 7–10 days earlier could help to avoid the peak
infection window thus reducing damage from this pest. However,
there is anecdotal evidence that earlier flowering varieties previ-
ously grown in the UK (e.g., ‘Cordiale’) have high OWBM infec-
tion levels so further detailed characterization is required. Given
the narrow genetic basis of current OWBM resistance (Zhang
et al., 2020), the availability of a wider selection of varietal flow-
ering time ranges may support the varietal blending approach de-
veloped and deployed to counter new virulences in Canada (Smith
et al., 2014). Combined with deployment of additional genetic
sources of resistance (Zhang et al., 2020) this should provide a
more robust resistance package for UK farmers.

While these potential benefits in relation to pests and patho-
gens were recognized among the agronomists consulted, there
was also acknowledgement that changing climates are likely to
affect the life cycle of pests and pathogens. The potential and
likelihoods for climate change-related effects on the frequency
and occurrence of wheat pathogens has been summarized and
reviewed (e.g., Chakraborty & Newton, 2011; Juroszek & von
Tiedemann, 2013). Therefore, any predicted reductions in risk
will need to be combined with modeling and assessment of these
factors.

4.2 | Increasing the risk of frost damage

Another potential risk identified and discussed was that of damage
to earlier flowering varieties from late frosts. Late frosts in spring
(and into summer) can harm floral organs and developing grains
leading to anther and embryo death and non-fertilization as well
as grain damage including small, shriveled, and shrunken kernels
leading to an overall reduction in grain production (Cromey et al.,
1998). The photoperiod-insensitive Ppd-D1a variety ‘Soissons’ was
discussed by some interviewees in this context, as it was known to
be particularly subject to late frosts in UK conditions. It was
also acknowledged that the risk of frost increases markedly in the
north, one region which could otherwise benefit significantly from
earlier flowering (see Section 3.2). Martino and Abbate (2019)
developed a model allowing for estimation of the frost damage
effect on subsequent wheat grain number across reproductive
development stages showing that maximum damage (in respect
to grain production) always included anthesis, indicating this as
the most critical period for frost-avoidance. Post-head-emergence
frost damage is a greater risk in varieties with faster development
(recently reviewed by Frederiks et al. (2015)). However, modeling
of crop damage risks in the UK from frosts under future climate
projections by Trnka et al. (2014) showed that severe frost risk is
extremely low with more recent work from Harkness et al. (2020)
also reporting that future risks of late frosts leading to medium to
severe yield losses across the UK’s wheat growing area are neg-
ligible. With these current models, it appears that frost may not
pose a major risk to early-flowering varieties in the future but, as
with any approach, this will require reconsideration as new data
becomes available.

4.3 | Dramatically altering phenology currently offers limited appeal

We asked the agronomists about the potential of spring wheat and
whether they were likely to recommend spring wheat varieties to
the farmers that they work with. Of the responses, some were fa-
orable while others were very negative. It was widely acknowl-
edged that a large amount of spring wheat would be planted in the
2019/20 season due to the extremely wet autumn which reduced
the sowing of winter wheat, so much so that there was a shortage
of spring wheat seed leading to the sourcing of seeds from other
parts of Europe. However, a lot of farmers have chosen instead to
go with spring barley, which is seen to have more favorable proper-
ties compared to spring wheat including more reliable yields, bet-
ter competitiveness against blackgrass, and lower pathogen and
pest issues with spring wheat being especially susceptible to infec-
tion by ergot (Menzies & Turkington, 2014) and gout fly (Chlorops
pumilionis; Kaniuczak, 2008). In addition, spring wheat must be
drilled early (March, or even February; Figure 1) which is not pos-
sible due to weather conditions in some regions and on some soil
types. There are relatively few options available in terms of spring
wheat varieties with only eight spring wheat varieties on the current
RL (AHDB, 2020a) and a corresponding low UK certified seed area
(1.6% of the total 2019 wheat certified area; NIAB TAG, 2020). Some
interviewees were dismissive about the importance of UK spring
wheat for the future and most thought that breeders’ efforts were
better concentrated on improving winter wheat varieties.
FUTURE PROSPECTS

Early flowering winter wheat varieties are clearly seen as a desirable option for UK farmers, particularly considering the limited choice that is currently available. The main advantage associated with an earlier flowering time, along with an earlier harvesting time, is in farm management: providing the opportunity for portfolios of varieties with different developmental timings so that the demands on labor and machinery can be better spread out during the season. This advantage depends on the size of the farm with larger farms being able to grow more varieties and take further advantage of this strategy. However, the interest in dramatically altering phenology to widespread cultivation of wheat as a spring crop was generally low.

Drought was clearly acknowledged as a problem that is already occurring and is likely to persist in the future. With forecasted effects of climate change leading to increasing temperature and extreme weather events, there is going to be more risk in general associated with arable crop production. Therefore, the more options there are for flexibility and resilience, such as a wide range of wheat varieties with beneficial agronomic properties, the better.

The issue of taking a yield penalty in early flowering or early harvesting winter wheat does not seem to be an insurmountable obstacle in terms of whether farmers will take up a new variety. One interviewee suggested that a 5%-6% yield penalty could be acceptable if the variety opened up other opportunities, for instance, if the variety had a higher value for output such as a milling wheat. Furthermore, it was recognized that there is a trade-off between possible penalty in yield from growing early flowering varieties versus loss in end-use quality or yield in later flowering varieties due to drought stress (or due to not being able to harvest in time). Yield must ultimately be balanced with the costs associated with its production (Swarbreck et al., 2019) so there is potential scope to introduce more balanced assessment and decision-making criteria. However, there is still the hurdle of having to obtain a yield within 2% of existing RL varieties in order to be included on the RL. Considering that 94% of varieties sold in the UK are on the RL at time of purchase (NIAB TAG, 2020), this is clearly a bottleneck for varieties that do not make the yield threshold but offer other favorable agronomic or production characteristics, such as early flowering.

CONCLUSION

In UK winter wheat varieties, alleles of major phenology genes are predominantly fixed (Bentley et al., 2014) which constricts the variation available due to major effects. Despite this, there is significant variation for flowering time in the wider northern European gene pool (Langer et al., 2014) which suggests that our defined 5- to 10-day earliness window is tractable to achieve using available genetic resources. We report that earlier flowering times are desirable for UK wheat producers particularly giving greater flexibility in more fluctuating seasonal conditions, mitigating drought stress and contributing to improving the logistics of crop management. It is therefore urgent to prioritize further research to identify additional genetic controllers of flowering response, plasticity of effects and the underlying genetics and physiology linking flowering, maturity and yield. The creation and field testing of near-isogenic lines in elite UK germplasm for genetic variation in phenology provides an ideal mechanism for geneticists and agronomists to work together to understand flowering time effects. This has been previously demonstrated to be effective for understanding the production impacts of developmental variation in wheat (Hunt et al., 2019). This will support future breeding strategies to deliver optimized flowering time to meet the evolving requirements of UK wheat production.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

HS and AB designed the study. HS conducted the agronomist interviews and analyzed the responses. HS and AB wrote the paper.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.