Agronomic Management of Malting Barley and Research Needs to Meet Demand by the Craft Brew Industry

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ABSTRACT
Malting barley (*Hordeum vulgare* L.) requires agronomic management that maximizes grain yield while meeting quality standards. The majority of published literature on agronomic management of malting barley is from the US Northwest and Northern Rockies and Plains where barley is traditionally grown. However, the majority of craft breweries are located in the Upper Midwest, Ohio Valley, and Northeast, creating a demand for locally sourced grain. The objectives of this review were to: (i) summarize the current body of knowledge regarding agronomic management of malting barley, and (ii) identify research needs in the Upper Midwest, Ohio Valley, and Northeast. Across all regions, planting date and N management were major factors influencing grain yield and quality. Timely planting of malting barley generally improved yield and quality. Barley yield tended to increase with N application rate while quality decreased due to increased protein concentration. Planting malting barley following corn (*Zea mays* L.) or small grains resulted in disease problems that could affect grain quality and yield. In the Upper Midwest, Ohio Valley, and Northeast regions, the prospect of double crop soybean (*Glycine max* [L.] Merr.) production after winter malting barley should be investigated, in addition to typical cropping sequences. Agronomic strategies to mitigate the negative effects of late-planting situations are also needed as these regions often have delayed planting due to wet soil conditions. Furthermore, N fertilizer management is much different in humid regions compared with the Northwest and Northern Rockies and Plains, and warrants future research on developing in-season N management strategies.

Core Ideas
- Agronomic management and environment affect malting barley yield and quality.
- Most agronomic guidelines are from the Northwest and Northern Rockies and Plains.
- Breweries in the Upper Midwest, Ohio Valley, and Northeast want local grain.
- Research on cropping sequence, seeding date and rate, and N management is needed.

In North America, barley (*Hordeum vulgare* L.) is mainly grown as a feed or malting grain. Barley has a broad ecological adaptation and thrives best in temperate climates with a cool and moderate dry season (Poehlman, 1985). In the United States, barley was introduced along the east coast shortly after the first English and Dutch settlers arrived in the 17th century (Poehlman, 1985; Hertrich, 2013). Barley cultivation moved west with the population to an area where corn (*Zea mays* L.) was not grown to avoid Fusarium head blight (FHB) (Poehlman, 1985). From the 1940s through the 1990s, the Red River Valley region of North Dakota and Minnesota were the predominant barley production areas in the United States. However, by the 1990s, high rainfall and increasing corn production provided suitable conditions for FHB, resulting in many producers within the region to abandon barley production. Currently, barley is mainly produced in the Northwest and Northern Rockies and Plains, where approximately 81% of the United States total barley is produced on 718,000 ha (USDA-NASS, 2018) (Fig. 1A). In these regions, spring barley types are predominately produced, planted in April or May and harvested in the fall. In other areas of the United States, where winterkill is less of a concern, winter malting barley types may be grown. Winter barley is planted in the fall, goes dormant through winter, and is harvested in late spring or early summer (Hertrich, 2013). More than three-fourths of the total barley produced in the United States is used for malting purposes, with the remainder for feed (Robertson and Wesenberg, 2003).

Although the majority of barley grain is produced in the Northwest and Northern Rockies and Plains, there is increasing interest in malting barley production in the Upper Midwest, Ohio Valley, and Northeast United States, driven by growth in the craft brewery industry (Fig. 1B) (Hmielowski, 2017). As of January 2018, the US craft brew industry consumed about 40% of the total malt used by US brewers (Brewers Association, 2018a). Many craft brewers want to source local ingredients, including malting barley grain (Hmielowski, 2017).

The goal of this review is to provide a comprehensive review on agronomic production of malting barley. Although the majority of malting barley production research has been focused in the Northwest and Northern Rockies and Plains, recent growth in the craft brewing industry in the Upper Midwest, Ohio Valley, and Northeast has created interest in agronomic production research in these regions. The objectives of this review were to...
(i) summarize the current body of knowledge regarding agronomic management of malting barley within four areas of the United States (Fig. 2), and (ii) identify research needs specifically in the Upper Midwest, Ohio Valley, and Northeast, where there is an expanding market for malting barley.

OVERVIEW OF GRAIN QUALITY PARAMETERS

Malting barley producers have the unique challenge of maximizing grain yield while maintaining certain quality parameters to receive premium prices by the malting industry. The specific criteria may vary slightly depending on the end-user and barley type. In general, malting barley grain should have high germination (≥95%), low protein (≤125 g kg⁻¹ on a dry-weight basis), high plumpness (>900 g kg⁻¹ and >800 g kg⁻¹ retention on a 2.38-mm slotted screen for two-row barley and six-row barley, respectively), low deoxynivalenol (DON) levels (<1 mg kg⁻¹), high test weight, minimal skinned and broken kernels (<5%), intact kernels and husks, kernel uniformity, free from blight and other diseases, and no signs of pre-harvest sprouting (Bamforth and Barclay, 1993; Kendall, 1994; Horsley et al., 2009). All of these grain quality factors are influenced by genetic, management, and environmental factors (Therrien et al., 1994; Bettenhausen et al., 2018).

NORTHWEST AND NORTHERN ROCKIES AND PLAINS REGIONS

Development of cultivars suitable for arid regions has helped make barley production under dryland conditions successful (Doncheck, 2000). As a result, US barley production has traditionally been concentrated in the Northwest and Northern Rockies and Plains. The majority of the barley grown in these regions include both two-row and six-row spring barley types (Buschena et al., 1998). The most obvious difference between a head of two-row barley and a head of six-row barley is the arrangement of the kernels when the head is viewed down its axis. In general, two-row malted barley has less protein and enzyme content and higher proportion of plump kernels than six-row malted barley, and therefore preferred by brewers (McKenzie et al., 2005; Schwarz and Horsley, 2019). This section includes the effect of management practices on malting barley grain yield and quality in the Northwest and Northern Rockies and Plains, including adjoining areas of Canada.

Tillage

Malting barley production is shifting from conventional clean-tillage to reduced or no-tillage (Carr et al., 2014). However, the effects of tillage on barley grain yield has been found to be variable, such as increasing (Carr et al., 2014), decreasing (Machado et al., 2007), or having no effect on grain yield (Sainju et al., 2013; Stevens et al., 2015) compared with malting barley produced without tillage. Tillage has been found to influence malting barley grain quality, especially barley grain protein concentration, averaging 131 g kg⁻¹ in a conventional tillage system, 121 g kg⁻¹ in a reduced tillage system (single tillage to 20-cm depth in the spring), and 113 g kg⁻¹ in a no-tillage system (Carr et al., 2014). Carr et al. (2014) suggested that the decrease in protein concentration with decreasing tillage intensity may be due to water conservation during grain development under no-tillage compared with conventional and reduced tillage. Similarly, in Montana, grain protein concentration was lower when barley was grown after fallow (Sainju et al., 2013), which is also a system that conserves water.

Cropping Sequence

Malting barley is typically grown in rotation with other crops. Barley planted after barley, corn, or wheat (Triticum aestivum L.) is not a recommended practice due to potential disease problems (Turkington et al., 2012). Emergence, head counts, grain yield, kernel weight, test weight, and kernel plumpness were lowest for barley grown on barley residue compared with canola (Brassica napus L.) and field pea (Pisum sativum L.) crop residue (Turkington et al., 2012).

The effect of a previous legume crop on malting barley grain quality has been found to be variable. In several studies, planting barley after a legume crop did not result in an increase in malting barley grain protein (Turkington et al., 2012; Sainju et al., 2013; O’Donovan et al., 2014; O’Donovan et al., 2017). However, Nedel et al. (1993) found that malting quality parameters, especially total malt protein and malt extract, were negatively affected when pea was the preceding crop and N application was >60 kg ha⁻¹. Nitrogen release from organic N sources, such as legume crops, is difficult to predict as N mineralization is influenced by soil moisture and temperature and...
varies based on location and year (Bundy et al., 1993; Agehara and Warncke, 2005). Nitrogen mineralization from the previous crop may not occur at the same time of rapid N uptake by malting barley. For example, in sandy soils, nitrate mineralized from soybean *Glycine max* (L). Merr. residue has been found to leach below the root zone before it could be recovered by the following corn crop (Bundy et al., 1993). Others have found N mineralization of red clover (*Trifolium pratense* L.) residue too slow to be available to the following crop due to low soil temperature (Henry et al., 2010).

**Planting Date**

Planting date is an important factor influencing malting barley grain yield and quality of spring barley (Table 1). In general, spring barley grain yield increases with earlier planting dates (mid-April to early May) compared with later planting dates (later than mid-May) (Jackson et al., 1962; Zubriski et al., 1970; Lauer and Partridge, 1990; Weston et al., 1993). Planting spring barley early is extremely important to achieve malting grade in addition to avoiding injury from drought, high temperatures, diseases, and insect pests (Robertson and Stark, 2003; Franzen and Goos, 2007). In Idaho, each 1-wk delay in planting after mid-April decreased grain yield by 336 to 448 kg ha–1 (Stark, 2003). Similar to other cereal grains, malting barley grain yield and protein were inversely related, resulting in greater grain protein concentrations as spring malting barley was planted later (Jackson et al., 1962; Zubriski et al., 1970; Fedak and Mack, 1977; Lauer and Partridge, 1990; Weston et al., 1993; McKenzie et al., 2005). Kernel plumpness has been found to decrease with later planting dates due to later maturation when soil may be drier and air temperatures are greater (Zubriski et al., 1970; Lauer and Partridge, 1990).

**Seeding Rate**

Seeding rate influences grain quality, but has little effect on yield (McKenzie et al., 2005). High seeding rates (>300 seeds m–2 or >3.0 million seeds ha–1) resulted in reduced grain weight, plumpness, and protein concentration of two-row barley (McKenzie et al., 2005; O’Donovan et al., 2011). However, high seeding rates were associated with increased grain uniformity (O’Donovan et al., 2011). Seeding malting barley at 3.0 million seeds ha–1 was usually optimum to balance grain yield and quality factors (O’Donovan et al., 2011).

**Nitrogen Management**

Nitrogen fertilizer application rate is the most influential agronomic factor controlling both grain yield and quality of malting barley (Reisenauer and Dickson, 1961; Zubriski et al., 1970; Varvel and Severson, 1987; McKenzie et al., 2005; Sainju et al., 2013). Although grain yield increases with N rates (Lauer and Partridge, 1990), for no-till malting barley–pea rotation, a N rate between 40 and 80 kg N ha–1 was recommended for optimum yield and grain quality (Sainju et al., 2013). Nitrogen fertilizer application increases grain protein concentration and decreases kernel plumpness (Zubriski et al., 1970; Pomeranz et al., 1976; Weston et al., 1993; Sainju et al., 2013) (Fig. 3 and 4). Barley grain protein increases with increasing N application rate because barley plants continue to use available N even after yield requirements are met (Batchelder, 1952; Reisenauer and Dickson, 1961; Jackson et al., 1962; Zubriski et al., 1970; Pomeranz et al., 1976; McGuire et al., 1979; Weston et al., 1993; Castro et al., 2008; Sainju et al., 2013).

Although the effect of N application rate on grain protein is consistent, actual grain protein concentration is variable among experiments presented in Fig. 3. For example, with no N fertilizer application, grain protein concentrations have ranged from...
<90 g kg⁻¹ in Oregon to >140 g kg⁻¹ in Idaho (Batchelder, 1952; Pomeranz et al., 1976). This variability has been attributed to differences in soil nitrate N content at planting (Soper and Huang, 1963), especially in dry climates. Stark and Brown (1987) have suggested measuring the amount of soil N just before fertilizer application as N is influenced by the previous fertilizer application, previous year's crop, soil type, soil organic matter, irrigation, and other management practices. When available N (residual soil N plus N fertilizer) exceeded 135 kg N ha⁻¹, the proportion of plump kernels fell below acceptable levels, whereas available N above 210 kg N ha⁻¹ resulted in grain protein levels >120 g kg⁻¹ (Stark and Brown, 2003).

Variability in grain protein concentration may also be an effect of the previous crop with greater residual soil N following a legume crop compared with a non-legume crop (Nedel et al., 1993). Grain protein concentration has also been found to be greater under dryland conditions compared with irrigated (Table 1; Lauer and Partridge, 1990). Furthermore, timing of N application can influence grain protein concentration, with later application increasing grain protein content (Christensen and Killorn, 1981; Petrie et al., 2002).

Split application of N fertilizer also influences grain protein concentration (Christensen and Killorn, 1981; Petrie et al., 2002). In spring barley, 100 kg N ha⁻¹ applied at planting resulted in grain protein of 94 g kg⁻¹, whereas a split application of 100 kg N ha⁻¹ (50 kg N ha⁻¹ applied at planting and 50 kg N ha⁻¹ applied at heading) resulted in grain protein of 100 g kg⁻¹ (Christensen and Killorn, 1981). A split N application applied even later (50 kg N ha⁻¹ applied at planting, 25 kg N ha⁻¹ applied at heading, and 25 kg N ha⁻¹ applied at flowering) resulted in grain protein of 102 g kg⁻¹ (Christensen and Killorn, 1981).

Compared with N, the effect of other nutrients on malting barley yield and quality have been studied less frequently. Barley fertilized with P has been found to mitigate the effect of drought in soil with medium soil test P levels, but not in soils with low soil test P (Jones et al., 2005). In a study conducted in North Dakota, application of 14 and 28 kg K ha⁻¹ increased plumpness in barley by 1.3 and 1.7% on early seeded (planted between late April and mid-May) fields and by 1.8 and 2.7% on late-seeded (planted between mid to late May) fields (Zubriski et al., 1970).
equations give a clear picture of the effects of increasing levels of available soil N on malting barley yield and quality. Researchers in southern Arizona developed tissue NO₃ test guidelines for N management to optimize yield and grain protein for malting barley applicable to irrigated production in this region using data from a field study with two cultivars of malting barley (Thompson et al., 2004). This study also suggested that lower-stem sap NO₃–N in malting barley should not be less than 300, 180, and 120 mg L⁻¹ and dry stem tissue NO₃–N should not be less than 3000, 1000, and 800 mg kg⁻¹ at Feekes growth stages 3, 7, and 10, respectively. In a corn–barley cropping system in a clay loam soil of Colorado, N fertilizer application increased grain yield linearly with increasing N rate with grain protein content of 130 g kg⁻¹ at the highest N rate of 112 kg N ha⁻¹ (Halvorson and Reule, 2007).

**SOUTH AND SOUTHEAST REGIONS**

In 2017, the South and Southeast regions accounted for approximately 1% of the barley production in the United States (USDA-NASS, 2018). Kansas, North Carolina, Oklahoma, Texas, and Virginia produce the majority of the barley in this region. Traditionally, malting barley was not popular in this region. However, the development of local malting facilities and demand for local ingredients by breweries created a market (Neely, 2015). In Texas, there has been a four-fold increase in area planted to barley since 2009 (AMBA, 2015).

In the Southeast (excluding Florida, North Carolina, and Virginia), growth in the brewing industry has been slow over the past 40 yr (Berning and McCullough, 2017). In North Carolina and Virginia, the development of winter malting barley cultivars and increasing local craft brewing industry has resulted in increased interest in growing malting barley (Griffey et al., 2010; Virginia Tech, 2013, 2017, 2018; Hart, 2017). This region lacks peer-reviewed publications on tillage, crop sequence, and seeding rate.
for those seeking a profitable rotational crop (Surjawan et al., 2004).

In 2017, the Upper Midwest, Ohio Valley, and Northeast regions accounted for 8% of the US total barley production (USDA-NASS, 2018). Within these regions, Minnesota, Pennsylvania, Maryland, and Delaware accounted for the majority of barley production. Malting barley produced in the Upper Midwest and Upper Northeast is mostly spring barley, whereas winter malting barley is predominately produced in the Ohio Valley and Lower Northeast. Soil moisture levels are usually non-limiting at seedling establishment in the fall and during grain-filling in the spring, creating favorable conditions for extremely high-quality grain for malting purposes, making this region attractive for growing winter malting barley (Stockinger, 2015). However, limited peer-reviewed publications are available on malting barley from this region. The majority of information is from research reports and extension bulletins.

**Planting Date and Seeding Rate**

Planting date has a significant impact on the development, yield potential, and malting quality of barley. Winter barley is recommended to plant after the Hessian fly (Mayetiola destructor)—safe date (Culman et al., 2018). This date typically falls on the third week of September with an earlier date in the northern region and a later date in the southern region. The Hessian fly—safe date coincides with reduced numbers of adult aphids (Aphis spp.), which can transmit barley yellow dwarf virus to seedlings in the autumn (Paul and Hammond, 2010). Generally, winter barley planted by mid-September and spring barley by 20 May resulted in higher yield and lower grain protein in Michigan (McFarland et al., 2014). A high seeding rate of 5 million seed ha\(^{-1}\) (300 seeds m\(^{-2}\)) on Benson rocky silt loam soil (loamy-skeletal, mixed, active, mesic Lithic Eutrudepts) in Vermont resulted in the best winter survival compared with seeding rates of 3 and 4 million seed ha\(^{-1}\) (300 and 400 seeds m\(^{-2}\)) (Darby et al., 2017). Seeding rate did not influence crude protein, DON, or test weight.

**Cropping Sequence**

In the Upper Midwest, Ohio Valley, and Eastern regions of the United States, there is limited information regarding the effect of crop rotation on malting barley grain yield and quality. One study found growing malting barley after potato (Solanum tuberosum L.), sunflower (Helianthus annuus L.), and sugarbeet (Beta vulgaris L.) to be successful (Peterson and Foster, 1974).

**Nutrient Management**

Studies conducted in Iowa (Atkins et al., 1955), Massachusetts (Wise et al., 2017), Minnesota (Varvel and Severson, 1987), and Vermont (Surjawan et al., 2004) indicated a negative effect of N fertilizer application on malting barley grain and malting quality (Fig. 7). In a silty clay loam soil of Minnesota, grain yield, grain N, and percentage plump kernels were affected by N rate (Varvel and Severson, 1987). However, in the same study, N application method was not a critical factor in N management for malting barley. In Massachusetts, all levels of spring N application (up to 73 kg N ha\(^{-1}\)) to winter barley resulted in grain protein of ≤96 g kg\(^{-1}\) (Wise et al., 2017), well within the acceptable range by malting industry. Although N applied in the fall did not provide measureable benefit, spring N application levels could be increased to improve yield without excessively increasing grain protein (Wise et al., 2017). In a study conducted in a silt loam soil in Iowa, N fertilizer application for maximum yield resulted in an undesirable increase in protein content and a reduction in malt extract (Atkins et al., 1955). Phosphorus fertilizer application improved malting quality by increasing grain weight and malt extract (Atkins et al., 1955).

**RESEARCH OPPORTUNITIES IN THE UPPER MIDWEST, OHIO VALLEY, AND NORTHEAST REGIONS**

Over half of the peer-reviewed publications on the management of malting barley have been from studies conducted in the Northwest and Northern Rockies and Plains (Fig. 8), which has a much different growing environment than the Upper Midwest, Ohio Valley, and Eastern regions of the United States.
There are trial reports, newsletters, fact sheets, and bulletins available on winter barley; however, it is challenging to know if these sources of information are peer-reviewed, research-based, observational, an extension to barley from another crop (i.e., based on winter wheat production), or some combination.

**New Cropping Sequences Should Be Investigated**

Different cropping systems will be employed in varying regions within the United States. Current agronomic crop production in the Upper Midwest, Ohio Valley, and Eastern regions of the United States is dominated by corn, soybean, and wheat. Incorporating malting barley into corn, soybean, and wheat systems has not been examined in the previously conducted research. Due to concerns of FHB, producers in these regions are likely to plant winter malting barley after soybean instead of corn (Culman et al., 2018). The relative maturity (RM) of the previous crop of soybean may need to be shortened to allow for timely planting of winter malting barley. The influence of soybean RM on grain yield will be important for producers to understand.

Furthermore, winter malting barley grown in the Ohio Valley and Lower Northeast (Maryland and Pennsylvania) is harvested approximately 10 d earlier than winter wheat, providing an opportunity for producers to plant double crop soybean after barley harvest (Culman et al., 2018). Early planting of double crop soybeans should promote greater yield as planting date has been found to strongly influence soybean seed yield (Hankinson et al., 2015; Edreira et al., 2017). Producers in these regions are likely to adopt a winter malting barley–double crop soybean cropping sequence to improve profitability by harvesting two cash crops within a year.

Winter malting barley–double crop soybean production is another area that warrants further research efforts, especially in areas where double crop soybean has not been traditionally produced. Delayed planting results in the soybean canopy fully closing later in the growing season, and in some cases, never completely closing (Steele and Grabau, 1997). Full canopy closure is necessary to minimize weed pressure, especially weeds with an extended emergence period, such as Palmer amaranth (*Amaranthus palmeri* (S.) Watson) (Hock et al., 2005; Jha and Norsworthy, 2009). Soybean management practices such as identifying appropriate relative maturity and seeding rates for double crop soybean production in areas that do not traditionally produce double crop soybean is needed. Furthermore, soybean planting date influences insect pest pressure (Hammond et al., 1991; Zeiss and Klubertanz, 1994) and soybean disease (Grau et al., 1994; Broders et al., 2007; Marburger et al., 2016), which is another area of research when information is limited.

**Timely Planting is Challenging Due to Inclement Weather**

Previously conducted research in the Northwest and Northern Rockies and Plains and South and Southeastern regions has shown a grain yield and quality benefit from early planting of spring barley (Stickler and Pauli, 1964; Lauer and Partridge, 1990; Stark, 2003; Franzen and Goos, 2015). However, in the Upper Midwest, Ohio Valley, and Northeast, timely planting in the spring or fall is often challenging due to inclement weather. In these regions, precipitation in the fall and spring has been mostly above average over the past 5 yr compared with the long-term average (NOAA, 2018). Therefore, research on management adjustments (e.g., increasing seeding rate) to mitigate the effects of late planting date in addition to studies on planting date is necessary for these regions. Early planting of winter barley may cause problems. For example, high biomass due to early planting may reduce the tolerance of the crop to harsh winters.

**Soil Test Nitrogen is Unpredictable in Humid Environments**

In the Upper Midwest, Ohio Valley, and Northeast regions there is almost three times more rainfall during the growing season compared with dry environments farther west.
The majority of malting barley production within the United States is in the Northwest and Western Rockies and Plains Region (USDA-NASS, 2018). However, with the rapid increase in operational craft breweries in the Upper Midwest, Ohio Valley, and Northeast (Brewers Association, 2018a), there is a need to expand agronomic research on malting barley in these regions. However, across all regions, planting date and N management were major factors influencing malting barley grain yield and quality. Timely planting of malting barley generally improved yield and quality. Barley yield tended to increase with N application rate whereas quality may decrease due to increased protein concentration. Planting malting barley following corn or small grains resulted in disease problems that could affect grain quality and yield. However, the degree to which these management factors influence grain yield and quality varies among regions due to differences in growing environments.

Based on this review, the top three primary areas of research focus for the Upper Midwest, Ohio Valley, and Northeast include:

1. Cropping sequence: Research on modern corn–soybean rotations with the inclusion of barley is absent from peer-reviewed research articles. Because this is the most common rotation, and the advantages for using winter malting barley in potential double cropping systems, it is critical multiple rotations be evaluated on barley production.
2. Planting date and seeding rate: Impact on grain yield and protein content, plumpness, and winter hardiness.
3. Nutrient management: Alternative nutrient management with respect to rainfall pattern of the region, malting barley grain yield and quality, N cycling and dynamics, and effect of soybean double crop on N dynamics.

**REFERENCES**


