

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

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Abbreviations: DON, deoxynivalenol; FHB, Fusarium head blight; RM, relative maturity.

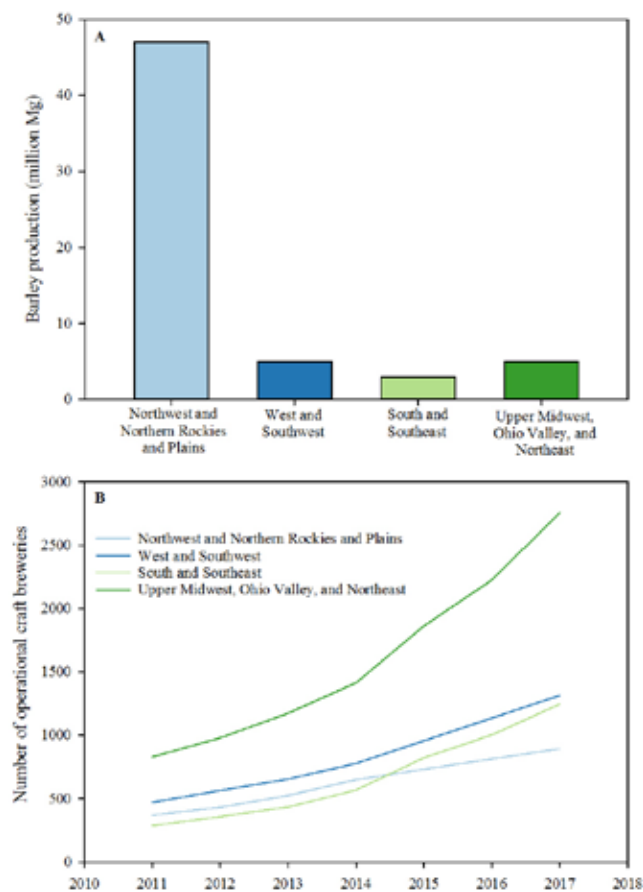


Fig. 1. Barley production according to the most recent USDA census, which was conducted in 2012 (USDA NASS, 2018) (A), and number of operational craft breweries from 2011 through 2017 (B) (Brewers Association, 2018b). (Note: The USDA does not distinguish between barley for feed and malt production.)

(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 ($\geq 95\%$), low protein ($\leq 125 \text{ g kg}^{-1}$ on a dry-weight basis), high plumpness ($>900 \text{ g kg}^{-1}$ and $>800 \text{ g kg}^{-1}$ retention on a 2.38-mm slotted screen for two-row barley and six-row barley, respectively), low deoxynivalenol (DON) levels ($<1 \text{ mg kg}^{-1}$), 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 $>60 \text{ kg ha}^{-1}$. 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

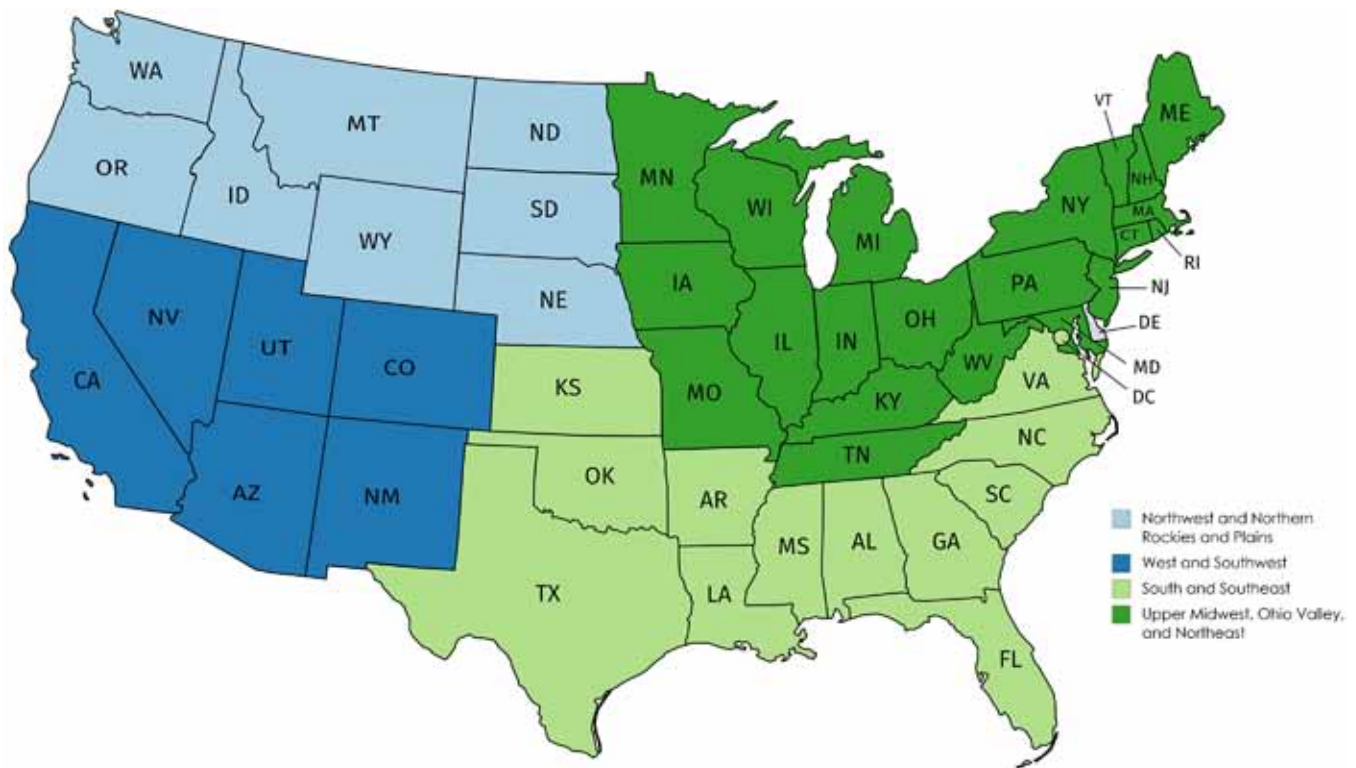


Fig. 2. Four regions within the contiguous United States discussed in this review article (modified from Karl and Koss, 1984).

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

Table 1. Effect of planting date on grain quality and yield of spring malting barley grown in the US Northwest and Northern Rockies and Plains regions.

State	Planting date	Grain protein	Grain plumpness	Grain yield	Reference
		g kg ⁻¹		Mg ha ⁻¹	
North Dakota	Late Apr.–mid-May	131	758	2.91	Zubriski et al., 1970
	Mid-May–late May	138	660	2.62	
North Dakota	25 Apr.–4 May	115	510	3.3	Weston et al., 1993
	16–22 May	126	422	2.3	
Oregon	31 Mar. (0 N)†	109	–‡	0.87	Jackson et al., 1962
	28 Apr. (0 N)	120	–	0.53	
	31 Mar. (45 N)	104	–	2.30	
	28 Apr. (45 N)	116	–	1.57	
	31 Mar. (90 N)	120	–	2.59	
	28 Apr. (90 N)	136	–	1.90	
	31 Mar. (135 N)	143	–	2.35	
	28 Apr. (135 N)	153	–	1.68	
Wyoming, irrigated	15–21 Apr.	115	976	4.75	Lauer and Partridge, 1990
	3–7 May	112	961	4.20	
	17–22 May	110	952	3.96	
Wyoming, dryland	15–21 Apr.	122	979	4.40	
	3–7 May	131	985	3.63	
	17–22 May	133	948	2.85	

† Nitrogen application rate (kg N ha⁻¹) indicated in parenthesis.

‡ Not measured.

<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).

WEST AND SOUTHWEST REGIONS

In 2017, the West and Southwest regions accounted for about 10% of the US total barley production (USDA-NASS, 2018). South central Colorado (primarily irrigated), the central valley (primarily irrigated) and south central coastal (primarily rainfed) areas of California, irrigated desert regions of Arizona, northwestern Nevada, and Utah produce the majority of barley (Davison et al., 2001; IPM Centers, 2002; Curtis and Bishop, 2008). Fall-planted six-row spring barley is common and grown primarily as a feed grain. Barley production in California is primarily of fall-planted 6-row feed barley grown in the Sacramento Valley, San Joaquin Valley, and coastal area (Jackson, 2011).

Spring-planted 2-row malting barley is grown in the Tulelake Basin and the intermountain valley of central and northern California (Puri et al., 1977; University of California, 2008; Jackson, 2011). Recently, the craft-scale malting industry has been growing in California (Bustamante, 2017). In northwestern Nevada, two-row spring malting barley is planted in early April where yields have been exceptionally high (9–10 Mg ha⁻¹) (Davison et al., 2001; Curtis and Bishop, 2008). This region lacks published research-based recommendations on tillage, planting date, seeding rate, and crop rotation.

Nutrient Management

Studies conducted in Colorado and Arizona have shown negative effects of N application above 100 kg ha⁻¹ on malting quality of barley (Fig. 5). Geist et al. (1970) developed a mathematical model to predict the N fertilizer requirements of malting barley utilizing both mineral and organic soil N. These prediction

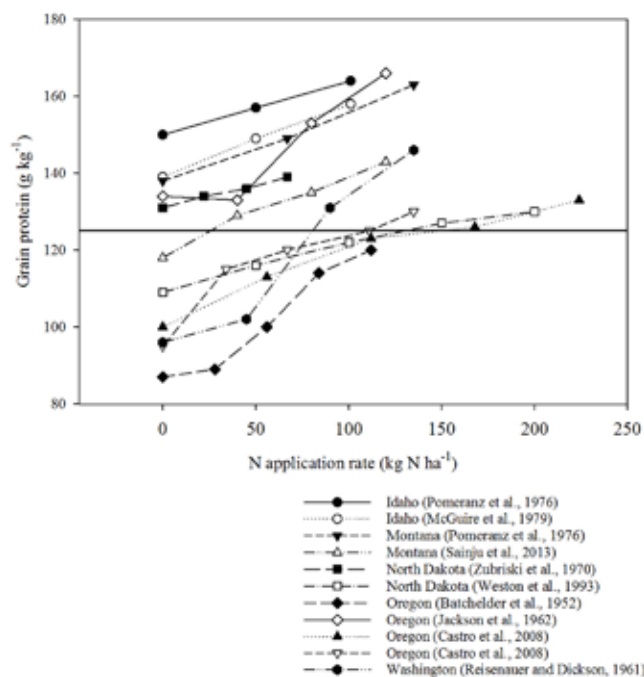


Fig. 3. Influence of N application rate on grain protein concentration by experiment conducted in the US Northwest and Northern Rockies and Plains regions. Grain protein content of $<125 \text{ g kg}^{-1}$ is desirable for malting (indicated by the horizontal line).

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 NO_3^- 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 NO_3^- -N in malting barley should not be less than 300, 180, and 120 mg L^{-1} and dry stem tissue NO_3^- -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.

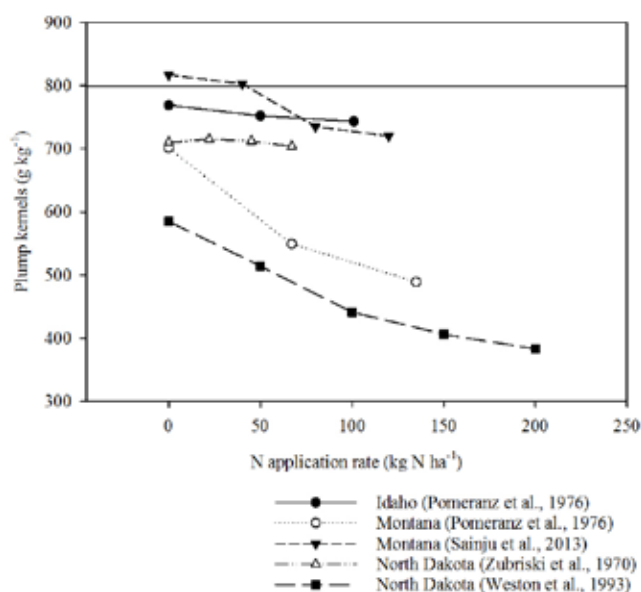


Fig. 4. Influence of N application rate on kernel plumpness by experiment conducted in the Northwest and Northern Rockies and Plains regions. For six-row barley, kernel retention should be $>800 \text{ g kg}^{-1}$ on a 2.38-mm slotted screen (indicated by the horizontal line).

Planting Date

Winter barley can be planted in this region from September through November (Jacobs, 2016). The level of winter hardiness was slightly higher when barley was planted 15 October compared with 1 October, but highest grain yield was achieved by planting 1 October (Stickler and Pauli, 1964). The effect of planting date on grain quality parameters is not available in the published literature.

Nutrient Management

Application of 112 kg N ha^{-1} maximized barley grain yield in Virginia (Thomason et al., 2012). Similar to other regions, studies conducted in Oklahoma (Keim, 1975) and Virginia (Thomason et al., 2012) have shown a negative effect of N fertilizer on barley grain and malting quality (Fig. 6). In Virginia, grain protein increased by 24% with N applied at a rate of 156 kg N ha^{-1} compared with a non-treated control (Thomason et al., 2012). In same study, grain protein also increased with late application of N fertilizer. The foliar application of potassium phosphate (KH_2PO_4) fertilizer at a rate of 4 kg K ha^{-1} and 6 kg P ha^{-1} at Feekes 4 to 5 growth stage did not influence grain protein (Thomason et al., 2012).

UPPER MIDWEST, OHIO VALLEY, AND NORTHEAST REGIONS

During the past few years, there has been an increase in the number of operational craft breweries in the Upper Midwest, Ohio Valley, and Northeast (Brewers Association, 2018a) (Fig. 1B). In 2017, there were more than 1100 operational craft breweries in Michigan, New York, Ohio, and Pennsylvania (Brewers Association, 2018a). Additionally, several new malting houses have been established and production capacity of existing malt houses has increased driven by demand for local brewing and distilling ingredients and supporting legislation for local foods (Darby, 2015; Hmielowski, 2017). Furthermore, for producers, malting barley provides a new source of revenue

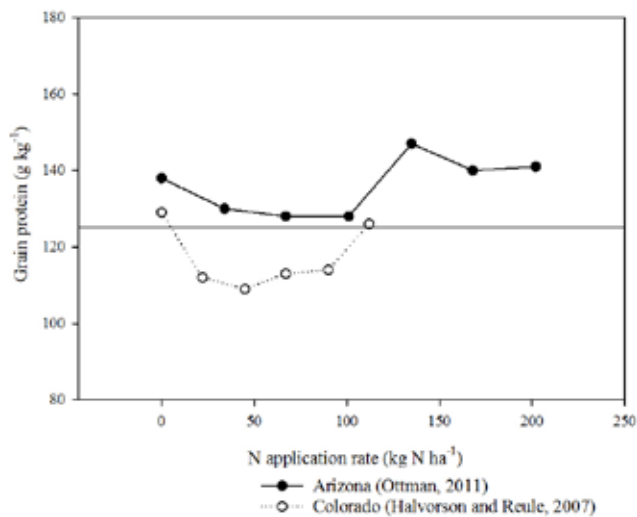


Fig. 5. Influence of N application rate on grain protein by experiment conducted in the West and Southwest regions. Grain protein content of $<125 \text{ g kg}^{-1}$ is desirable for malting (indicated by the horizontal line).

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.

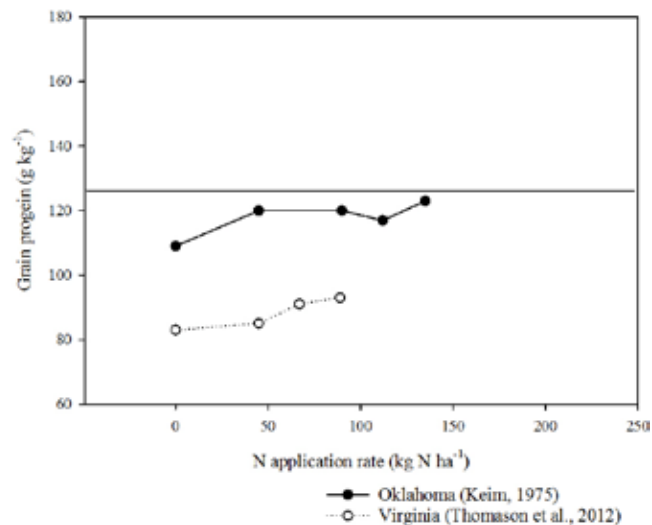


Fig. 6. Influence of N application rate on grain protein by experiment conducted in the US South and Southeast regions. Grain protein content of $<125 \text{ g kg}^{-1}$ is desirable for malting (indicated by the horizontal line).

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 $\leq 96 \text{ g kg}^{-1}$ (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.

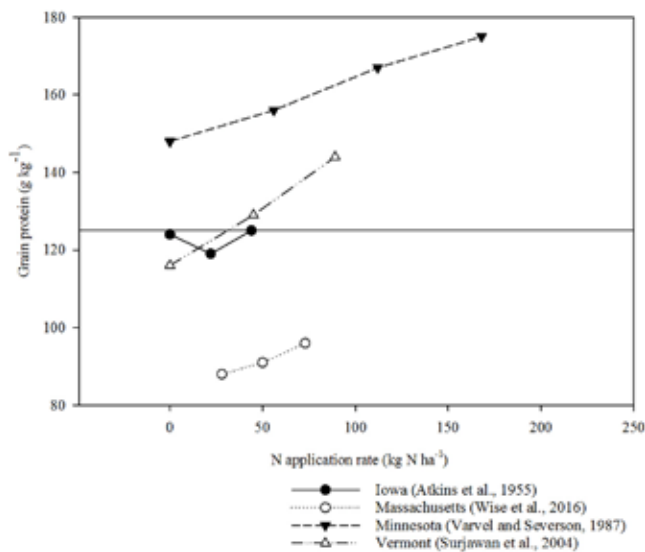


Fig. 7. Influence of N application rate on grain protein by experiment conducted in the US Upper Midwest, Ohio Valley, and Northeast regions.

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 soybean 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 future 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

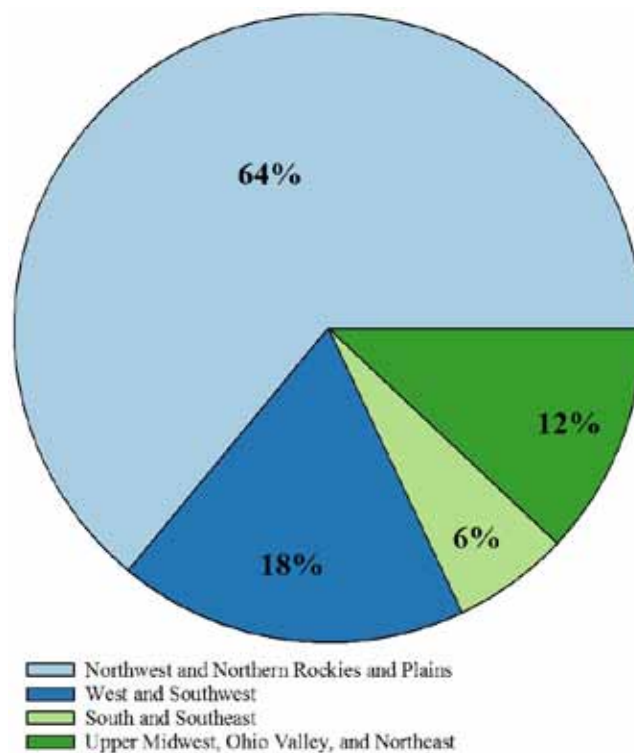


Fig. 8. Peer-reviewed publications on the effects of agronomic management on malting barley by region within the United States.

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

(NCDC-NOAA, 2018). In the Northwest and Northern Rockies and Plains, soil test N has been used to adjust N fertilizer application rates (Soper and Huang, 1963; Stark and Brown, 2003). However, the soil test N is unpredictable and usually low in humid environments such as the Upper Midwest, Ohio Valley, and Northeast (Ma et al., 2005; Bast et al., 2012). In humid environments, N is subject to loss through leaching and denitrification (Mahler and Guy, 2007; Gu and Riley, 2010; McVay et al., 2017), and soil N supply is dominated by in-season mineralization (St. Luce et al., 2011). Nitrogen fertilizer application based on soil mineral N content is unreliable in humid regions (Ma et al., 2005; Bast et al., 2012). In the Upper Midwest, Ohio Valley, and Northeast, future research should be aimed at making N application rate recommendations without the use of soil test N, potentially including optical sensor methods (Franzen et al., 2016), chlorophyll meters (Wienhold and Krupinsky, 1999), or economic return models (Sawyer et al., 2006). The optical sensor method can reliably determine N status by measuring chlorophyll content and establishing yield potential prediction equations, providing guideline for mid-season N-fertilization, increasing N use efficiency, and maintaining grain yield and quality (Raun et al., 2005; Samborski et al., 2009). Chlorophyll meter detects the onset of N stress before it is visible to the human eye, and early enough to correct N deficiency without sacrificing yields (Shapiro et al., 2013). Chlorophyll meter measures the amount of chlorophyll that is a function of the amount of chlorophyll in a leaf, and the amount of near-infrared light (940 nm) transmitted, which is an internal reference to compensate for leaf thickness and moisture content (Schröder et al., 2000).

CONCLUSION

The majority of malting barley production within the United States is in the Northwest and Northern 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 influences 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

- Agehara, S., and D.D. Warncke. 2005. Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. *Soil Sci. Soc. Am. J.* 69:1844–1855. doi:10.2136/sssaj2004.0361
- AMBA (American Malting Barley Association). 2015. 2015 Research grant program executive summaries. AMBA, Milwaukee, WI. http://ambainc.org/media/AMBA_PDFs/News/AMBA_2015_Grant_Summaries.pdf (accessed 3 Dec. 2018).
- Atkins, R.E., G. Stanford, and L. Dumenil. 1955. Plant nutrition effects, effects of nitrogen and phosphorus fertilizer on yield and malting quality of barley. *J. Agric. Food Chem.* 3:609–615. doi:10.1021/jf60053a007
- Bamforth, C.W., and A.H.P. Barclay. 1993. Malting technology and the uses of malt In: A.W. MacGregor and R.S. Bhatti, editors, *Barley chemistry and technology*. Am. Assoc. of Cereal Chemists, St. Paul, MN. p. 297–354.
- Bast, L.E., R.W. Mullen, D.J. Eckert, and P.R. Thomison. 2012. Evaluation of the pre-sidedress soil nitrate test in Ohio. *Crop Manag.* 11. doi:10.1094/CM-2012-0409-01-RS
- Batchelder, F.C. 1952. Effect of different nitrogen fertilizer treatments on malting quality of Hannchen barley. M.S. thesis. Oregon State Univ., Corvallis.
- Berning, J., and M.P. McCullough. 2017. The US brewing industry from farm to pint. *Choices* 32:1–7 <https://www.jstor.org/stable/90015010> (accessed 1 Dec. 2018).
- Bettenhausen, H.M., L. Barr, C.D. Broeckling, J.M. Chaparro, C. Holbrook, D. Sedin, and A.L. Heuberger. 2018. Influence of malt source on beer chemistry, flavor, and flavor stability. *Food Res. Int.* 113:487–504. doi:10.1016/j.foodres.2018.07.024
- Brewers Association. 2018a. Malting barley characteristics. *Brewers Assoc.*, Boulder, CO. <https://www.brewersassociation.org/best-practices/malt/malting-barley-characteristics> (accessed 14 Nov. 2018).
- Brewers Association. 2018b. State craft beer sales and production statistics, 2017. *Brewers Assoc.*, Boulder, CO. <https://www.brewersassociation.org/statistics/by-state> (accessed 1 Aug. 2018).
- Broders, K.D., P.E. Lipps, P.A. Paul, and A.E. Dorrance. 2007. Characterization of *Pythium* spp. associated with corn and soybean seed and seedling disease in Ohio. *Plant Dis.* 91:727–735. doi:10.1094/PDIS-91-6-0727
- Bundy, L.G., T.W. Andraski, and R.P. Wolkowski. 1993. Nitrogen credits in soybean-corn crop sequences on three soils. *Agron. J.* 85:1061–1067. doi:10.2134/agronj1993.00021962008500050020x
- Buschena, D., R.S. Gray, and E. Severson. 1998. Changing structures in the barley production and malting industries of the United States and Canada. *Policy Issues Pap.* 8. Montana State Univ., Bozeman. <https://ageconsearch.umn.edu/record/29168/files/pip08.pdf> (accessed 1 Dec. 2018).
- Bustamante, L. 2017. Admiral maltings germinates California alt malt in Alameda. *San Francisco Chronicle*, 7 July 2017. <http://www.sfchronicle.com/restaurants/article/Admiral-Maltings-germinates-California-altmalt-11273732.php> (accessed 14 Oct. 2018).
- Carr, P.M., R.D. Horsley, G.B. Martin, and M.R. Hochhalter. 2014. Malt barley cultivar ranking under long-term tillage systems in a semiarid region. *Agron. J.* 106:2067–2074. doi:10.2134/agronj14.0316
- Castro, A., S. Petrie, A. Budde, A. Corey, P. Hayes, J. Kling, and K. Rhinhart. 2008. Variety and N management effects on grain yield and quality of winter barley. *Crop Manag.* 7. doi:10.1094/CM-2008-1125-01-RS
- Christensen, N.W., and R.J. Killorn. 1981. Wheat and barley growth and N fertilizer utilization under sprinkler irrigation. *Agron. J.* 73:307–312. doi:10.2134/agronj1981.00021962007300020015x

- Culman, S., L. Lindsey, M. Loux, P. Paul, and E. Stockinger. 2018. Management of Ohio winter malting barley. The Ohio State Univ., Columbus. <https://stepupsoy.osu.edu/sites/hcs-soy/files/malting%20barley%20spring%202018%20final.pdf> (accessed 1 Nov. 2018).
- Curtis, K.R., and C. Bishop. 2008. Northern Nevada two row malt barley production cost and returns, 2008. Spec. Publ. 08-08. Univ. of Nevada, Reno. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.579.7565&rep=rep1&type=pdf> (accessed 1 Dec. 2018).
- Darby, H. 2015. 2015 Research grant program executive summaries. AMBA, Milwaukee, WI. http://ambainc.org/media/AMBA_PDFs/News/AMBA_2015_Grant_Summaries.pdf (accessed 1 July 2018).
- Darby, H., E. Hillary, and E. Cummings. 2017. 2016 Winter barley seeding rate, cover crop and variety trial. Univ. of Vermont, Burlington. <http://www.uvm.edu/extension/crops/soil/wp-content/uploads/2016-Winter-Barley-SRxCcXVar-Report.pdf> (accessed 1 July 2018).
- Davison, J., B. Schultz, and A. Widaman. 2001. Malting barley in Nevada. Fact Sheet FS-01-47. Univ. of Nevada, Reno. <https://www.unce.unr.edu/publications/files/ag/2001/fs0147.pdf> (accessed 1 Dec. 2018).
- Doncheck, J.A. 2000. Malts and malting. Kirk-Othmer encyclopedia of chemical technology. doi:10.1002/0471238961.1301122004151403.a01
- Edreira, J.I.R., S. Mourtzinis, S.P. Conley, A.C. Roth, I.A. Ciampitti, M.A. Licht, H. Kandel, P.M. Kyveryga, L.E. Lindsey, D.S. Mueller, S.L. Naeve, E. Nafziger, J.E. Specht, J. Stanley, M.J. Staton, and P. Grassini. 2017. Assessing causes of yield gaps in agricultural areas with diversity in climate and soils. *Agric. For. Meteorol.* 247:170–180. doi:10.1016/j.agrformet.2017.07.010
- Fedak, G., and A.R. Mack. 1977. Influence of soil moisture levels and planting dates on yield and chemical fractions in two barley cultivars. *Can. J. Plant Sci.* 57:261–267. doi:10.4141/cjps77-036
- Franzen, D., N. Kitchen, K. Holland, J. Schepers, and W. Raun. 2016. Algorithms for in-season nutrient management in cereals. *Agron. J.* 108:1775–1781. doi:10.2134/agronj2016.01.0041
- Franzen, D.W., and R.J. Goos. 2007. Fertilizing malting and feed barley. Ext. Bull. SF-723. North Dakota State Univ., Fargo. <https://library.ndsu.edu/ir/bitstream/handle/10365/5439/sf723.pdf?sequence=1> (accessed 1 July 2018).
- Franzen, D.W., and R.J. Goos. 2015. Fertilizing malting and feed barley. Ext. Bull. SF-723 (revised). North Dakota State Univ., Fargo. <https://www.ag.ndsu.edu/crops/barley-articles/fertilizing-barley-sf723-2015> (accessed 1 Dec. 2018).
- Geist, J.M., J.O. Reuss, and D.D. Johnson. 1970. Prediction of nitrogen fertilizer requirements of field crops. II. Application of theoretical models to malting barley. *Agron. J.* 62:385–389. doi:10.2134/agronj1970.00021962006200030023x
- Grau, C.R., E.S. Oplinger, E.A. Adee, E.A. Hinkens, and M.J. Martinka. 1994. Planting date and row width effect on severity of brown stem rot and soybean productivity. *J. Prod. Agric.* 7:347–351. doi:10.2134/jpa1994.0347
- Griffey, C., W. Brooks, M. Kurantz, W. Thomason, F. Taylor, D. Obert, R. Moreau, R. Flores, M. Sohn, and K. Hicks. 2010. Grain composition of Virginia winter barley and implications for use in feed, food, and biofuels production. *J. Cereal Sci.* 51:41–49. doi:10.1016/j.jcs.2009.09.004
- Gu, C., and W.J. Riley. 2010. Combined effects of short-term rainfall patterns and soil texture on soil nitrogen cycling: A modeling analysis. *J. Contam. Hydrol.* 112:141–154. doi:10.1016/j.jconhyd.2009.12.003
- Halvorson, A.D., and C.A. Reule. 2007. Irrigated, no-till corn and barley response to nitrogen in northern Colorado. *Agron. J.* 99:1521–1529. doi:10.2134/agronj2006.0356
- Hammond, R.B., R.A. Higgins, T.P. Mack, L.P. Pedigo, and E.J. Bechinski. 1991. Soybean pest management. In: D. Pimentel, editor, CRC handbook of pest management in agriculture. Vol. 3, 2nd ed. CRC, Boca Raton, FL. p. 341–472.
- Hankinson, M.W., L.E. Lindsey, and S.W. Culman. 2015. Effect of planting date and starter fertilizer on soybean grain yield. *Crop Forage Turfgrass Manage.* 1:1–6. doi:10.2134/cftm2015.0178
- Hart, J. 2017. Growing malting barley pays a premium but demands a lot more care. Southeast Farm Press. 8 June 2017. <https://www.southeastfarmpress.com/crops/growing-malting-barley-pays-premium-demands-lot-more-care> (accessed 1 Dec. 2018).
- Henry, D.C., R.W. Mullen, C.E. Dygert, K.A. Diedrick, and A. Sundermeier. 2010. Nitrogen contribution from red clover for corn following wheat in western Ohio. *Agron. J.* 102:210–215. doi:10.2134/agronj2009.0187
- Hertrich, J. 2013. Topics in brewing: Malting barley. *Tech. Q. Master Brew. Assoc. Am.* 50:29–41.
- Hmielowski, T. 2017. From field to pint: Malting barley in the eastern U.S. *Crops and Soils* 50:10–13. doi:10.2134/cs2017.50.0504
- Hock, S.M., S.Z. Knezevic, A.R. Martin, and J.L. Lindquist. 2005. Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. *Weed Sci.* 54:38–46. doi:10.1614/WS-05-011R.1
- Horsley, R.D., J.D. Franckowiak, and P.B. Schwarz. 2009. Barley. In: M.J. Carena, editor, Handbook of plant breeding: Cereals. Springer Science, Heidelberg, New York. p. 227–250.
- IPM Centers. 2002. Crop profile for barley in Colorado. Southern IPM Center, USDA, Raleigh, NC. <https://ipmdata.ipmcenters.org/documents/cropprofiles/CObarley.pdf> (accessed 1 July 2018).
- Jackson, L. 2011. Characteristics of barley cultivars grown in California. Univ. of California, Davis. https://smallgrains.ucdavis.edu/cereal_files/CvCharsLee11Barley.pdf (accessed 1 July 2018).
- Jackson, T.L., W.H. Foote, and E.A. Dickason. 1962. Effect of fertilizer treatments and planting dates on yield and quality of barley. *Tech. Bull.* 65. Agric. Exp. Stn., Oregon State Univ., Corvallis. <https://ir.library.oregonstate.edu/downloads/0r967499z> (accessed 1 July 2018).
- Jacobs, A.A. 2016. Plant guide for common barley (*Hordeum vulgare* L.). USDA-Natural Resources Conservation Service, Coffeerville, MS.
- Jha, P., and J.K. Norsworthy. 2009. Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a nature seed bank. *Weed Sci.* 57:644–651. doi:10.1614/WS-09-074.1
- Jones, C.A., J.S. Jacobsen, and J.M. Wraith. 2005. Response of malt barley to phosphorus fertilization under drought conditions. *J. Plant Nutr.* 28:1605–1617. doi:10.1080/01904160500203531
- Karl, T.R., and W.J. Koss. 1984. Regional and national monthly, seasonal, and annual temperature weighted by area, 1895–1983. Historical Climatology Series 4-3. National Climatic Data Center, Asheville, NC.
- Keim, K.R. 1975. The effects of nitrogen fertilization on yield and malting quality of a winter malting barley grown in Oklahoma. M.S. thesis. Oklahoma State Univ., Stillwater. <https://shareok.org/bitstream/handle/11244/20054/Thesis-1975K27e.pdf?sequence=1&isAllowed=y> (accessed 1 Dec. 2018).
- Kendall, N.T. 1994. Barley and malt. In: W.A. Hardwick, editor, Handbook of brewing. Marcel Dekker, New York. p. 109–120.
- Lauer, J.G., and J.R. Partridge. 1990. Planting date and nitrogen rate effects on spring malting barley. *Agron. J.* 82:1083–1088. doi:10.2134/agronj1990.00021962008200060011x
- Ma, B.L., K.D. Subedi, and C. Costa. 2005. Comparison of crop-based indicators with soil nitrate test for corn nitrogen requirement. *Agron. J.* 97:462–471. doi:10.2134/agronj2005.0462

- Machado, S., S. Petrie, K. Rhinhart, and A. Qu. 2007. Long-term continuous cropping in the Pacific Northwest: Tillage and fertilizer effects on winter wheat, spring wheat, and spring barley production. *Soil Tillage Res.* 94:473–481. doi:10.1016/j.still.2006.09.007
- Mahler, R.L., and S.O. Guy. 2007. Northern Idaho fertilizer guide: Winter barley. CIS 954. Univ. of Idaho, Moscow. www.extension.uidaho.edu/publishing/pdf/CIS/CIS0954.pdf (accessed 1 Dec. 2018).
- Marburger, D.A., D.L. Smith, and S.P. Conley. 2016. Revisiting planting date and cultivar effects on soybean sudden death syndrome development and yield loss. *Plant Dis.* 100:2152–2157. doi:10.1094/PDIS-12-15-1411-RE
- McFarland, A., C. Kapp, R. Freed, J. Isleib, and S. Graham. 2014. Malting barley production in Michigan. Ext. Bull. GMI-035. Michigan State Univ., East Lansing. https://www.canr.msu.edu/uploads/396/36753/Research_Files/Malting_Barley_Production_in_Michigan_-_GMI035.pdf (accessed 1 Dec. 2018).
- McGuire, C.F., E.A. Hockett, and D.M. Wesenberg. 1979. Response of agronomic and barley quality traits to nitrogen fertilizer. *Can. J. Plant Sci.* 59:831–837. doi:10.4141/cjps79-125
- McKenzie, R.H., A.B. Middleton, and E. Bremer. 2005. Fertilization, seeding date, and seeding rate for malting barley yield and quality in southern Alberta. *Can. J. Plant Sci.* 85:603–614. doi:10.4141/P04-152
- McVay, K., M. Burrows, C. Jones, K. Wanner, and F. Menalled. 2017. Montana barley production guide. EB0186. Montana State Univ., Bozeman. http://msuextension.org/publications/AgandNaturalResources/EB0186.pdf (accessed 1 Dec. 2018).
- NCDC-NOAA. 2018. Climate data. National Climatic Data Center, U.S. Department of Commerce, Washington, DC. https://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp (accessed 28 Sept. 2018).
- Nedel, J.L., S.E. Ullrich, J.A. Clancy, and W.L. Pan. 1993. Barley semi-dwarf and standard isotype yield and malting quality response to nitrogen. *Crop Sci.* 33:258–263. doi:10.2135/cropsci1993.0011183X003300020008x
- Neely, C. 2015. Malting barley production in Texas. In: American Malting Barley Association, 2015 Research Grant Program Executive Summaries. AMBA, Milwaukee, WI. p. 9–10. http://ambainc.org/media/AMBA_PDFs/News/AMBA_2015_Grant_Summaries.pdf (accessed 1 Dec. 2018).
- NOAA. 2018. National temperature and precipitation maps. NOAA, National Centers for Environmental Information, Asheville, NC. https://www.ncdc.noaa.gov/temp-and-precip/us-maps/1/201605?products[]=statewidepcprank#us-maps-select (accessed 3 Dec. 2018).
- O'Donovan, J.T., C.A. Grant, R.E. Blackshaw, K.N. Harker, E.N. Johnson, Y. Gan, G.P. Lafond, W.E. May, T.K. Turkington, N.Z. Lupwayi, F.C. Stevenson, D.L. McLaren, M. Khakbazan, and E.G. Smith. 2014. Rotational effects of legumes and non-legumes on hybrid canola and malting barley. *Agron. J.* 106:1921–1932. doi:10.2134/agronj14.0236
- O'Donovan, J.T., M.S. Izydorczyk, B. Tidemann, M.J. Edney, T.K. Turkington, C.A. Grant, K.N. Harker, and Y. Gan. 2017. Effect of preceding crop and nitrogen application on malting barley quality. *Can. J. Plant Sci.* 97:1014–1023.
- O'Donovan, J.T., T.K. Turkington, M.J. Edney, G.W. Clayton, R.H. McKenzie, P.E. Juskiw, G.P. Lafond, C.A. Grant, S. Brandt, K.N. Harker, E.N. Johnson, and W.E. May. 2011. Seeding rate, nitrogen rate, and cultivar effects on malting barley production. *Agron. J.* 103:709–716. doi:10.2134/agronj2010.0490
- Paul, P., and R. Hammond. 2010. The Hessian fly-safe date is not only about Hessian fly. *Ohio's County Journal*, Columbus, OH. 24 Sept. 2010. http://ocj.com/2010/09/the-hessian-fly-safe-date-is-not-only-about-hessian-fly (accessed 1 Dec. 2018).
- Peterson, G.A., and A.E. Foster. 1974. Malting barley in the United States. *Adv. Agron.* 25:327–378. doi:10.1016/S0065-2113(08)60784-1
- Petrie, S., P. Hayes, J. Kling, K. Rinehart, and A. Corey. 2002. Nitrogen management for winter malting barley. In: 2002 Columbia Basin Agricultural Research Center Annual Report. Spec. Rep. 1040. Columbia Basin Agricultural Research Center, Pendleton, OR. p. 30–36. http://library.state.or.us/repository/2012/201204091557431/2002.pdf#page=35 (accessed 1 Nov. 2018).
- Poehlman, J.M. 1985. Adaptation and distribution. In: D.C. Rasmusson, editor, *Barley*. Agron. Monogr. 26. ASA, CSSA, SSSA, Madison, WI. p. 1–17. doi:10.2134/agronmonogr26.c1
- Pomeranz, Y., N.N. Standridge, E.A. Hockett, D.M. Wesenberg, and G.D. Booth. 1976. Effects of nitrogen fertilizer on malting quality of widely varying barley cultivars. *Cereal Chem.* 53:574–585.
- Puri, Y., K. Baghott, and J. Prato. 1977. Wheat and barley response to nitrogen. *Calif. Agric.* 31:10–11.
- Raun, W.R., J.B. Solie, M.L. Stone, K.L. Martin, K.W. Freeman, R.W. Mullen, H. Zhang, J.S. Schepers, and G.V. Johnson. 2005. Optical sensor based algorithm for crop nitrogen fertilization. *Commun. Soil Sci. Plant Anal.* 36:2759–2781. doi:10.1080/00103620500303988
- Reisenauer, H.M., and A.D. Dickson. 1961. Effects of nitrogen and sulfur fertilization on yield and malting quality of barley. *Agron. J.* 53:192–195. doi:10.2134/agronj1961.00021962005300030020x
- Robertson, L.D., and J.C. Stark, editors. 2003. Idaho spring barley production guide. Bull. 742. Univ. of Idaho, Moscow.
- Robertson, L.D., and D.M. Wesenberg. 2003. Major uses of barley. In: LD. Robertson and J.C. Stark, editors, Idaho spring barley production guide. Bull. 742. Univ. of Idaho, Moscow.
- Sainju, U.M., A.W. Lenssen, and J.L. Barsotti. 2013. Dryland malt barley yield and quality affected by tillage, cropping sequence, and nitrogen fertilization. *Agron. J.* 105:329–340.
- Samborski, S.M., N. Tremblay, and E. Fallon. 2009. Strategies to make use of plant sensors-based diagnostic information for nitrogen recommendations. *Agron. J.* 101:800–816. doi:10.2134/agronj2008.0162Rx
- Sawyer, J., E. Nafziger, G. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. Concepts and rationale for regional nitrogen rate guidelines for corn. PM 2015. Iowa State Univ., Ames.
- Schröder, J.J., J.J. Neeteson, O. Enema, and P.C. Struik. 2000. Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. *Field Crops Res.* 66:151–164. doi:10.1016/S0378-4290(00)00072-1
- Schwarz, P., and R. Horsley. 2019. A comparison of north American two-row and six-rows malting barley. ProBrewer. https://www.probrewer.com/library/malt/a-comparison-of-north-american-two-row-and-six-row-malting-barley (accessed 22 Jan. 2019).
- Shapiro, C.A., D.D. Francis, R.B. Ferguson, G.W. Hergert, T.M. Shaver, and C.S. Wortmann. 2013. Using chlorophyll meter to improve N management. NebGuide G1632. Univ. of Nebraska, Lincoln. http://extensionpublications.unl.edu/assets/pdf/g1632.pdf (accessed 1 Dec. 2018).
- Soper, R.J., and P.M. Huang. 1963. The effect of nitrate nitrogen in the soil profile on the response of barley to fertilizer nitrogen. *Can. J. Soil Sci.* 43:350–358. doi:10.4141/cjss63-041
- St. Luce, M., J.K. Whalen, N. Ziadi, and B.J. Zebarth. 2011. Nitrogen dynamics and indices to predict soil nitrogen supply in humid temperate soils. *Adv. Agron.* 112:55–102. doi:10.1016/B978-0-12-385538-1.00002-0
- Stark, J.C. 2003. Seeding practices. In: LD. Robertson and J.C. Stark, editors, Idaho spring barley production guide. Bull. 742. Univ. of Idaho, Moscow. p. 15–16.
- Stark, J.C., and B.D. Brown. 1987. Estimating nitrogen requirements for irrigated malting barley. *Commun. Soil Sci. Plant Anal.* 18:433–444. doi:10.1080/00103628709367831

- Stark, J.C., and B.D. Brown. 2003. Nutrient management. In: L.D. Robertson and J.C. Stark, editors, Idaho spring barley production guide. Bull. 742. Univ. of Idaho, Moscow. p. 22–26.
- Steele, C.C., and L.J. Grabau. 1997. Planting date for early-maturing soybean cultivars. *Agron. J.* 89:449–453. doi:10.2134/agronj1997.00021962008900030013x
- Stevens, W.B., U.M. Sainju, T. Caesar-TonThat, and W.M. Iversen. 2015. Malt barley yield and quality affected by irrigation, tillage, crop rotation, and nitrogen fertilization. *Agron. J.* 107:2107–2119. doi:10.2134/agronj15.0027
- Stickler, F.C., and A.W. Pauli. 1964. Yield and winter survival of winter barley varieties as affected by date and rate of planting. *Crop Sci.* 4:487–489. doi:10.2135/cropsci1964.0011183X000400050015x
- Stockinger, E.J. 2015. Practical considerations for growing malting-quality barley in Ohio. Stockinger Lab, The Ohio State Univ., Wooster OH. <https://stockingerlab.osu.edu/malting-barley-resources> (accessed 4 Sept. 2018).
- Surjawan, I., M.P. Dougherty, M.E. Camire, and J.J. Jemison. 2004. MR433: Malting quality of Maine-grown barley. Misc. Rep. 433. The Maine Agricultural and Forest Experiment Station, Univ. of Maine, Orono. https://digitalcommons.library.umaine.edu/cgi/viewcontent.cgi?article=1009&context=aes_ (accessed 1 Jan. 2018).
- Therrien, M.C., C.A. Carmichael, J.S. Noll, and C.A. Grant. 1994. Effect of fertilizer management, genotype, and environmental factors on some malting quality characteristics in barley. *Can. J. Plant Sci.* 74:545–547. doi:10.4141/cjps94-098
- Thomason, W.E., S.B. Phillips, J.A. Warren, and M.M. Alley. 2012. Winter hulless barley response to nitrogen rate and timing and foliar phosphorus. *J. Plant Nutr.* 35:225–234. doi:10.1080/01904167.2012.636125
- Thompson, T.L., M.J. Ottman, and E. Riley-Saxton. 2004. Basal stem nitrate tests for irrigated malting barley. *Agron. J.* 96:516–524. doi:10.2134/agronj2004.5160
- Turkington, T.K., J.T. O'Donovan, M.J. Edney, P.E. Juskiw, R.H. McKenzie, K.N. Harker, G.W. Clayton, K. Xi, G.P. Lafond, R.B. Irvine, S. Brandt, E.N. Johnson, W.E. May, and E. Smith. 2012. Effect of crop residue, nitrogen rate and fungicide application on malting barley productivity, quality, and foliar disease severity. *Can. J. Plant Sci.* 92:577–588. doi:10.4141/cjps2011-216
- University of California. 2008. Small grain production manual. ANR Publ. 8177. Univ. of California Div. of Agriculture and Natural Resources, Davis. <https://anrcatalog.ucanr.edu/pdf/8208.pdf> (accessed 1 Dec. 2018).
- USDA-NASS. 2018. Quick stats. USDA-NASS, Washington, DC. <https://quickstats.nass.usda.gov/results/D279436F-8348-3A21-A264-FBE3A36D284E> (accessed 7 Mar. 2018).
- Varvel, G.E., and R.K. Severson. 1987. Evaluation of cultivar and nitrogen management options for malting barley. *Agron. J.* 79:459–463. doi:10.2134/agronj1987.00021962007900030010x
- Virginia Tech. 2013. Small grains in 2013. CSES-62NP. Virginia Coop. Ext., Virginia State Univ., Petersburg. https://www.sites.ext.vt.edu/newsletter-archive/small-grains/CSES-62_pdf.pdf (assessed 17 Aug. 2018).
- Virginia Tech. 2017. Small grains in 2017. CSES-198. Virginia Coop. Ext., Virginia State Univ., Petersburg. https://pubs.ext.vt.edu/content/dam/pubs_ext_vt_edu/CSES/cses-198/CSES-198.pdf (assessed 17 Aug. 2018).
- Virginia Tech. 2018. 2018 Wheat and barley testing results. Virginia State Univ., Petersburg. <https://www.grains.cses.vt.edu> (accessed 17 Aug. 2018).
- Weston, D.T., R.D. Horsley, P.B. Schwarz, and R.J. Goos. 1993. Nitrogen and planting date effects on low-protein spring barley. *Agron. J.* 85:1170–1174. doi:10.2134/agronj1993.00021962008500060015x
- Wienhold, B.J., and J.M. Krupinsky. 1999. Chlorophyll meter as nitrogen management tool in malting barley. *Commun. Soil Sci. Plant Anal.* 30:2551–2562. doi:10.1080/00103629909370394
- Wise, C., M. Hashemi, and T. Aronson. 2017. Date of planting and nitrogen management for malt barley production in the Northeast. Agronomy Research Reports. The Center for Agriculture, Food and the Environment, Univ. of Massachusetts, Amherst. https://ag.umass.edu/sites/ag.umass.edu/files/research-reports/date_of_planting_and_nitrogen_management_for_malt_barley_production_in_the_northeast_0.pdf (accessed 1 Dec. 2018).
- Zeiss, M.R., and T.H. Klubertanz. 1994. Sampling programs for soybean arthropods. In: L.P. Pedigo and G.D. Buntin, editors, Handbook of sampling methods for arthropods in agriculture. CRC, Boca, Raton, FL. p. 539–601.
- Zubriski, J.C., E.H. Vasey, and E.B. Norum. 1970. Influence of nitrogen and potassium fertilizers and dates of seeding on yield and quality of malting barley. *Agron. J.* 62:216–219. doi:10.2134/agronj1970.00021962006200020012x