Comparisons of Copy Number, Genomic Structure, and Conserved Motifs for α-Amylase Genes from Barley, Rice, and Wheat

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Barley is an important crop for the production of malt and beer. However, crops such as rice and wheat are rarely used for malting. α-amylase is the key enzyme that degrades starch during malting. In this study, we compared the genomic properties, gene copies, and conserved promoter motifs of α-amylase genes in barley, rice, and wheat. In all three crops, α-amylase consists of four subfamilies designated amy1, amy2, amy3, and amy4. In wheat and barley, members of amy1 and amy2 genes are localized on chromosomes 6 and 7, respectively. In rice, members of amy1 genes are found on chromosomes 1 and 2, and amy2 genes on chromosome 6. The barley genome has six amy1 members and three amy2 members. The wheat B genome contains four amy1 members and three amy2 members, while the rice genome has three amy1 members and one amy2 member. The B genome has mostly amy1 and amy2 members among the three wheat genomes. Amy1 promoters from all three crop genomes contain a GA-responsive complex consisting of a GA-responsive element (CAATAAA), pyrimidine box (CCTTTT) and TATCCAT/C box. This study has shown that amy1 and amy2 from both wheat and barley have similar genomic properties, including exon/intron structures and GA-responsive elements on promoters, but these differ in rice. Like barley, wheat should have sufficient amy activity to degrade starch completely during malting. Other factors, such as high protein with haze issues and the lack of husk causing Lauting difficulty, may limit the use of wheat for brewing.

Keywords: α-amylase, barley, conserved motif, genome, gibberellin responsive complex, promoter

INTRODUCTION

The best quality barley grains are used predominantly for making malts and subsequently beer and whiskey. Malting consists of steeping, germination, and kilning (Gupta et al., 2010). Steeping and germination allow production of hydrolyzing enzymes including α-amylase (amy), β-amylase, limit dextrinase, and α-glucosidase for starch degradation (Bak-Jensen et al., 2007; Evans et al., 2010; Fincher, 2010; Shahpiri et al., 2015). Starch comprises an α-D-glucose homo-polymer amylase and branched amylopectin. The former is a linear molecule of α-1,4-linked glucose molecules, while the latter is a larger molecule with α-1,6 branching points (Bahaji et al., 2014). Amy [α-(1,4)-D-glucan glucanohydrolase, EC 3.2.1.1] cleaves α-(1,4) glycosidic linkage internally to produce...
oligosaccharides and amyllopectin. Amy is the most important enzyme for starch degradation during malting and mashing. Barley malts contain sufficient active amy enzymes to almost completely hydrolyze starch during malting and mashing.

Activation of amy expression is strictly controlled by the phytohormones gibberellin and ABA. During grain development, amy expression is repressed by ABA. However, in a genetic defect wheat, a high level of high pI amy genes could be expressed, resulting in poor grain quality during late grain development. This is normally referred to as late maturity α-amilase (LMA) (Barrero et al., 2013). During seed germination, amy expression is induced by elevated GA levels (Lanahan et al., 1992; Gómez-Cadenas et al., 2001; Woodger et al., 2010).

Genetic mapping associated barley malt amy activities with amy1 and amy2 loci on chromosomes 6H and 7H, respectively (Hayes et al., 1993; Oziel et al., 1996; Zale et al., 2000; Gao et al., 2004; Li et al., 2010). Isoelectric focusing electrophoresis identified low and high pI amy isoforms in barley aleurone extracts (Jacobsen and Higgins, 1982; Svensson et al., 1985). However, the number of amy isoforms in the barley genome is unknown but predicted to be from three to eight (Jacobsen and Higgins, 1982; Muthukrishnan et al., 1984; Svensson et al., 1985; Khursheed and Rogers, 1988; Evans et al., 2010). Nomenclatures of amys are complicated. Two families of amy were namedAMY1 and AMY2, referred to low and high pI enzymes, respectively (MacGregor et al., 1971; Jacobsen and Higgins, 1982; Svensson et al., 1985; Evans et al., 2010). A genomic clone and two cDNA clones coding for amy enzymes have been named amy32b, amy6-4, and amy46 (Rogers and Milliman, 1983; Whitier et al., 1987; Khursheed and Rogers, 1988). In a recently published barley genomic sequencing paper, new amy nomenclatures have been proposed. The barley genome contains at least 12 amy genes, grouped into four subfamilies amy1, amy2, amy3, and amy4 (Mascher et al., 2017). Here, we compared gene copy numbers, genomic structures and promoter conserved motifs of amy1 and amy2 subfamilies from barley, wheat, and rice. We hypothesize that the expansion in amy1 members combined with the presence of conserved regulatory motifs on promoters of amy1 and amy2 genes are important determinants for selecting barley as a malting crop.

**MATERIALS AND METHODS**

Genome sequences were downloaded to a local computer from ftp://ftp.ensemblgenomes.org/pub/plants/release-35/fasta/hordeum_vulgare/dna/ for barley; ftp://ftp.ensemblgenomes.org/pub/plants/release-35/fasta/oryza_sativa/dna/ for rice, and ftp://ftp.ensemblgenomes.org/pub/plants/release-35/fasta/triticum_aestivum/dna/ for wheat. The identification of barley, wheat, and rice amy genes are described in Mascher et al. (2017). Amy coding and promoter sequences (500 bp upstream of the translation start codon ATG) for all three crops were extracted after being blasted with the amy genes. Briefly, the amy genes were used to blast standalone blastable genomic databases to obtain amy gene nucleotide positions in pseudomolecules. According to these positions, the amy gene coding and promoter sequences were calculated and extracted with a Perl script. The promoter sequences were aligned with a ClustalW program and conserved motifs were examined.

**RESULTS AND DISCUSSION**

**Barley amy Copy Numbers – Historical and Genomic Evidence**

Barley amy genes were initially mapped to chromosomes 6H and 7H with wheat–barley addition lines (Brown and Jacobsen, 1982; Muthukrishnan et al., 1984). Southern blot analysis of two different amy gene DNA probes detected at least six and three hybridization bands from addition lines containing barley chromosomes 6H and 7H, respectively (Muthukrishnan et al., 1984; Rogers and Milliman, 1984). There were multiple amy protein bands on SDS PAGE purified from the barley aleurone using cycloheptaamylose-sepharose affinity chromatography and at least four amy activity peaks separated by DEAE cellulose chromatography (Jacobsen and Higgins, 1982). These offered early experimental evidence of the amy multigene family. Isoelectric focusing (IEF) electrophoresis showed that purified amy proteins could be divided into two distinct groups, a low pI group with an isoelectric point of 4.5–5.1 and a high pI group with an isoelectric point of 5.0–6.6 (Jacobsen and Higgins, 1982). Due to its commercial and biological importance, a significant effort was made to clone amy genes. A genomic clone was identified as an amy gene (amy32b) and belongs to a low pI amy protein (Rogers and Milliman, 1983; Whitier et al., 1987). Two cDNA clones were also characterized as amy genes (amy6-4 and amy46) that belong to high pI enzymes (Khursheed and Rogers, 1988). Furthermore, 3D structures have been resolved for two barley amy proteins; one belonging to a low pI amy protein (1AMY) and the other to a high pI amy protein (1HT6) (Kadziała et al., 1994; Robert et al., 2003).

While experimental data has shown that amy proteins are coded by multigene families, the exact numbers of genes are unknown. Barley genome sequencing is a useful resource for identifying the number of amy genes and discovering their genomic features. The barley genome contained 12 amy genes (Mascher et al., 2017), which were grouped into four subfamilies (Table 1). Subfamily 1 consists of six members—four on chromosome 6H (533880485–542858990 bp) and two on the unsorted chromosome (195047130–196261798 bp). Table 1—designated amy1_1a to amy1_1e and amy1_2. Four of which (amy1_1a to amy1_1d) have almost 100% sequence identity among members (Additional File 1: Supplementary Table S1A). One member (amy1_1e) is a truncated protein missing the carbohydrate-binding domain. Sequence identity analysis showed that the five amy1_1 proteins matched the cloned gene amy6_4 (Khursheed and Rogers, 1988), while the amy1_2 protein, with 95% sequence identity with amy1_1a, matched the cloned gene amy46 in both promoter and coding regions (Khursheed and Rogers, 1988). All amy1 members belong to

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1. [http://www.genome.jp/tools/clustalw/](http://www.genome.jp/tools/clustalw/)
TABLE 1 | Barley amy nomenclatures, gene ID, locations, and the association of old and new nomenclatures.

| New names | IBSC gene ID | Chr | Genomic location | SF | Old nomenclatures |
|-----------|--------------|-----|------------------|----|-------------------|
| amy1_1a   | HORVU6Hr1G078330 | 6H  | 533880485/533879015 | 1  | amy6_4, 1AMY, high pl |
| amy1_1b   | HORVU6Hr1G078360 | 6H  | 534112867/534114337 | 1  | amy6_4, 1AMY, high pl |
| amy1_1c   | HORVU6Hr1G078420 | 6H  | 534499529/534498059 | 1  | amy6_4, 1AMY, high pl |
| amy1_1d   | HORVU6Hr1G0302700 | 0H | 195047130/195048600 | 1  | amy6_4, 1AMY, high pl |
| amy1_1e   | HORVU6Hr1G0302850 | 0H | 196262954/196261798 | 1  | amy6_4, 1AMY, high pl |
| amy1_2    | HORVU6Hr1G080790 | 6H  | 542857506/542858990 | 1  | amy46, 1AMY, high pl |
| amy2_1    | HORVU7Hr1G091150 | 7H  | 556169663/556167920 | 2  | low pl |
| amy2_2    | HORVU7Hr1G091240 | 7H  | 557388785/557397068 | 2  | low pl |
| amy2_3    | HORVU7Hr1G091250 | 7H  | 557428810/557427021 | 2  | amy32b, 1HT6, low pl |
| amy3      | HORVU5Hr1G068350 | 5H  | 517452674/517454307 | 3  | N/A |
| amy4_1    | HORVU2Hr1G071710 | 2H  | 511664000/511667683 | 4  | N/A |
| amy4_2    | HORVU3Hr1G067620 | 3H  | 513488473/513485533 | 4  | N/A |

Chr, chromosome; SF, subfamily.

Barley amy Gene Genomic Arrangement

Four barley amy1 genes (amy1_1a to amy1_1d) had the same genomic arrangements as two introns and three exons. The nucleotide numbers for the introns and exons were the same as amy1_1a to amy1_1d, being 23 and 107 bp for the introns and 87, 1002, and 252 bp for the exons (Supplementary Table S2). While amy1_2 had two introns and three exons, the nucleotide numbers differed from the amy1_1a to amy1_1d members, being 95 and 106 bp for the introns and 87, 945, and 252 bp for the exons. Amy2-1 to amy2_3 had three introns and four exons, but the nucleotide numbers for all introns and exons differed among the three amy genes (Supplementary Table S2). Amy3 had three introns and four exons like amy2, but the nucleotide numbers differed from amy2. Amy4 had more than five introns and six exons.

Barley amy Gene Promoter Conserved Motifs

Promoters of all barley amy1 genes contained a conserved GA response complex (GARC) consisting of GARE (TAACAAA), pyrimidine (CCTTTT) and TATCCAC(T) boxes (Supplementary Table S3A and Figure 2) (Skriver et al., 1991; Gubler and Jacobsen, 1992). There was also a cAMP-like response element (TGAGCTC) on amy1 promoters (Gubler and Jacobsen, 1992), which represses gibberellin action. Pyrimidine and TATCCAC boxes enhanced the expression of amy1 proteins. The conserved motifs on subfamily 2 members differed from those on subfamily 1 genes and also among subfamily 2 members (Supplementary Table S3B and Figure 3). All three amy2 genes had GARE (TAACAGAG) and pyrimidine (CCTTTT) boxes. The pyrimidine box was much closer to the translation start site (−17 bp) for amy2_2, but further away for amy2_1, and amy2_3 at −211 and −236 bp, respectively. The original pyrimidine box of the amy2_2 gene, at a similar position to amy2_1, and amy2_3, was mutated to CCATTG on amy2_2 (Figure 3). A TATCCAC box was found in two amy2 genes (amy2_2 and amy2_3), but it was replaced with TACCATC in the amy2_2 gene. Furthermore, the amy2_2 promoter had a conserved O2S box (CCTGxxTCATC) and cAMP-like box (TGAGCTC). Genomic high pl enzymes (Table 1) and have high sequence identity with a 3D structure-resolved protein 1AMY (Kadziola et al., 1994). Subfamily amy2 has three members on chromosome 7H (556169683–557427021 bp, Table 1), and are designated amy2_1 to amy2_3. They have >92% sequence identity among the members, and >72% when compared to amy1_1a. Amy2_3 has a high sequence identity with cloned gene amy32b (Rogers, 1985; Whittier et al., 1987) and 3D structure-resolved protein 1AMY (Kadziola et al., 1994; Robert et al., 2003). They belong to genes coding for low pI enzymes (Table 1). Amy3 has one member localized on chromosome 5H (designated amy3), while amy4 has two members localized on chromosomes 2H and 3H (designated amy4_1 and amy4_2). The amy4 members have about 48% sequence identities compared between the members, or 43–46% sequence identity when compared to amy1_1a (Supplementary Table S1A).

Since amy1 and amy2 were located on chromosomes 6H and 7H, respectively, and many important malt quality QTLs were associated with these genetic loci, we believed that they were the most important members in relation to barley malt qualities (Hayes et al., 1993; Oziel et al., 1996; Zale et al., 2000; Gao et al., 2004; Li et al., 2010), we decided to investigate and compare gene and promoter structures for these two subfamilies in barley, rice, and wheat.

Barley amy Protein Secondary Structure

All amy proteins from amy1 and amy2 had the catalytic amino acid residues Asp303, Glu328, and Asp310 (amy1_1a positions), apart from amy1_1c, which was a truncated protein missing Asp310 (Figure 1). The near full-length proteins consisted of a central domain A forming (α/β)6 barrel, a structural loop domain B and a carbohydrate-binding domain C (Figure 1). Domain C formed five anti-parallel sheets (Kadziola et al., 1994; Robert et al., 2003). Barley amy proteins from amy3 and amy4 also contain the catalytic amino acids and a carbohydrate-binding module as discovered in the Domain Database at NCBI. However, Asp310 on the active site was replaced with Glu310 for the two amy4 proteins (Figure 1).
sequence analysis showed that both *amy1* and *amy2* genes had a GARC, where GARE was required for GA induction of amy expression with pyrimidine and TA(T/C)CCAT box controlling gene expression levels (Lanahan et al., 1992).

When promoter regions (−500 bp) of subfamilies 1 and 2 were analyzed, the sequence identities were high (>99%) among *amy1_1a*, *amy1_1b*, and *amy1_1d* (Supplementary Table S4A). However, the *amy1_1c* promoter region was truncated to −151 bp, despite being 100% identical to the promoter sequence of *amy1_1a* gene. The promoter region of *amy1_1c* had high sequence identity within −350 bp, but low sequence identity beyond −350 bp, compared to *amy1_1a* (Figure 2). The sequence of the *amy1_2* promoter (−500 bp) was 64% identical to the *amy1_1a* promoter. The genomic locations of the conserved motifs in *amy1* were the same for all *amy1_1* members at −180, −199, −220, and −225 bp for TATCCA, GARE, cAMY-like and pyrimidine boxes, respectively (Supplementary Table S3A). However, the locations of these motifs from the *amy1_2* gene was a nucleotide closer to the ATG translation start site compared to the locations of *amy1_1* members (Supplementary Table S3A). The sequences of *amy2* promoters had low sequence identity (59–68%) compared to their members (Supplementary Table S4B).
FIGURE 2 | Barley amy1 promoter sequence alignments and conserved motifs. All amy1 promoters (except amy1_1e, which is truncated) contain a GA-responsive element (GARE) TAACAAA (red box). It requires for GA induction. They also contain a pyrimidine box (CCTTTT) and a TATCCA(C/T) box (blue boxes), which enhance gene expression after GA responses (Gubler and Jacobsen, 1992). A cAMP-like responsive element (TGAGCTC) is conserved (green box).

FIGURE 3 | Barley amy2 promoter sequence alignments and conserved motif analysis. All three amy2 promoters contain a GA-responsive element (GARE) TAACAGAG (red box) required for GA induction. Promoters of amy2_1 and amy2_3 contained a pyrimidine box (CCTTTT) and a TATCCA(C/T) box (blue boxes), which enhance gene expression (Gubler and Jacobsen, 1992). A pyrimidine box (blue box), a cAMP-like responsive element (TGAGCTC) (green box) and an O2S (CTTGXXTCATC) (green box) were present on amy2_2 promoter.
Rice **amy** Gene Numbers and Conserved Motifs on Promoters

The rice genome contained 10 **amy** genes with three, one, four, and two members in subfamilies 1, 2, 3, and 4, respectively (Table 2). The number of **amy1** and **amy2** genes in rice was four, much less than the sum of **amy1** and **amy2** in barley. Rice **amy3** had the most gene members. Two of the **amy1** genes (LOC_Os02g52700 and LOC_Os02g52710) had three introns (Supplementary Table S2), unlike the barley **amy1** genes, which all had two introns. The other **amy1** gene (LOC_Os01g25510) had two introns. Alignment of the three **amy1** protein sequences identified one protein (LOC_Os01g25510) with a very low sequence identity (24–30%) compared to the other two **amy** proteins (LOC_Os02g52700 and LOC_Os02g52710) (Supplementary Table S1B and Figure S1). The two **amy1** proteins and one **amy2** protein had similar secondary structures to the barley **amy** proteins. However, the amino acid compositions differed substantially on most of the β-strains and α-helices (Supplementary Figure S1). Rice had the same catalytic amino acids (Aps, Ghu, and Asp) as barley. The promoters of the three **amy1** genes had >65% sequence identities (Supplementary Table S4C). They contained the GARE (TAACAAA), pyrimidine (CCTTTT) and TATCCAT boxes (Supplementary Table S3C and Figure S2A) but not the cAMY-like box. The rice **amy2** protein (LOC_Os06g49970) had 72% sequence identity compared to the two **amy1** proteins (LOC_Os02g527100 and LOC_Os02g52710). However, the promoter of the rice **amy2** gene only contained GARE (TAACAGAG), but not pyrimidine, TATCCAT or TATCCAC boxes (Supplementary Table S3C and Figure S2B).

Wheat **amy** Gene Numbers and Conserved Motifs on Promoters

The number of **amy** genes in the wheat A, B, and D genomes was 6, 10, and 8, respectively. The other four **amy** genes are located in unsorted chromosomes (Table 2). The wheat B genome had the most **amy** genes with four, three, one and two members in subfamilies **amy1**, **amy2**, **amy3**, and **amy4**, respectively. The number of **amy1** and **amy2** genes in each wheat genome did not exceed those in the barley genome (Table 2). All of the wheat **amy2** genes had the same genomic arrangement as the barley **amy2** genes with three introns and four exons (Supplementary Table S2). Most of the wheat **amy1** genes had two introns and three exons except for 6BL4, Un1 and Un2, which had three or four introns. The protein sequence identities were high within the wheat **amy1** or **amy2**, being >80% (Supplementary Tables S1C,D and Figures S3, S4). The sequence identities for promoters of **amy1** genes were 50–100%, but much lower for **amy2** gene promoters (Supplementary Tables S4D,E). The promoters of all wheat **amy1** genes contained GARE (TAACAAA), pyrimidine, TATCCAT or TATCCAC boxes (Supplementary Figure S5). They also had a cAMP-like motif (TGAGCTC) box as per the barley **amy1** gene promoters. Five of the wheat **amy2** gene promoters contained a GARE (TAACAGAG) box, six contained pyrimidine and TATCCAT boxes, and seven had O2S motifs. The O2S motifs in the wheat genomes contained four variable nucleotides between the conserved CTTC and TCATC (Supplementary Figure S6), while the O2S in the barley **amy2** promoters had two variable nucleotides (Figure 3).

A Comparison of **amy** Gene Copy Numbers and Sequence Properties from Barley, Rice, and Wheat

Barley had the highest number of **amy1** genes (six), while wheat had four in the B genome and rice had three (Table 2). Both barley and wheat had the same number of **amy2** genes (B genome only), while rice had one. Rice contained the most **amy3** genes (four), while barley and wheat had one each. All the barley, wheat and rice genomes contained two **amy4** genes (Table 2). The intron numbers for **amy2** genes were the same for barley, wheat and rice, but differed for the **amy1** genes: barley had two, wheat had two or four, and rice had two or three (Supplementary Table S2). The intron numbers for **amy3** and **amy4** genes differed, ranging from two to nine (Supplementary Table S2). Barley **amy1** genes had high sequence identities with wheat **amy1** genes ranging from 83 to 97% (Supplementary Table S5). Barley **amy2** genes also had high sequence identities with wheat **amy2** genes (80–96%) (Supplementary Table S5). The barley and wheat **amy1** and **amy2** genes had similar promoter regions with sequence identities ranging from 50 to 76% (Supplementary Table S6). However, there was no similarity between barley and rice promoter sequences.

Expanded **amy1** and **amy2** Genes Are Important for Barley Malting Qualities

Barley **amy** proteins are grouped into four subfamilies according to their sequence properties (Mascher et al., 2017). The biological functions for each subfamily are unclear. Genetic mapping using molecular marker technologies showed that the regions associated with the genetic markers **amy1** and **amy2** on chromosomes 6 and 7 are important for malting qualities including amy enzyme activities and malt extracts (Hayes et al., 1993; Han and Ullrich, 1994; Oziel et al., 1996; Marquez-Cedillo et al., 2000; Emembiri et al., 2004). Thus, we conclude that **amy1** and **amy2** are the major genes responsible for starch degradation during seed germination. Other indirect evidence includes the induced expression of **amy1** and **amy2** genes during seed germination by GA (Khursheed and Rogers, 1988; Karrer et al., 1991). The abundance of mRNA levels ranks **amy32b** (**amy2_3**) > **amy6-4** (**amy1_1a** to **amy1_1c**, possibly sum) > **amy46** (**amy1_2**) about 24 h after GA induction (Khursheed and Rogers, 1988; Karrer et al., 1991). Barley **amy1** have expanded members due to genome duplication, which may play a key role in barley becoming a malting commodity. Furthermore, many amy genomic and cDNA clones had been deposited on Genbank. Their relationships for some of the clones with **amy1** and **amy2** was shown by a phylogenetic tree at Supplementary Figure S7.

There was no direct evidence for the function of **amy3** and **amy4** proteins in barley. In wheat, **amy3** was highly expressed during seed germination by GA (Khursheed and Rogers, 1988; Karrer et al., 1991). Many of the wheat amy1 or amy2 proteins were induced by GA and diacylglycerol accumulation (Whan et al., 2014), while...
TABLE 2 | Orthologs of rice and wheat α-amylase genes.

| SF | Rice | Wheat |
|----|------|-------|
|    |      | A     | B     | D     | Unanchored |
| amy1 | LOC_Os02g52700 | 6AL_amy1 | 6BL_amy2 | 6DL_amy1 |
|     | LOC_Os02g52710 | 6AL_amy2 | 6BL_amy3 | 6DL_amy2 |
|     | LOC_Os01g25510 | 6AL_amy3 | 6BL_amy4 | 6DL_amy3 |
|     |                | 6BL_amy5 |        |        |
| amy2 | LOC_Os06g49970 | 7AL_amy1 | 7BL_amy1 | 7DL_amy1 |
|     |                | 7BL_amy2 | 7DL_amy2 | Un_amy1 |
|     |                | 7BL_amy3 |        | Un_amy2 |
| amy3 | LOC_Os09g28400 | 5AL_amy1 | 5BL_amy1 | 5DL_amy1 |
|     | LOC_Os09g28420 |        |        |        |
|     | LOC_Os08g36900 |        |        |        |
|     | LOC_Os08g36910 |        |        |        |
| amy4 | LOC_Os04g33040 | 2AL_amy1 | 2BL_amy1 | 2DL_amy1 |
|     | LOC_Os01g51754 | 3BL_amy1 | 3DL_amy1 | Un_amy4 |

Rice and wheat amy protein sequences were downloaded from ftp://ftp.ensemblgenomes.org/pub/plants/release-35/fasta/oryza_sativa/dna/ and ftp://ftp.ensemblgenomes.org/pub/plants/release-35/fasta/triticum_aestivum/dna/, respectively. They were aligned with barley amy protein sequences using the clustalW program (http://www.genome.jp/tools/clustalw/). Sequences in the same clades were regarded as the same subfamily (SF) members. A, B, and D: wheat A, B, and D genomes.

the amy4 gene may be involved in starch degradation working in partnership with amy1 proteins (Mieog et al., 2017).

Significance of Conserved Motifs on Promoters of amy1 and amy2 in the Induction of amy Gene Expression

Barley amy enzymes are synthesized in barley aleurone layers induced by gibberellin (GA) (Chrispeels and Varner, 1967; Jacobsen et al., 1970). Two groups of proteins (A and B) were detected after GA induction. Their responses to GA induction differed in a time and GA concentration dependent manner (Jacobsen and Higgins, 1982). The group A proteins expressed earlier and required a low GA concentration, while the group B proteins were not detectable till 8 h after GA addition and required a higher GA concentration. However, the synthesis of group B proteins accelerated once expressed, and one of group B isoforms was most abundant at 24 h (Jacobsen and Higgins, 1982). The group A and B proteins were likely to be the products of amy1 and amy2 genes, respectively, as shown by changes in mRNA levels in response to GA (Khursheed and Rogers, 1988). Conserved motifs on amy1 and amy2 promoters played key roles in the induction of gene expression. A comparison of amy1 with amy2 promoters showed substantial differences in nucleotide composition of the conserved motifs. The GA-responsive element is TAACAAA on all amy1 promoters, but TAACAGAG on all amy2 promoters for all three crops. There is a cAMY-like responsive element close to the pyrimidine box on barley and wheat amy1 promoters, but not amy2 promoters. The difference in the conserved motifs may play a key role in GA-induced gene expression.

Gene expression induced by GA may have the same mechanism for all amy1 members, since they contain extract same number of motifs with same nucleotide sequences except Hvamy1_2 gene on which the TATCCAC box was replaced by TATCCAT. In contrast, barley amy2 members may be differentially regulated, particularly for the Hvamy2_2 gene, since the conserved motifs differed substantially from amy1, amy2_1, and amy2_3. Furthermore, no similar motifs were found in the promoters of amy3 and amy4.

Genomic Properties of Wheat amy Genes Did Not Differ from Those of Barley amy Genes

Barley grains are often used for malting. Barley malts contain sufficient diastatic power (enzymatic hydrolytic activities) to completely convert starch to fermentable sugars. Extended numbers of amy genes and the presence of GA-regulatory motifs are important for barley to be used for malts (Table 1 and Figures 2, 3). However, wheat amy genes had similar genomic properties to barley amy genes with similar intron and exon structures (Supplementary Table S2). They also contained GA-regulatory motifs as in barley amy gene promoters (Supplementary Figures S5, S6). This could explain why wheat can also be used for malting (Fleming et al., 1960; Faltermaier et al., 2013). However, there are some problems with using wheat malts for brewing. Wheat grains lack husk, which is a problem for a brewing process called Lautering. Wheat also has higher protein (up to 20%). Wheat proteins promote foam formation, but also enhance haze issues (Faltermaier et al., 2015).

CONCLUSION

Subfamilies amy1 and amy2 have similar genomic properties in wheat and barley—including the number of exon/intron structures, localized on chromosomes 6 and 7, with
GA-responsive elements on promoters—but differ in rice. Interestingly, the barley genome contains at least three more amy1 genes on chromosome 6H. Wheat should contain sufficient amy activity to completely degrade starch during malting. Other factors, such as high protein and the lack of husk, may limit the use of wheat for brewing.

AUTHOR CONTRIBUTIONS
All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

SUPPLEMENTARY MATERIAL
The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpls.2017.01727/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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