Assembly and analysis of a qingke reference genome demonstrate its close genetic relation to modern cultivated barley

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Abstract

Qingke, the local name of hulless barley in the Tibetan Plateau, is a staple food for Tibetans. The availability of its reference genome sequences could be useful for studies on breeding and molecular evolution. Taking advantage of the third-generation sequencer (PacBio), we de novo assembled a 4.84-Gb genome sequence of qingke, cv. Zangqing320 and anchored a 4.59-Gb sequence to seven chromosomes. Of the 46,787 annotated ‘high-confidence’ genes, 31 564 were validated by RNA-sequencing data of 39 wild and cultivated barley genotypes with wide genetic diversity, and the results were also confirmed by nonredundant protein database from NCBI. As some gaps in the reference genome of Morex were covered in the reference genome of Zangqing320 by PacBio reads, we believe that the Zangqing320 genome provides the useful supplements for the Morex genome. Using the qingke genome as a reference, we conducted a genome comparison, revealing a close genetic relationship between a hulled barley (cv. Morex) and a hulless barley (cv. Zangqing320), which is strongly supported by the low-diversity regions in the two genomes. Considering the origin of Morex from its breeding pedigree, we then demonstrated a close genomic relationship between modern cultivated barley and qingke. Given this genomic relationship and the large genetic diversity between qingke and modern cultivated barley, we propose that qingke could provide elite genes for barley improvement.

Keywords: genomic contribution, hulless barley, reference genome, RNA-sequencing, third-generation sequencing.

Introduction

Barley (Hordeum vulgare L.) ranks the fourth largest cereal in planting area worldwide and is one of the earliest domesticated crops (Purugganan and Fuller, 2009). As an excellent model plant for understanding agronomic and physiological responses to climate change (Dawson et al., 2015), barley may provide insight into the mechanisms of abiotic stress adaptation and tolerance in cereal crops. The Tibetan Plateau is the home of qingke, the local name of hulless barley, which has been used as a staple food of Tibetans for thousands of years (Xu, 1982). The Near East Fertile Crescent is well-recognized as an original site of wild barley (Hordeum spontaneum L.) and a major domestication centre of cultivated barley (Nevo, 2006, Zohary et al., 2012), but increasing evidence supports a theory of polyphyletic origin of cultivated barley (Azhaguvel and Komatsuda, 2007; Dai et al., 2012, Dai et al., 2014; Molina-Cano et al., 2005, Morrell and Clegg, 2007).

Barley is an annual diploid grass species with a large haploid genome of 5.1 Gb which contains a high abundance of repetitive elements (Mayer et al., 2012). An accurate genome sequence is a prerequisite for molecular breeding and a deeper understanding of its evolution. The high-throughput sequencing capacity of second-generation sequencers enables more timely, and cost-effective assembly of diploid plant genomes (Michael and VanBuren, 2015), but can be difficult to assemble a high-quality reference genome sequence for plants like barley with large genomes (Zeng et al., 2015). The Pacific Biosciences real-time single-molecule (PacBio RS) third-generation sequencer has the potential to increase read lengths dramatically and thus improve de novo genome assembly (Gordon et al., 2016; Rasko et al., 2011), the PacBio RS can generate kilo-base long reads to fill gaps in scaffolds assembled from second-generation sequencers.

Recently, a 3.48-Gb (anchored to seven chromosomes) draft genome of hulless barley, cv. Lasa Goumang has been reported (Zeng et al., 2015), but this genome is not yet available publicly. As a member of the International Barley Genome Sequencing Consortium, we have access to the latest genome sequence data set of hulless barley cv. Morex (Mascher et al., 2017), which has been used to conduct a comparative genomic study. In this study, we aimed to (1) construct a complementary reference genome sequence of hulless barley cv. Zangqing320 using a leading sequencing strategy to combine the whole-genome shotgun method with PacBio third-generation sequencing and (2) demonstrate the genomic relationship between qingke and modern cultivated barley.

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Results

Sequencing and de novo assembly of a reference genome of hulless barley cv. Zangqing320

A whole-genome shotgun method combined with the third-generation sequencing strategy was used to resequence, and de novo assemble the reference genome of hulless barley cv. Zangqing320 from the Tibetan Plateau. We generated 269.81 Gb of Illumina sequence data including 32.37, 84.63 and 17.12 Gb from libraries of 250, 300 and 500 bp, respectively, and 117.40 and 18.29 Gb from the 2- and 6-kb mate-pair libraries, respectively (Table S1). Moreover, PacBio third-generation sequencers generated much longer reads with an average subread length of 3 kb (Table S1).

De novo contig assembly was performed after filtration and error correction of raw reads (Figure 1), generating 632,382 contigs (3.29 Gb) with 44.28% GC content and an N50 length of 5.94 kb (Table 1). Mate-pair reads of the 2- and 6-kb libraries, and those of 5- to 40-kb libraries (SRR1804516-SRR1804532) adapted from Zeng et al. (2015), were used to link contigs into scaffolds, resulting in 104,997 scaffolds (scaffolds_1, 3.67 Gb) with 103,894 gaps, 9.32% N content, 44.28% GC content and an N50 length of 173.83 kb (Table 1, Figure 1). Gaps in scaffolds_1 were filled with 38.46 Gb PacBio reads, resulting in scaffolds_2 (3.73 Gb) with 89,678 gaps and 91,879 scaffolds (Table 1, Figure 1). Using the framework of reference genome sequence of hulled barley cv. Morex (Mascher et al., 2017), we constructed a 4.84-Gb reference genome of hulless barley cv. Zangqing320 for research on molecular evolution, domestication, gene cloning and functional analysis, and molecular breeding in barley (available at http://www.ibgs.zju.edu.cn/ZJU_barleygenome.htm), with 8.0% N and 44.44% GC content, and 4.59 Gb anchored to seven chromosomes (Table 1, Figure 1).

Genome annotation identifies a large number of high-confidence genes

We conducted a genome annotation using 1.17 billion RNA-sequencing (RNA-Seq) reads from seedling leaves of 39 wild and cultivated barley genotypes with wide genetic diversity (Table S2). After removing genes shorter than 300 bp or longer than 20 kb, we identified 38,085 genes in the Zangqing320 genome. Based

Figure 1 Schematic workflow for genome assembly of a hulless barley, cv. Zangqing320 from the Tibetan Plateau. Data from the current study are dark blue, data adapted from previous studies are light blue, operation processes are green, and assembly results are orange. 1 Data from Zeng et al. (2015). 2 The reference genome of Morex from Mascher et al. (2017).
on annotated genes in the assembly genome of Morex (version: 082214v1, http://plants.ensembl.org/index.html) and homolog support of nonredundant (nr) protein database from the National Center for Biological Information (NCBI) using Blast2GO, 31,564 genes in the reference genomes of Zangqing320 were deemed ‘high-confidence’ genes.

As all of the RNA-Seq data used for gene prediction were obtained from leaf tissues at the vegetative stage, we further performed de novo gene prediction to generate a complete genome annotation file. A total of 197,063 genes were de novo predicted, including 32,482 genes with homolog support from the NCBI nr protein database. Excluding genes encoding protein which less than 100 amino acids or containing Ns, 30,539 de novo predicted genes supported from the nr protein database were compared to the 31,564 RNA-Seq predicted ‘high-confidence’ genes to identify common genes. After excluding those common genes, 15,223 de novo predicted genes were added, to generate a genome annotation file of Zangqing320 with 46,787 annotated genes.

Genome comparison reveals a close genetic relation between Morex and Zangqing320 in genome structure

To compare the genome similarity between Morex and Zangqing320, we annotated the genome of Morex with the RNA-Seq data of 39 barley genotypes and identified 30,362 ‘high-confidence’ genes. We then compared sequences of the RNA-Seq predicted ‘high-confidence’ genes in Morex and Zangqing320 using tblastx. We found 26,687 common genes along with 3,675 and 4,877 potential private genes in Morex and Zangqing320, respectively (Figure 2a). Private genes refer to those detected only in Morex or

| Genomic statistics          | Contigs | Scaffolds_1* | Scaffolds_2† | Genome |
|-----------------------------|---------|--------------|--------------|--------|
| Total sequence length       | 3.29 Gb | 3.67 Gb      | 3.73 Gb      | 4.84 Gb|
| Number of contig/scaffold/chromosome | 632 382 | 104 997      | 91 879       | 7†     |
| Longest contig/scaffold/chromosome | 298.21 kb | 2.69 Mb      | 2.69 Mb      | 768.77 Mb|
| N50 length                  | 5.94 kb | 173.83 kb    | 171.11 kb    | –      |
| Average length              | 5.21 kb | 35.00 kb     | 40.56 kb     | 604.76 Mb|
| Gap number                  | 0       | 103,894      | 89,678       | 1,172,646|
| N content (%)               | 0.00    | 9.32         | 7.74         | 8.00   |
| GC content (%)              | 44.28   | 44.28        | 43.64        | 44.44  |

*Scaffolds_1 were assembled from second-generation contigs, gaps in which were filled with PacBio RS reads and resulted in Scaffolds_2 refer to Figure 1. †Sequence not anchored to chromosomes 1H–7H were named as chrUn.

Table 1 Statistics of the reference genome of a hulless barley, cv. Zangqing320 from the Tibetan Plateau.

Figure 2 Genome comparison (a) and genomic similarity analysis (b). (a) Common and specific annotated genes in the reference genome of Morex and Zangqing320. Private genes (shown in brackets) had no homologous gene in the other genotype. (b) Analysis of genomic similarities between the modern cultivated barley group and the other three barley groups. The outer track of the circos diagram shows the seven chromosomes (1H–7H) of barley in each of the four groups: purple, modern cultivated barley (MCB); red, hulless barley from the Tibetan Plateau (QK); blue, wild barley from the Tibetan Plateau (Wb-T); yellow, wild barley from the Near East (Wb-NE). The number on each chromosome indicates the genomic position on the genome of Zangqing320 (Mb). Similar blocks are connected with lines, and each line represents one unique window (500 kb) of the genome with the highest similarity between MCB and the other three barley groups.

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Zangqing320. Further comparison of potential private genes using tblastx excluded similar genes and detected 99 and 125 private genes in Morex and Zangqing320, respectively (Figure 2a). The low number of private genes indicates a close genetic relation between Morex and Zangqing320 in genome structure. The position of single nucleotide variants (SNVs) and CpG island densities (Figure 3a,b) also support this finding. For example, the seven chromosomes of Morex and Zangqing320 contained 206 049 and 206 152 CpG islands, respectively (Table S3), with the highest density on chromosome 3H in both genotypes.

Whole-genome similarity analysis demonstrates a close genomic relationship between modern cultivated barley and qingke

In addition to genome comparison, we further analysed the genomic similarity between modern cultivated barley and qingke using the method in our previous study (Dai et al., 2014) with one additional cultivar and 15 qingke accessions. Aligning RNA-Seq reads in each of the 39 samples to the Zangqing320 genome, we identified 1 148 006 SNVs on the seven chromosomes (Tables S2 and S3). Wide genetic variation was detected in both wild (including those from the Tibetan Plateau and the Near East) and cultivated barley genotypes, with an average of 147 797 and 126 955 SNVs, respectively (Table S2). However, in 18 qingke accessions, only an average of 109 050 SNVs was detected (Table S2). To avoid unreliable inferences caused by missing and multiple variation sites, we constructed a data set containing 125 157 SNVs with homozygous loci and no missing data in 39 samples to perform genomic similarity analysis (Figure 3a). We divided the 39 barley genotypes into four groups according to phylogenetic trees (Figures 4 and S1), population structure (Figure S2), information on collection sites (Table S2) and the results of our previous study (Dai et al., 2014): (1) modern cultivated barley (MCB, nine modern barley cultivars), (2) QK (18 qingke accessions), (3) wild barley from the Tibetan Plateau (Wb-T, including XZ2, XZ12, XZ15, XZ21, XZ174 and XZ181) and (4) wild barley from the Near East (Wb-NE, including ECI-2-0, ECI-6-0, Tabigha-B-63, Tabigha-T-0, Iran-6-26 and Turkey-19-24) (Table S2).

As described in previous studies (Dai et al., 2014; Rubin et al., 2010), each group of barley genotypes was combined as a gene pool. With 500-kb windows and 250-kb overlapping slide windows along the Zangqing320 genome, 714 similar genetic windows containing 35 665 SNVs met the selection criteria, accounting for 5.9% of the genome. The genomic similarities between MCB and QK, and Wb-T and Wb-NE were visualized with a circos diagram (Figure 2b). As expected, the two cultivated barley groups, MCB and QK, had a tight genomic relationship (Figure 2b, Table S4). Only 154 similar genetic windows were identified between MCB and Wb-NE, while 334 and 226 unique genetic windows were detected between MCB and QK, and MCB and Wb-T, respectively (Table S4). The genomic similarity of MCB and the other three barley groups was calculated based on the total length of unique genomic windows. MCB and QK had a

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**Figure 3** Genome characterization of Zangqing320 (a) and Morex (b). The four tracks from outside to inside are chromosomes (red for Zangqing320, purple for Morex), CpG island density (orange), gene density (heatmap), and single nucleotide variant (SNV) density (dark blue). The densities of the CpG island, gene and SNV are represented by the number in nonoverlapping 500-kb windows. SNVs in (a) show the 125,157 SNV data set with homozygous loci and no missing data called by mapping RNA-Seq reads of the 39 barley accessions to the reference genome of hulless barley cv. Zangqing320, while SNVs in (b) are called after mapping reads of Zangqing320 to the genome of Morex. Black triangles in the innermost track of (b) refer to genomic regions with low genetic diversity between Morex and Zangqing320.
high genomic similarity value on chromosomes 1H, 2H, 3H and 4H, being 60.67%, 59.63%, 55.56% and 49.18%, respectively (Table S4). The genomic similarity between MCB and Wb-T was 41.98% on chromosome 6H (Table S4).

Moreover, to confirm our previous finding on qingke’s close genetic relationship with Tibetan wild barley, while different from modern cultivated barley (Dai et al., 2014), we performed genomic similarity analysis focusing on QK to determine the genomic relationships among the four barley groups. Wb-T had the tightest genomic relationship with QK, followed by MCB and Wb-NE (Figure S3a, Table S4), which also reflected the reliability of grouping. Among the wild barley groups, the genomic similarity between QK and Wb-T was more than fivefold higher than that between QK and Wb-NE (Figure S3b, Table S4). Obviously, qingke is closely associated with the Tibetan wild barley at the genome level.

Figure 4 Phylogenetic trees of cultivated barley (a) and wild barley (b) based on the 125,157 SNVs data set randomly distributed in the seven barley chromosomes. The neighbour-joining method was used with 1000 bootstraps. Branches marked by red dots, purple dots, blue triangles and yellow triangles represent hulless barley from the Tibetan Plateau, modern cultivated barley, wild barley from the Tibetan Plateau, and wild barley from the Near East, respectively.

Figure 5 Distribution of windowed $F_{ST}$ values between qingke (QK) and modern cultivated barley (MCB) across the whole genome (a) or along each chromosome (b, c, d, e, f, g, h) of Zangqin320. $F_{ST}$ value was calculated in each 500-kb region in 250-kb steps. (a) The x-axis indicates the value of $F_{ST}$ and the y-axis shows the frequency of $F_{ST}$ value. The red dash vertical line (in panel a) indicates the threshold value which is chosen based on the distribution of all windowed $F_{ST}$. (b, c, d, e, f, g, h) X-axis indicates the physical position of each chromosome and y-axis shows the cumulative percentage. The red horizontal line indicates the threshold value which is chosen based on the distribution of all windowed $F_{ST}$.
Methane metabolism
Purine metabolism
Glycine, serine and threonine metabolism
Biosynthesis of antibiotics
Glycerolipid metabolism
Glyoxylate and dicarboxylate metabolism
Inositol phosphate metabolism
Carbon fixation in photosynthetic organisms
Porphyrin and chlorophyll metabolism
Galactose metabolism
Fructose and mannose metabolism
Glycolysis/Gluconeogenesis
Amino sugar and nucleotide sugar metabolism
Starch and sucrose metabolism

(a) Biological process

Molecular function

Cellular component

(b)
Selective sweep analysis reveals novel genes between modern cultivated barley and *qingke*

Selective sweep analysis, a major method used to detect environmental or natural selection signatures, was performed between MCB and QK to detect the genome regions under selective sweeps affected by the unique growth environment in the Tibetan Plateau. Fixation index ($F_{ST}$) was used to measure genetic differentiation of the two barley groups, and genome regions with $F_{ST} > 0.65$ (about 5% top $F_{ST}$ windows) between MCB and QK were determined as selective sweeps (Figure 5). The above analysis identified 7.25% of the genome sequence and 5.44% (2,544) of the annotated genes as involved in the selection (Figure 5, Data S1). Interestingly, up to 16.33% of chromosome 4H was under selective sweeps (Figure 5). Gene Ontology (GO) analysis of the 2,544 genes under selective sweeps revealed that ‘integral component of membrane’, ‘ATP binding’ and ‘regulation of transcription, DNA-templated’ were the most enriched terms in cellular component, molecular function, and biological process, respectively, followed by ‘mitochondrion’, ‘nucleic acid binding’, and ‘oxidation-reduction process’, and then ‘plastid’, ‘zinc ion binding’ and ‘protein phosphorylation’ (Figure 6a). In addition, the Kyoto Encyclopedia of Genes and Genomes (KEGG) analysis showed that they are mainly enriched in pathways associated with carbohydrate metabolism (e.g. starch and sucrose metabolism, amino sugar and nucleotide sugar metabolism, glycolysis/gluconeogenesis, fructose and mannose metabolism, and galactose metabolism), photosynthesis (e.g. porphyrin and chlorophyll metabolism and carbon fixation in photosynthetic organisms) and glycerolipid metabolism (Figure 6b).

**Discussion**

**Third-generation sequencing provides a high-quality reference genome of hulless barley cv. Zangqing320**

The read length of second-generation sequencers could not span the long, repetitive sequences that make up more than 80% of the barley genome (Mayer et al., 2012; Wicker et al., 2009). Third-generation sequencers, however, have the potential to dramatically improve the read length for de novo genome assembly (Gordon et al., 2016; Rasko et al., 2011). In the current study, we employed the PacBio RS sequencer to cross over the long, repetitive sequences in the barley genome. The PacBio RS reads fill the gaps in scaffolds de novo assembled from second-generation reads, closing 13.68% of the gaps, eliminating 15.77% of the Ns, and increasing the average scaffold length in scaffolds_1 by 15.80%, thus resulting in scaffolds_2 (Table 1, Figure 1). Comparing scaffolds_1 and scaffolds_2, the latter had fewer scaffolds shorter than 15 kb and more scaffolds ranging from 15 to 60 kb (Figure 7). The number of scaffolds longer than 60 kb declined slightly in scaffolds_2, possibly because the gaps with excessive Ns in scaffolds_1, introduced from the mate-pair reads, were filled with shorter-than-expected sequences. Taking advantage of the PacBio RS reads, we generated a high-quality reference genome of hulless barley cv. Zangqing320 that was 1.11 Gb larger than the recently reported 3.48-Gb (anchored to seven chromosomes) genome of hulless barley cv. Lasa Goumang (Zeng et al., 2015). The reference genome of Zangqing320 showed comparable length to that of hulled barley cv. Morex. As some gaps in the reference genome of Morex were covered in the reference genome of Zangqing320 by third-generation PacBio reads, we believe both reference genomes would be useful for barley breeding and genetic research in Triticeae.

**Genomic-based analysis revealed genetic diversity of *qingke***

The genome structure of Morex and Zangqing320 indicated a close genetic relationship. However, we detected large genetic diversity in the two sequenced reference barley genomes. By mapping the in-depth resequencing reads of Zangqing320 to the reference genome of Morex, 6 053 445 SNVs were detected on the seven chromosomes (Figure 3b, Table S3). The difference was also reflected in the 3675 and 4877 specific annotated genes in the reference genome of Morex and Zangqing320, respectively. Gene Ontology (GO) analysis of specific genes indicated that 19.04% and 44.92% GO terms are found exclusively in Morex and Zangqing320, respectively, although the top 1% GO terms are highly identical (Figure S4). For instance, enriched unique GO terms of specific genes in Morex were associated with salicylic acid signalling, kinase, and membrane-involution autophagy and transport, while those in Zangqing320 were relevant to cytokinin signalling, phosphatase, cell division, polysaccharide catalytic, transcription and post-translational modification (Figure S5). Surprisingly, 19 548 975 and 23 394 190 SNVs were detected on seven chromosomes by mapping the in-depth resequencing reads of barley cultivars Igri and Barke to the reference genome of hulless barley cv. Zangqing320, respectively. The vast number of SNVs may be due to the higher completion of the reference genome of hulless barley cv. Zangqing320. The results also indicated that, compared with cv. Morex, cv. Zangqing320 has a greater genetic difference between cv. Igri and cv. Barke.

In addition to the genomic sequence analysis, we conducted a comparative population analysis at the transcriptome level and found a significant genetic difference between modern cultivated barley and *qingke*. About 1.73% of unique SNVs in the 125 157 SNVs data set were detected in QK, which will be a valuable genetic resource for *qingke* utilization and gene mining. According to the selective sweep analysis and gene annotation, we detected nine, seven, and five genes under selective sweeps encoding peroxidase, TRANSPARENT TESTA 12, and ultraviolet-B receptor UVB8, respectively (Data S1). It is reported that *qingke* is well adapted to harsh environments which include the strong ultraviolet light and unpredictable diurnal temperature fluctuations in the Tibetan Plateau (Xu, 1982). Thus, these results should be useful for future barley improvement.

**Qingke genome may have contributed to modern cultivated barley**

In our previous study, we proposed that *qingke* probably existed in an early stage of domestication (Dai et al., 2014). Here, we provide further evidence to support the idea that *qingke* shares a large proportion of its genome with modern cultivated barley. Gene comparison among cereal species can identify genomic

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**Figure 6** Top 1% Gene Ontology (GO) terms (a) and top 15% Kyoto Encyclopedia of Genes and Genomes (KEGG) pathways (b) analysis of the 2544 genes in selection sweep regions of *qingke* (QK) and modern cultivated barley (MCB). Numbers of genes with a certain GO term are listed after GO names separated by a comma (a), while those for the KEGG pathway are marked on the right side of the bar (b).
regions that are highly conserved or rapidly evolving, providing deeper insight into genome evolution, speciation and domestication (Matsumoto et al., 2005). Interestingly, there were four genomic regions larger than 100 Megabase (Mb) on chromosomes 1H (74.5–305.0 Mb), 2H (106.5–258.0 Mb and 399.5–500.5 Mb) and 7H (222.0–427.0 Mb), showing very low genetic diversity between Zangqing320 and Morex (Figure 3b). In contrast, the conserved regions on chromosomes 1H and 2H were much narrower between Zangqing320 and Igri (1H: 101.0–272.0 Mb, 2H: 128.0–174.0 Mb and 409.5–438.0 Mb), and between Zangqing320 and Barke (1H: 101.0–315.0 Mb, 2H: 121.0–174.0 Mb and 409.5–496.0 Mb), while the conserved region of 205 Mb on 7H between Zangqing320 and Morex was not detected between Zangqing320 and Igri or Barke (Figure S6).

It is well documented that barley used for breeding and cultivation in North America initially came from germplasm introduced mainly from Europe and East Asia (Horsley and Harvey, 2011). For instance, the most significant genetic donor of Morex is Manchuria, a six-rowed barley landrace introduced from Northeast China in the early 1900s, where part of its genome made a substantial genomic contribution to modern cultivated barley.

**Experimental procedures**

**Plant materials**

A hulless barley cultivar Zangqing320 from the Tibetan Plateau was used in this study for in-depth genome resequencing and de novo assembly. Zangqing320 was derived from a cross between a breeding line 7323 (derived from a cross between Zangq ing 334 × Lashabaqinqke) and cv. Zangqing 7239. Fifteen qingke accessions (Table S2) and a malting barley cultivar, Triumph, were used to conduct RNA-Seq at the seedling stage for SNV analysis. In addition, RNA-Seq data of 12 wild and 11 cultivated barley genotypes (including three qingke genotypes) (Table S2) from our previous study were used for SNV analysis (Dai et al., 2014; Wang et al., 2016).

**Genome sequencing**

Genomic DNA was isolated from leaves of Zangqing320 at the seedling stage. For each short-insert size library construction, 5 μg of DNA was fragmented, end-repaired, size-selected at 250, 300 and 500 base pairs (bp) on agarose gels, and ligated to Illumina PCR-free paired-end adapters. For each large-insert size mate-pair library, 20–60 μg of genomic DNA was sheared to the desired insert size using nebulization for 2 kb or HydroShear for 6 kb. DNA fragments were biotin-labelled, size-selected and circularized. Circular DNA molecules were sheared with Adaptive Focused Acoustic (Covaris, Woburn, MA) to an average size of 450 bp. Biotinylated fragments were purified on magnetic beads (Invitrogen, Carlsbad, CA) and used to construct libraries. DNA paired-end libraries of 250 and 300 bp were sequenced using Illumina HiSeq 2500 sequencing platform (Illumina, San Diego, CA). DNA paired-end libraries of 500 bp were sequenced using Illumina NextSeq 500 platform (Illumina). DNA mate-pair libraries of 2 and 6 kb were sequenced using Illumina HiSeq 2000 platform (Illumina) (Table S1).

Single-molecule real-time (SMRT) bell genomic libraries and SMRT sequence data (P4C2 chemistry, RSII platform) were generated and sequenced using a Pacific Biosciences (PacBio) SMRT sequencer (Pacific Biosciences, Menlo Park, CA) (Eid et al., 2009). The raw data reported in this study have been deposited in the National Center for Biotechnology Information Sequence Read Archive (www.ncbi.nlm.nih.gov).

**Genome assembly**

Raw reads were stringently filtered by removing: (1) reads containing more than 2% Ns or with poly-A structure, (2) reads containing 40% and 60% or more low-quality bases for short-insert and large-insert size libraries, respectively, (3) adapter-polluted reads, (4) reads overlapping between read1 and read2, and (5) PCR-duplicated reads. The 17-mer analysis was performed using the sequencing data from the 250 bp × 2 × 125 paired-end library, indicating that the peak frequency of K depth was about 21. Error correcting was undertaken using Allpaths-lg’s tools (Gnerre et al., 2011).

De novo contig assembly was conducted by Minia v1.6906 (Chikhi and Rizk, 2013). SSPACE-STANDARD-3.0 (Boetzer et al., 2011) was used to link contigs into scaffolds with mate-pair reads. Gaps in scaffolds_1 were filled using PBJelly 14.9.9 (English et al., 2012) with PacBio reads. Based on the reference genome of Morex (Mascher et al., 2017), blastn was performed with the definition standards of ‘more than 80% coverage and more than 95% similarity’ to anchor scaffolds and short contigs not making up scaffolds onto chromosomes (Figure 1).

**Genome annotation and comparison between cv. Morex and cv. Zangqing320**

After removing all adaptor sequences and low-quality reads (Q < 30 and length <50 bp), RNA-Seq reads of 39 genotypes were mapped to the genomes of Morex and Zangqing320 using Hisat2 v2.0.4 (Kim et al., 2015) with parameters of ‘--dta --score-min L,0,.08 -5 -10 -3 10’. SAM files created by Hisat2 were cleaned by CleanSam.jar program of picard-tools-1.119 (http://picard.sourceforge.net) and converted to BAM files using SAMtools (Li et al., 2009). After sorting and correcting with SAM-tools
After removing genes shorter than 300 bp and longer than 20 kb, gene sequences constructed by Stringtie were aligned with annotated gene sequences in the assembly genome of cv. Morex (version: 082214v1, http://plantsensembl.org/index.html) using blastn of Blast v2.2.28 (Altschul et al., 1990) with parameters of ‘-max_target_seqs 1 -evalue 1E-5’ and then filtered with a mapping quality score ≥2. Raw SNVs and indels were called with SAMtools mpileup and bcftools (Li et al., 2009) and then filtered with mapping quality scores ≥25 and reads coverage ≥2.

**Phylogenetic, population structure and genomic similarity analysis**

A data set of 125 157 SNVs with homozygous loci and no missing data in 39 samples were used to conduct phylogenetic and population structure analyses. The phylogenetic tree of the 39 accessions was constructed using MEGA 5.05 (Tamura et al., 2011) with neighbour-joining methods (1000 bootstraps). The population structure was investigated using frappe1.1 (Tang et al., 2005) based on a maximum-likelihood method, with 10 000 iterations and the number of clusters (K) set from 2 to 6. According to the results of the phylogenetic trees (Figures 4 and S1), population structure (Figure S2) analysis, information on collection sites (Table S2) and results from our previous study (Dai et al., 2014), we divided the 39 barley genotypes into four groups for genomic similarity analysis.

Genomic similarity analysis was performed according to Rubin et al. (2010) and Dai et al. (2014). Briefly, each SNV type with a known site was allocated to one of four groups (MCB, OK, WB-T and WB-NE) to construct four barley gene pools. We used 500-kb windows and 250-kb overlapping slide windows along the genome of Zangqing320. Unique genetic windows with the highest similarity were selected using the following criterion: ‘the number of SNVs in each window ≥25’ and ‘the similarity of each window between two groups >95%’. The unique genetic windows between MCB and the other three groups were visualized as similar genome regions using an online software ClicO FS v2.0.0 (http://codoncloud.com:3000/) (Cheong et al., 2015).

**Selective sweep analysis**

Selective sweep analysis was conducted by measuring the patterns of allele frequencies in each 500-kb fragment in 250-kb steps along chromosomes, using the SNV data of QK and MCB (Table S2). Genomic regions under selective sweeps were measured by the fixation index (FS) using VCFTools v0.1.13 (Danecak et al., 2011). Genomic regions with FS values >0.65 (about 5% top FS windows) were considered under strong selective sweeps.

**Data deposition**

The reference genome sequence and annotation file of *qingke* (cv. Zangqing 320) are available at http://www.ibgs.zju.edu.cn/ZJU_barleygenome.htm. Raw reads were deposited in the Sequence Read Archive of NCBI (www.ncbi.nlm.nih.gov), and accession numbers are listed in Tables S1 and S2.

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Conflict of interest
The authors declare no conflict of interest.

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Supporting information
Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1 Phylogenetic trees of 39 barley genotypes based on the 125 157 SNVs data set randomly distributed in the seven barley chromosomes.

Figure S2 Population structure analysis of 39 barley genotypes.

Figure S3 Genomic similarity analysis between qingke (QK) and the other three barley groups (a), or wild barley from Tibet (Wb-T) and wild barley from the Near East (Wb-NE) (b).

Figure S4 Gene Ontology (GO) analysis of the 3675 and 4877 specific genes in the reference genome of Morex and Zangqing320, respectively.

Figure S5 Unique Gene Ontology (GO) terms in Morex and Zangqing320 held by at least four specific genes.

Figure S6 Single nucleotide variant (SNV) density of Igri and Barke along the reference genome of hulless barley cv. Zangqing320.

Table S1 Summary of Zangqing320 WGS sequencing data.

Table S2 Mapping RNA-Seq reads of 39 samples to the genome of a hulless barley cv. Zangqing320 from the Tibetan Plateau.

Table S3 Number of SNVs and CpG islands.

Table S4 Genomic similarity analysis among the four barley groups based on unique genetic windows.

Data S1 Physical position and annotation of the 2544 genes in selection sweep regions of qingke (QK) and modern cultivated barley (MCB).