

A Distinct Genetic Cluster in Cultivated Chickpea as Revealed by Genome-wide Marker Discovery and Genotyping

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Abstract

The accurate description of plant biodiversity is of utmost importance to efficiently address efforts in conservation genetics and breeding. Herein, we report the successful application of a genotyping-by-sequencing (GBS) approach in chickpea (*Cicer arietinum* L.), resulting in the characterization of a cultivated germplasm collection with 3187 high-quality single nucleotide polymorphism (SNP) markers. Genetic structure inference, principal component analysis, and hierarchical clustering all indicated the identification of a genetic cluster corresponding to black-seeded genotypes traditionally cultivated in Southern Italy. Remarkably, this cluster was clearly distinct at both genetic and phenotypic levels from germplasm groups reflecting commercial chickpea classification into *desi* and *kabuli* seed types. Fixation index estimates for individual polymorphisms pointed out loci and genomic regions that might be of significance for the diversification of agronomic and commercial traits. Overall, our findings provide information on genetic relationships within cultivated chickpea and highlight a gene pool of great interest for the scientific community and chickpea breeding, which is limited by the low genetic diversity available in the primary gene pool.

Core Ideas

- Genotyping-by-sequencing analysis in cultivated chickpea generated 3187 high-quality single nucleotide polymorphisms.
- Analysis of genetic diversity supports the identification of three subpopulations.
- Accessions traditionally grown in Italy form a clearly distinct genetic cluster.
- We identified genomic regions putatively resulting from directional selection.
- Our findings are of interest for chickpea conservation genetics and breeding.

THE GRAIN LEGUME CHICKPEA is an important dietary source of proteins and essential amino acids and helps to maintain soil fertility through symbiotic N fixation. Together with wild species of the genus *Cicer*, chickpea originates from the Fertile Crescent. Its domestication dates back to the “Neolithic Revolution”, which took place in the Near East about ten thousand years ago (Abbo et al., 2007). By the Bronze Age, chickpea

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Abbreviations: F_{ST} , pairwise fixation index; GBS, genotyping-by-sequencing; K, number of hypothetical subpopulations; LD, linkage disequilibrium; PCA, principal component analysis; SNP, single nucleotide polymorphism; SVS, SNP & Variation Suite.

Published in Plant Genome
Volume 10. doi: 10.3835/plantgenome2016.11.0115

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cultivation had spread throughout the Mediterranean Basin, Central Asia, and Africa. To date, chickpea is the second most abundantly grown food legume in the world. India is the world leader in chickpea production, followed by Pakistan and Turkey. Other major producers are Ethiopia and Mexico (Mansfeld, 2008).

Despite its economic importance and the availability of several cultivars, the world average yield of chickpea (0.96 t ha^{-1} , FAOSTAT 2014) is far below the potential yield of about 5 t ha^{-1} . This gap is mainly attributable to poor resistance to biotic and abiotic stresses (Amin and Melkamu, 2014). Breeding efforts to increase chickpea yield are frustrated by the limited genetic diversity available within cultivated germplasm. This is thought to be the result of four evolutionary bottlenecks, caused by the narrow eco-geographic distribution of the wild progenitor (*Cicer reticulatum* Ladiz.), the founder effect associated with domestication, the selection of genotypes adapted to spring sowing, and the replacement of local landraces (Abbo et al., 2003).

The study of DNA diversity is of great importance for addressing conservation programs contrasting the erosion of cultivated gene pools and to guide the use of germplasm in breeding. In chickpea, the first studies on genetic diversity were, in most cases, based on simple sequence repeat molecular markers (Nayak et al., 2010). More recently, with the advent of next-generation sequencing technologies and the complete sequencing of the chickpea genome (Jain et al., 2013; Varshney et al., 2013), single nucleotide polymorphism (SNP) markers have been widely used, as they are present in a large number and merge excellent genetic attributes (Kujur et al., 2013). At present, the genotyping-by-sequencing (GBS) assay is considered one of the most convenient approaches for simultaneous large-scale SNP discovery and genotyping (Elshire et al., 2011).

Previous studies partitioned the diversity of cultivated chickpea in two gene pools, broadly reflecting the occurrence of two main commercial seed types: *desi* (small and dark-colored) and *kabuli* (large and cream-colored) (Upadhyaya et al., 2008; Bajaj et al., 2015a). A third, uncommon type of chickpea has a centuries-long tradition of cultivation in the region of Apulia in the southeast of Italy. It is called black chickpea (*cece nero*, in Italian) and was recently reported to be darker and bigger than common *desi* types (Mohammadi, 2015). Similarly to other traditional landraces, Apulian black chickpea is being replaced by modern cultivars and is thus at risk of genetic erosion.

In this study, we used a GBS approach to describe chickpea biodiversity. For the first time, the Apulian black chickpea was included in a study on genetic diversity and it is reported to form a clearly distinct genetic and phenotypic cluster of great interest for the scientific community and for breeding.

Materials and Methods

Plant Material

Details on the germplasm characterized in this study are provided in Supplementary Table S1. A set of 29 *desi* and 28 *kabuli* chickpea accessions were selected from the *ex situ* collections of the USDA-ARS, the Department of Plant, Soil and Food Science of the University of Bari (Italy), and the Institute of Biosciences and Bioresources of the Italian National Research Council. Accessions were mainly selected for their origin, to represent the geographic distribution of chickpea global cultivation, and included black-seeded accessions. A set of 25 Apulian chickpea accessions, now included in the Department of Plant, Soil and Food Science of the University of Bari repository, was collected by means of missions performed throughout the Apulian territory.

Genotyping-by-sequencing, Genotyping, and SNP Validation

Genomic DNA was isolated from young leaf samples using the DNeasy Plant Mini Kit (Qiagen). An *ApeKI* GBS library was prepared as described by Elshire et al. (2011) and sequenced using the Illumina HiSeq 2500 device (Illumina Inc., San Diego, CA). The FASTQ files used to generate the VCF file are available at the National Center for Biotechnology Information Short Read Archive (<http://www.ncbi.nlm.nih.gov/sra/>, accessed 10 Apr. 2017) database under the accession number SRX1706615. Master tags (i.e., collapsed unique sequence tags) were aligned to the reference chickpea 1.0 genome (Varshney et al., 2013) by the Burrows–Wheeler Aligner tool (version 0.7.8-r455) with default settings. Single nucleotide polymorphism calling implemented within the TASSEL-GBS pipeline (Glaubitz et al., 2014) was used to generate a VCF file. Biallelic SNPs were filtered for minimum depth of five reads, a minor allele frequency higher than 1%, a call rate higher than 90%, and an inbreeding coefficient higher than 0.8 using TASSEL (version 5.2.20) (Bradbury et al., 2007). A threshold of 15% was set to remove accessions with missing data. Vcf-annotate from VCFtools (version 0.1.13) (Danecek et al. 2011) and the *Cicer arietinum* gene annotation (ftp://climb.genomics.cn/pub/10.5524/100001_101000/100076/Cicer_arietinum_GA_v1.0.gene.gff, accessed 10 Apr. 2017) allowed the mapping of SNPs on genic or intergenic regions. The VCFtools package also served to derive the percentage of homozygous or heterozygous loci and the distribution of SNP substitution types. To validate the polymorphisms detected with the GBS assay, amplicons harboring seven randomly selected SNP loci were obtained from the three accessions ‘Califfo’ (*kabuli*), ‘W610046’ (*desi*), and ‘MG29’ (*Apulian*) by means of the primers reported in Supplementary Table S2 and used for Sanger sequencing.

Population Structure and Molecular Diversity

The software STRUCTURE (version 2.3.4) (Pritchard et al., 2000) was used to estimate the number of hypothetical subpopulations (K) and the probability of individual accessions to fall in each subpopulation. As the STRUCTURE algorithm assumes that the loci are independent, the SNP dataset was pruned prior to analysis, on the basis of pairwise linkage disequilibrium (LD) between adjacent markers, using the SNP & Variation Suite (SVS) software package (version 8.4.0, Golden Helix Inc.) and the 0.5 r^2 threshold. A Bayesian clustering approach was used, in which the hypothesis of 1 to 10 subpopulations was set and a Markov chain Monte Carlo of 100,000 burn-in phases followed by 100,000 iterations was run independently 10 times using an admixture model. The value of the ad hoc quantity ΔK was chosen as a criterion to estimate the true K (Evanno et al., 2005). Individual samples were assigned to any of the subpopulations if the value of the corresponding membership coefficient (q) was higher than 0.6; otherwise, they were considered to be of admixed ancestry.

Molecular diversity among accessions was analyzed with the principal component analysis (PCA) tool implemented in SVS, using the LD-pruned SNP dataset as input. In addition, a neighbor-joining tree was obtained via MEGA6 (Tamura et al., 2013), performing 1000 bootstrap replications.

Pairwise fixation index (F_{ST}) estimates among the three chickpea subpopulations identified by STRUCTURE were calculated using the formula of Weir and Cockerham (1984) implemented in SVS, excluding admixed individuals. To estimate overall F_{ST} , LD-pruned SNP were used. Instead, single-marker F_{ST} estimates were computed on the whole SNP dataset. Markers with pairwise estimates higher than 0.9 were used to draw a custom Venn diagram (<http://bioinformatics.psb.ugent.be/webtools/Venn/>, accessed 10 Apr. 2017). A plot of single-marker F_{ST} estimates against the chickpea 1.0 genome assembly was obtained by using the GenomeBrowse function in SVS.

Phenotypic Evaluation of Seed Weight

The germplasm collection described in Supplementary Table S1 was grown at the experimental farm P. Martucci of the University of Bari (41°01'22.1"N 16°54'21.0"E) during the growing season of 2013–2014. Plants were disposed according to a randomized block design with four replicates, each replicate containing 10 individual plants. At crop maturity, 25 seeds from each block were used to measure the weight of 100 seeds. For cultivated accessions included in the chickpea reference set collection (Upadhyaya et al., 2008), the weight of 100 seeds parameter was extracted from the Germplasm Resources Information Network web server database (<http://www.ars-grin.gov>, accessed 10 Apr. 2017). Significant differences in pairwise comparisons among groups of accessions were inferred by Student's t -test.

Results

Single Nucleotide Polymorphism Discovery, Genotyping, and Validation

Sequencing of the ApeKI GBS library yielded about 198 million good barcoded reads from *desi* (29) and *kabuli* (28) accessions, originating from the main chickpea growing countries, and 25 Apulian black chickpea accessions (Supplementary Table S1). This corresponds, on average, to 2.5 million good reads per sample. Alignment of the reads with the chickpea reference genome yielded 80% tags aligned to unique positions, 10% to multiple positions, and 10% tags that could not be aligned.

Biallelic SNPs were selected and filtered on the basis of the call rate ($\geq 90\%$), minimum depth (5 \times) and minor allele frequency (≥ 0.01), resulting in 37,495 polymorphisms. A further filter based on the inbreeding coefficient F_{IT} was applied, as suggested by Glaubitz et al. (2014), to remove error-prone SNPs and spurious SNPs from paralogy. At the end of the process, 3187 SNPs were obtained in a final dataset of 82 genotypes. The accession W617430 was removed from further analyses because of an excess of missing data. The average depth of coverage was 28.6 reads per SNP locus; the observed depth of coverage distribution across accessions is reported in Supplementary Fig. S1. Single nucleotide polymorphism quality was tested via Sanger sequencing of seven randomly selected SNP loci from three different accessions (see Materials and Methods), resulting in the validation of all the polymorphisms called by the GBS assay. Chromosomes 1–8 contained 561, 275, 249, 851, 197, 438, 269, and 138 SNP loci, respectively, with an average density of one locus per 112.797 kb. The remaining 209 markers were positioned on scaffolds that could not be placed on any chickpea chromosome. Using the available gene coordinates (Varshney et al., 2013), 69 and 31% of the SNP loci were assigned to genic and intergenic regions, respectively. The vast majority of SNP loci was homozygous for either the reference (72.8%) or the alternate allele (24.8%), whereas a few loci were scored as heterozygous (1.6%) or were associated with missing data (0.7%) (Supplementary Fig. S2). Concerning SNP substitutions, the observed transition/transversion ratio was 1.61, resulting from 1748 transitions and 1083 transversions. The most and less represented substitution types were the A–G transition (28.4%) and the C–G transversion (6.9%).

Genetic Structure

An admixture-based clustering model was used to infer the genetic structure of the germplasm collection genotyped in this study. As the model assumes independent loci, prior to analysis, the SNP dataset was pruned by setting a maximum threshold of LD between adjacent markers, resulting in an input file of 1015 markers. According to the ΔK inference approach, a model with three subpopulations best fitted the data (Supplementary Fig. S3), in which 94% of the accessions were assigned to

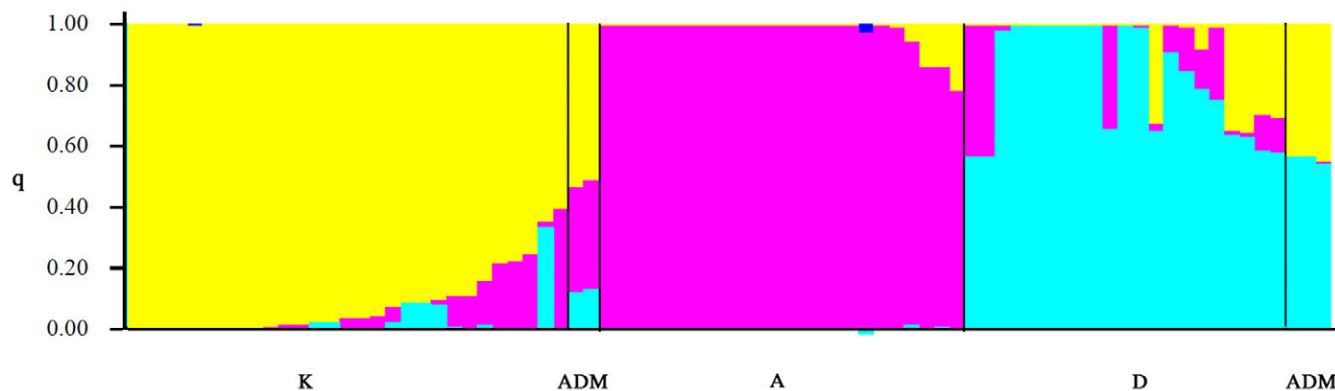


Fig. 1. Population structure analysis of cultivated chickpea germplasm. Results are shown for $K = 3$, which corresponds to the number of subpopulations that sufficiently defines genetic variation (see Fig. S3). These are named K, A, and D as they mostly group *kabuli*, Apulian black chickpea, and *desi* genotypes, respectively. Each individual is represented by a vertical line, which is partitioned into colored segments that represent the estimated membership fractions (q) in each subpopulation. Individuals of admixed (ADM) ancestry (highest $q < 0.6$) are indicated.

a specific subpopulation (membership coefficient $q \geq 0.6$) and 6% of accessions showed admixed ancestry. Notably, one of the subpopulations, named A, contained 21 accessions of Apulian black chickpea, suggesting the identification of a peculiar gene pool. The second subpopulation (K) grouped all the *kabuli* accessions and four accessions of Apulian chickpea ('MG_9', 'MG_15', 'MG_17', and 'MG_24'). The third subpopulation (D) contained all the *desi* accessions and two *kabuli* accessions (PI 292005 and PI 343014) (Fig. 1). Pairwise fixation index (F_{ST}) estimates were 0.31 between A and K, 0.26 between A and D, and 0.19 between K and D.

Genetic Relationships among Individuals

Principal component analysis substantiated the results obtained from structural analysis and indicated patterns of molecular diversity among individual accessions. As shown in Fig. 2a, a PCA cluster consisted entirely of the Apulian black chickpea accessions falling within the A subpopulation. Another PCA group was formed by *kabuli* types and the Apulian chickpea accessions MG_9, MG_15, MG_17, and MG_24. *Desi* chickpeas were more scattered throughout the PCA plot, indicating higher genetic variability. Neighbor-joining clustering analysis provided bootstrap support for differentiating a monophyletic clade corresponding to Subpopulation A and gave a measure of genetic distance among the accessions genotyped in this study (Fig. 2b).

Phenotypic Evaluation of the Collection

To provide phenotypic support to the GBS results, we characterized our germplasm collection for the 100-seed weight (Supplementary Table S1) and extracted 100-seed weight estimates from the reference set collection reported by Upadhyaya et al. (2008), previously indicated as being representative of chickpea genetic variation. The average weight measured for the A cluster (26.4 g) resulted significantly higher than the one displayed by *desi* genotypes present in our collection (18 g) and in

the reference set collection (16.7 g). Analogous conclusions could be drawn when comparing the A group with black-seeded *desi* germplasm (Supplementary Table S3). Remarkably, many A accessions were associated with seed weights that were comparable with or exceeding the maximum value observed for *desi* germplasm (Supplementary Tables S1 and S3), thus substantiating the notion that A forms a distinct gene pool.

Genetic Divergence at Individual Loci

To identify genomic regions putatively subjected to different selection pressures in the subpopulations A, D and K, we estimated, at individual SNP loci, the pairwise fixation index (F_{ST}). This parameter approaches the upper limit of 1 when two genetic groups tend to fix alternative alleles. The genomic distribution of SNP loci in the function of the F_{ST} distance highlighted two large genomic windows on chickpea chromosomes 1 and 4 differentiating the germplasm of K from that of A and D (Fig. 3).

Aiming to detect SNPs that are highly polymorphic among A, D, and K, we selected loci associated with pairwise F_{ST} estimates higher than 0.9. No locus of this type was found when we examined K and D. Conversely, 11 loci were detected when we compared A and D, positioned on five different regions of chromosomes 4, 5, 6, 7, and 8 and 4 loci were detected when we compared A and K, positioned on four different regions of chromosomes 4, 5, and 6 (Fig. 4 and Supplementary Table S4). Two loci on chromosomes 4 and 5 were highly polymorphic in both the A–D and the A–K pairwise comparisons. One of them (4:38978423-SNV) defined a private allele, unique for the A group ($F_{ST[A \text{ vs. } K]} = 1$ and $F_{ST[A \text{ vs. } D]} = 1$) (Fig. 4 and Supplementary Table S4).

Discussion

Understanding genetic variation in cultivated plant species is of utmost importance for adopting efficient strategies for germplasm conservation and for coping with breeding issues. Therefore, in the last few years, several

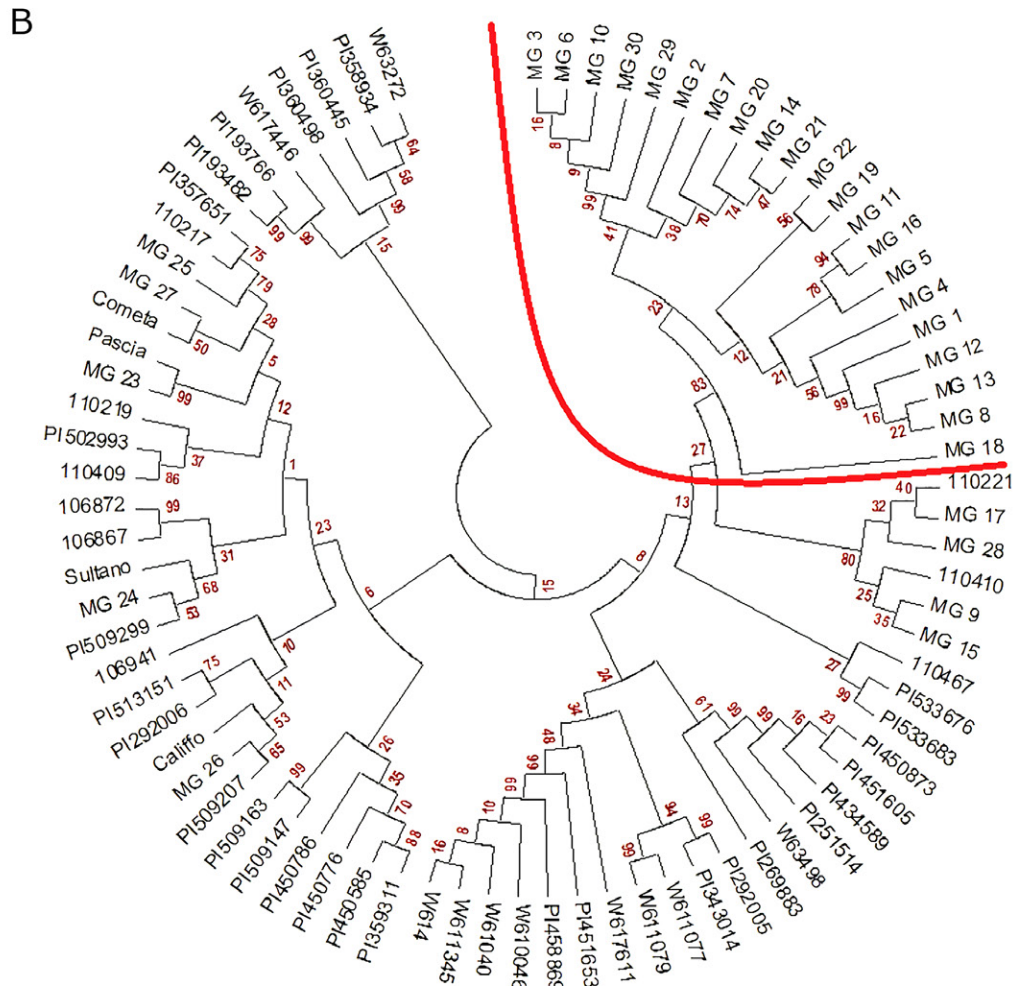
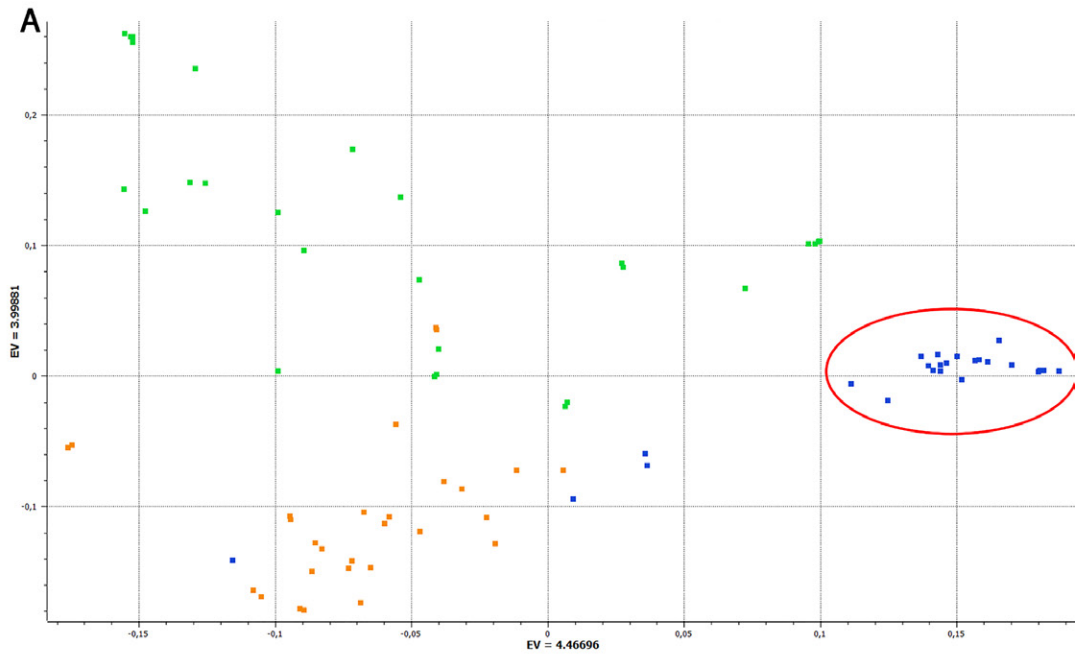


Fig. 2. Genetic relationships within the germplasm collection used in this study. (A) Principal component analysis (PCA) plot of the first two components. Different colors represent *desi* (green), *kabuli* (orange), and Apulian black chickpea (blue) accessions. A cluster of Apulian black chickpea accessions corresponding to the A subpopulation is circled. (B) Neighbor-joining tree. A monophyletic clade containing accessions of the A subpopulation is delimited by an arch.

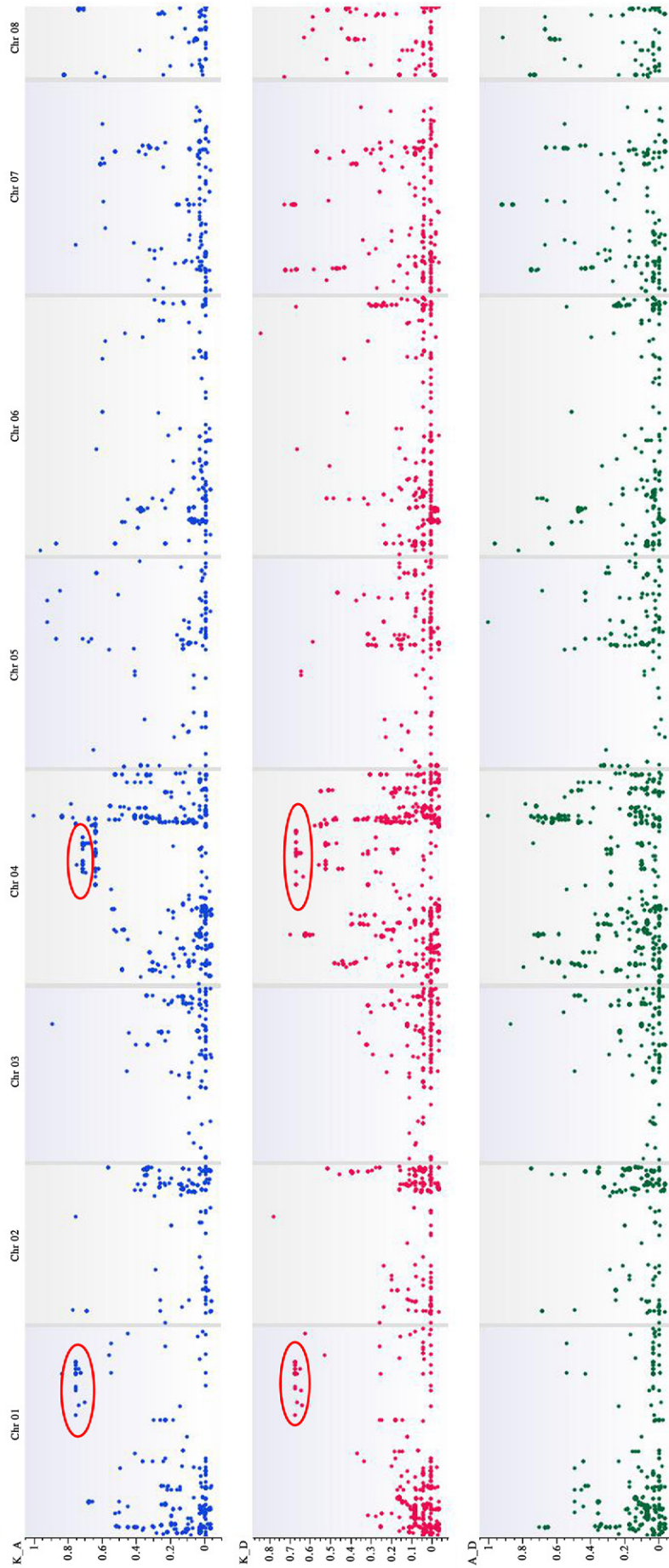


Fig. 3. Genomic distribution of 3187 single nucleotide polymorphism (SNP) markers identified in this study in the function of pairwise F_{ST} estimates between the D, K, and A subpopulations identified by structure analysis. Highly polymorphic genomic regions on chromosomes 1 and 4 are highlighted.

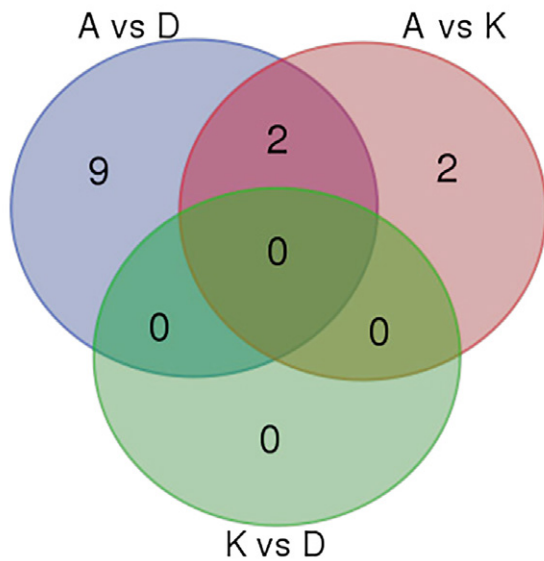


Fig. 4. Distribution of single nucleotide polymorphism (SNP) markers among subpopulations identified by STRUCTURE analysis. Accessions of admixed ancestry were excluded. The Venn diagram refers to markers associated with pairwise F_{ST} estimates higher than 0.9.

investigations addressed the characterization of DNA polymorphisms in chickpea. In this study, we used GBS as an efficient and cost-effective strategy to simultaneously discover and genotype a large number of polymorphisms. Similarly to previous GBS assays on chickpea (Bajaj et al., 2015a, 2015b), we obtained, on average, 2.5 million good reads per sample. We applied a strong SNP calling filter by setting 0.8 as the minimum value of the inbreeding coefficient F_{IT} , as suggested by Glaubitz et al. (2014). We believe that this is a reliable strategy for removing error-prone SNPs and spurious SNPs from paralogy without losing valid information, as chickpea is a strictly self-pollinated species and thus is expected to be highly homozygous. Indeed, except for the accessions PI 458706 and 106867, which might derive from relatively recent hybridization events, our germplasm collection was characterized by a very low percentage of heterozygous SNP loci (ranging from 0.14 to 6.3%) (Supplementary Fig. S2). First-generation sequencing of random SNP loci provided a direct indication of the high quality of the SNP dataset used in this study.

Prior to this study, the Apulian black chickpea was mentioned by Mohammadi (2015), indicating its peculiar features compared with the commercial types *desi* and *kabuli*. However, no work has addressed its genetic characterization. Here, inference on chickpea's genetic structure resulted in the characterization of a subpopulation (A) that only contained Apulian black accessions, separated by a considerably high F_{ST} distance from *desi* and *kabuli* subpopulations (Fig. 1). Principal component analysis, hierarchical clustering, and phenotypic data further indicated the peculiarity of the A genetic group (Fig. 2 and Supplementary Table S3). The collection used in this study contained chickpea germplasm from

different geographical origins, including non-Italian black-seeded accessions. However, it has a moderate size and thus it is possible that future genetic analyses will not result in the same clear-cut separation between the A cluster and other cultivated germplasm reported here. However, the phenotypic and genetic data provided in this study clearly indicate that Apulian black chickpeas are distinct from common cultivated germplasm. In support of this notion, we showed that the A group significantly differs, at the phenotypic level, from the *desi* and *kabuli* accessions included in a collection previously indicated as being representative of chickpea genetic variation (Upadhyaya et al., 2008).

The F_{ST} estimates at individual SNP loci indicate the occurrence of several A alleles that are absent or present at very low frequencies in D and K (Fig. 4 and Supplementary Table S4), further indicating the necessity of preserving the A gene pool from genetic erosion. The plot of pairwise F_{ST} estimates at individual loci indicated the presence of two large regions on chickpea chromosomes 1 and 4 that were associated with F_{ST} values around 0.7, differentiating K from A and D (Fig. 3). These regions might be of great significance for the diversification of peculiar traits within cultivated chickpea germplasm. Loci showing high pairwise F_{ST} did not overlap with any of the 15 genomic *loci* predicted to control seed coat color (Bajaj et al., 2015a). As this trait is known to be quantitatively inherited (Bajaj et al., 2015a), our findings indicate that there are no peculiar QTL alleles for seed color in the subpopulations characterized in this study.

Interestingly, we found that four Apulian black chickpea accessions, namely MG_9, MG_15, MG_17, and MG_24, were genetically close to the cream-colored seed *kabuli* genotypes and grouped in the K subpopulation (Fig. 1 and Fig. 2). Apart from the color, seeds of these accessions are similar to *kabuli* types, as they are large and smooth (Fig. 5). We conclude that these accessions might originate from artificial or natural crosses between A and K genotypes, followed by selection by local farmers. In further support of this hypothesis, the same four accessions contain several SNP alleles typical of the A subpopulation. The exclusion of these accessions from F_{ST} analysis raises the number of *loci* associated with $F_{ST}^{[A \text{ vs. } K]} > 0.9$ to 35, the number of alleles associated with $F_{ST}^{[A \text{ vs. } K]} > 0.9$ and $F_{ST}^{[A \text{ vs. } D]} > 0.9$ to five, and the number of A private alleles to two (Supplementary Fig. S4).

We found that two accessions with a *kabuli* type seed (PI 292005 and PI 343014) actually fall within the D subpopulation. Moreover, we could not detect highly polymorphic loci when we compared D and K (Fig. 4). This is consistent with the hypothesis of the relatively recent evolution of *kabuli* chickpeas from *desi* ancestors (Roorkiwal et al., 2014). Apulian chickpeas might also stem from *desi* types. In this case, high genetic distance between A and D might be the result of peculiar selection pressures, genetic drift, or both. Clearly, future studies might provide insights into the evolution of Apulian germplasm.



Fig. 5. Seed phenotype of a typical *kabuli* accession (cv. Cometa) (a), a typical accession of Apulian black chickpea (MG_21) (b), and the accessions MG_9 (c), MG_15 (d), MG_17 (e), and MG_24 (f).

In conclusion, our results provide insights into molecular diversity and relationships within cultivated chickpea and identify a gene pool of great interest for chickpea conservation genetics and breeding, which suffers from the narrow genetic basis available in the primary chickpea gene pool. Information on the Apulian black chickpea is still scarce. We are currently performing an extensive characterization of its agronomic, nutritional, and technological properties to detect features of interest for breeding purposes.

Supplemental Information

Supplementary Table S1. Cultivated chickpea accessions genotyped in this study.

Supplementary Table S2. List of primer pairs used to validate GBS polymorphisms via Sanger sequencing.

Supplementary Table S3. Pairwise 100-seed weight mean comparisons among different groups of accessions. A, D and K stand for the subpopulations identified by STRUCTURE analysis; *Desi* and *Kabuli* refer to groups extracted from the chickpea reference set collection; ** and n.s. indicate significant and non-significant differences ($p < 0.01$) with the A group, respectively.

Supplementary Table S4. List of markers with pairwise F_{ST} estimates (A vs D and A vs K) higher than 0.9. The locus 4:38978423-SNV, harbouring an allele unique to A, is highlighted. For each SNP locus falling into a gene, gene identification (Cicer_arietinum_GA_v1.0) and gene description are reported.

Supplementary Figure S1. Mean read depth for each accession.

Supplementary Figure S2. Frequency distribution of homozygous loci, heterozygous loci and missing data for each accession.

Supplementary Figure S3. ΔK distribution from STRUCTURE analysis. $K=3$ shows a peak indicating that three subpopulations sufficiently define genetic variation in the cultivated chickpea dataset used in this study.

Supplementary Figure S4. Distribution of SNP polymorphisms among subpopulations identified by STRUCTURE analysis. Accessions of admixed ancestry (highest $q < 0.6$) and the accessions MG_9, MG_15, MG_17, and MG_24 were excluded from analysis. The Venn diagram refers to markers associated with pairwise F_{ST} estimates higher than 0.9.

Conflict of Interest Disclosure

The authors declare no conflicts of interest.

Acknowledgments

Financial support to this work was granted by the project “Recupero, caratterizzazione, Salvaguardia e Valorizzazione di leguminose e cereali da GRAanella e foraggio IN PUGLIA (SaVeGraINPuglia)”, Programma di Sviluppo Rurale (PSR), European Agricultural Fund for Rural Development (EAFRD) 2007-2013, Council Regulation (EC) No 1698/2005. The authors acknowledge the farm “Iannone Anna” for kindly providing several accessions of Apulian black chickpea and Mrs. Anita Morgese for technical help.

References

- Abbo, S., J. Berger, and N.C. Turner. 2003. Evolution of cultivated chickpea: Four bottlenecks limit diversity and constrain adaptation. *Funct. Plant Biol.* 30:1081–1087. doi:10.1071/FP03084
- Abbo, S., R.J. Redden, and S.S. Yadav. 2007. Utilization of wild relatives. In: S.S. Yadav, R.J. Redden, W. Chen, and B. Sharma, editors, Chickpea breeding and management. CAB International, Wallingford, UK. p. 338–354.
- Amin, M., and F. Melkamu. 2014. Management of *Ascochyta* blight (*Ascochyta rabiei*) in chickpea using a new fungicide. *Res. Plant Sci.* 2:27–32. doi:10.12691/plant-2-1-6

- Bajaj, D., S. Das, H.D. Upadhyaya, R. Ranjan, S. Badoni, V. Kumar, et al. 2015a. A genome-wide combinatorial strategy dissects complex genetic architecture of seed coat color in chickpea. *Front. Plant Sci.* 6:979. doi:10.3389/fpls.2015.00979
- Bajaj, D., M.S. Saxena, A. Kujur, S. Das, S. Badoni, S. Tripathi, et al. 2015b. Genome-wide conserved non-coding microsatellite (CNMS) marker-based integrative genomics for quantitative dissection of seed weight in chickpea. *J. Exp. Bot.* 66:1271–1290. doi:10.1093/jxb/eru478
- Bradbury, P.J., Z. Zhang, D.E. Kroon, T.M. Casstevens, Y. Ramdoss, and E.S. Buckler. 2007. TASSEL: Software for association mapping of complex traits in diverse samples. *Bioinformatics* 23:2633–2635. doi:10.1093/bioinformatics/btm308
- Danecek, P., A. Auton, G. Abecasis, C.A. Albers, E. Banks, M.A. DePristo, et al. 2011. The variant call format and VCFtools. *Bioinformatics* 27:2156–2158.
- Elshire, R.J., J.C. Glaubitz, Q. Sun, J.A. Poland, K. Kawamoto, E.S. Buckler, et al. 2011. A robust, simple genotyping-by-sequencing (GBS) approach for high diversity species. *PLoS ONE* 6:e19379. doi:10.1371/journal.pone.0019379
- Evanno, G., S. Regnaut, and J. Goudet. 2005. Detecting the number of clusters of individuals using the software STRUCTURE: A simulation study. *Mol. Ecol.* 14:2611–2620. doi:10.1111/j.1365-294X.2005.02553.x
- FAOSTAT. 2014. FAO statistical databases. Food and Agricultural Organization. <http://faostat.fao.org/> (accessed 10 Apr. 2017)
- Glaubitz, J.C., T.M. Casstevens, L. Fei, J. Harriman, R.J. Elshire, and Q. Sun. 2014. TASSEL-GBS: A high capacity genotyping by sequencing analysis pipeline. *PLoS ONE* 9:e90346. doi:10.1371/journal.pone.0090346
- Jain, M., G. Misra, R.K. Patel, P. Priya, S. Jhanwar, A.W. Khan, et al. 2013. A draft genome sequence of the pulse crop chickpea (*Cicer arietinum* L.). *Plant J.* 74:715–729. doi:10.1111/tpj.12173
- Kujur, A., D. Bajaj, M.S. Saxena, S. Tripathi, H.D. Upadhyaya, C.L. Gowda, et al. 2013. Functionally relevant microsatellite markers from chickpea transcription factor genes for efficient genotyping applications and trait association mapping. *DNA Res.* 20:355–374. doi:10.1093/dnares/dst015
- Mansfeld. 2008. *Cicer arietinum* subsp. *arietinum*. Mansfeld's world database of agricultural and horticultural crops. IPK Gatersleben. http://mansfeld.ipk-gatersleben.de/apex/f?p=185:145:::NO::P3_BOTNAME:Cicer%20arietinum (accessed 10 Apr. 2017)
- Mohammadi, K. 2015. Nutritional composition of Iranian desi and kabuli chickpea (*Cicer arietinum* L.) cultivars in autumn sowing. *Int. J. Biol., Biomolecular, Agric. Food and Biotech. Eng.* 9:514–517.
- Nayak, S.N., H. Zhu, N. Varghese, S. Datta, H.K. Choi, R. Horres, et al. 2010. Integration of novel SSR and gene-based SNP marker loci in the chickpea genetic map and establishment of new anchor points with *Medicago truncatula* genome. *Theor. Appl. Genet.* 120:1415–1441. doi:10.1007/s00122-010-1265-1
- Pritchard, J.K., M. Stephens, and P. Donnelly. 2000. Inference of population structure using multilocus genotype data. *Genetics* 155:945–959.
- Roorikwal, M., S.N. Nayak, M. Thurdi, H.D. Upadhyaya, D. Brunel, P. Mournet, et al. 2014. Allele diversity for abiotic stress responsive candidate genes in chickpea reference set using gene based SNP markers. *Front. Plant Sci.* 5:248. doi:10.3389/fpls.2014.00248
- Tamura, K., G. Stecher, D. Peterson, A. Filipski, and S. Kumar. 2013. MEGA6: Molecular evolutionary genetics analysis version 6.0. *Mol. Biol. Evol.* 30:2725–2729. doi:10.1093/molbev/mst197
- Upadhyaya, H.D., S.L. Dwivedi, M. Baum, R.K. Varshney, S.M. Udupa, C.L.L. Gowda, et al. 2008. Genetic structure, diversity, and allelic richness in composite collection and reference set in chickpea (*Cicer arietinum* L.). *BMC Plant Biol.* 8:106. doi:10.1186/1471-2229-8-106
- Varshney, R.K., C. Song, R.K. Saxena, S. Azam, S. Yu, A.G. Sharpe, et al. 2013. Draft genome sequence of chickpea (*Cicer arietinum*) provides a resource for trait improvement. *Nat. Biotechnol.* 31:240–246. doi:10.1038/nbt.2491
- Weir, B.S., and C.C. Cockerham. 1984. Estimating F-statistics for the analysis of population structure. *Evolution* 38:1358–1370. doi:10.2307/2408641