ARTICLE

Elucidation of the ‘Honeycrisp’ pedigree through haplotype analysis with a multi-family integrated SNP linkage map and a large apple (*Malus × domestica*) pedigree-connected SNP data set

Nicholas P Howard¹, Eric van de Weg², David S Bedford¹, Cameron P Peace³, Stijn Vanderzande³, Matthew D Clark¹, Soon Li Teh¹, Lichun Cai⁴ and James J Luby¹

The apple (*Malus × domestica*) cultivar Honeycrisp has become important economically and as a breeding parent. An earlier study with SSR markers indicated the original recorded pedigree of ‘Honeycrisp’ was incorrect and ‘Keepsake’ was identified as one putative parent, the other being unknown. The objective of this study was to verify ‘Keepsake’ as a parent and identify and genetically describe the unknown parent and its grandparents. A multi-family based dense and high-quality integrated SNP map was created using the apple 8 K Illumina Infinium SNP array. This map was used alongside a large pedigree-connected data set from the RosBREED project to build extended SNP haplotypes and to identify pedigree relationships. ‘Keepsake’ was verified as one parent of ‘Honeycrisp’ and ‘Duchess of Oldenburg’ and ‘Golden Delicious’ were identified as grandparents through the unknown parent. Following this finding, siblings of ‘Honeycrisp’ were identified using the SNP data. Breeding records from several of these siblings suggested that the previously unreported parent is a University of Minnesota selection, MN1627. This selection is no longer available, but now is genetically described through imputed SNP haplotypes. We also present the mosaic grandparental composition of ‘Honeycrisp’ for each of its 17 chromosome pairs. This new pedigree and genetic information will be useful in future pedigree-based genetic studies to connect ‘Honeycrisp’ with other cultivars used widely in apple breeding programs. The created SNP linkage map will benefit future research using the data from the Illumina apple 8 and 20 K and Affymetrix 480 K SNP arrays.

Horticulture Research (2017) 4, 17003; doi:10.1038/hortres.2017.3; Published online 22 February 2017

INTRODUCTION

‘Honeycrisp’ has emerged as an economically lucrative apple (*Malus × domestica*) cultivar in North America that has steadily gained market share since its introduction by the University of Minnesota (UMN) apple breeding program in 1991. It has also been an increasingly important parent due to its reportedly ultracrisp texture, its ability to retain this high level of crispness in storage and its resistance to apple scab. ‘Honeycrisp’ is a parent of multiple commercially released cultivars including ‘Minneiska’,8 ‘New York 1’,9 ‘CN B60’,10 ‘CN 121’,11 ‘DS 22’,12 ‘WA 38’,13 ‘MAIA1’,14 ‘MNSS’15 and new Chinese cultivars, with many additional offspring under testing around the world as advanced breeding selections. The importance of ‘Honeycrisp’ in production and breeding has led to many studies of the physiology and genetics of the variety. It was quickly discovered that the originally recorded parentage, ‘Honeygold’ × ‘Macoun’,2 did not complement phenotype information for several key traits.4 As DNA markers became increasingly available for apple, analysis of simple sequence repeat (SSR) markers confirmed that the recorded parentage was incorrect.16 Breeding records of the UMN apple breeding program indicated that the cross that begat ‘Honeycrisp’ was likely made around 1960, but a lack of records from this period rendered direct validation of parentage inconclusive.

‘Honeycrisp’ was first selected from a seedling block as MN1711 in 1974. The original tree had been discarded due to winter injury in 1977. Four clonal propagules that were planted in a testing orchard had also been flagged for removal, but they were spared and kept for further evaluation by the newly appointed breeder, David Bedford, because the trees had been planted in a poor site and there had been insufficient evaluation notes taken for the selection. No additional records were available that could be used to identify likely parents and it had been speculated that the original parent might have been an older selection from the program that was discarded.16 ‘Keepsake’ was identified as one of the parents based on results from 11 SSR markers, but the identity of the second parent has remained a mystery.

Past studies evaluating pedigree relationships in apple have been conducted with a range of genetic marker types including SNPs in chloroplast DNA,17 randomly amplified polymorphic DNA18 and SSRs.16,19 Recently, single-nucleotide polymorphism (SNP) arrays have become available for apple,20–22 making possible the generation of a large amount of standardized genetic data that are useful for relationship analyses. SNP array-based parental testing has been successfully used to identify ‘Common Antonovka’ as the parent of a series of selections that had been widely used in the breeding for scab resistance.23 In sweet cherry (*Prunus avium*), SNP

¹Department of Horticultural Science, University of Minnesota, St Paul, MN 55104, USA; ²Department of Plant Breeding, Wageningen University and Research, Wageningen 6700AJ, The Netherlands; ³Department of Horticulture and Landscape Architecture, Washington State University, Pullman, WA 99164, USA and ⁴Department of Horticulture, Michigan State University, East Lansing, MI 48824, USA.

Correspondence: JJ Luby (lubyx001@umn.edu)

Received: 16 January 2017; Revised: 27 January 2017; Accepted: 30 January 2017
array data have been successfully used for the identification of the previously unknown paternal parent of the important U.S. cultivar Bing. The SNP arrays and wealth of genetic data generated through the RosBREED project, funded in part by the USDA-Specialty Crop Research Initiative, has provided an excellent opportunity for this type of relationship testing. The objective of this study was to test an earlier hypothesis that ‘Keesaple’ is one parent of ‘Honeycrisp’ and to identify and genetically describe the unknown parent and grandparents of ‘Honeycrisp’ using a much larger set of DNA markers than was previously available with this germplasm. This work relied on the adequate phasing of thousands of SNP markers, which was made possible through the development and use of a high-quality integrated SNP linkage map, also described in this study, that was developed by closely following many methods used by Di Pierro et al.

MATERIALS AND METHODS

Genetic map creation

Five families with ‘Honeycrisp’ as a common parent were used in the creation of the integrated genetic map used in this study. These families were described by McKay et al. and planted as clonal replicates on ‘Budagovsky 9’ rootstocks at the UMIN’s Horticultural Research Center in Chanhassen, Minnesota, USA in 2010. These families were ‘Honeycrisp’ × MN1764 (n = 156), ‘Honeycrisp’ × ‘Monark’ (n = 91), ‘Honeycrisp’ × ‘Tomator’ Pineapple (n = 60), ‘Honeycrisp’ × ‘Jonafree’ (n = 57) and ‘Honeycrisp’ × MN1702 (n = 49). Leaf samples were collected from these individuals for extraction of DNA that was hybridized onto the International RosBREED SNP Consortium 8 K Illumina Infinium array v1.23 following the methods outlined in Clark et al. The first two of these five populations were previously used in the creation of an earlier ‘Honeycrisp’ consensus genetic map. The raw iScan data output from the apple 8 K SNP array from all individuals was imported into the genotyping module of GenomeStudio software version 1.9.4 for SNP scoring (Illumina, Inc., San Diego, CA, USA). SNP scores were coded as A and B in GenomeStudio. SNP probe sequences were used at each step to order the SNPs in a way that approximated the original marker order was created for all of the markers across all of the mapping families. Hereo initial marker orders were determined through the construction of a consensus map created using the LPmerge package in the statistical software R version 3.2.4. This initial marker order was refined iteratively, starting first with markers that were heterozygous in ‘Honeycrisp’. Following this, SNPs that were heterozygous in gradually fewer of the other parents were built into the order. Graphical genotyping was used at each step to order the SNPs in a way that approximated the consensus map created using LPmerge, but without instances of false double recombinations caused by incorrect map order. This ordering process was also aided by a draft of the linkage map created by Di Pierro et al. SNPs within areas of no recombination were ordered based on physical position information where possible from version 1.0 of the ‘Golden Delicious’ genome assembly. The raw data were organized into haploblocks and then used along with fixed SNP orders for the haploblocks to calculate mapping distances in the integrated genetic map. Each individual marker was used along with fixed SNP orders for the haploblocks to calculate mapping distances in the integrated genetic map.
if the reordering could resolve double recombination events observed in the pedigree-connected data set and not introduce double recombination events within the mapping set. Following this process, haplblock Aggregator and JoinMap were again used to create a revised integrated map. Following publication of the Di Pierro et al. linkage map, 20 SNPs that were polymorphic in only one of the five families in this study that had insufficient physical position information available and were within large blocks of SNPs that were inherited together were reassigned to haplblocks to make this linkage map more consistent with the Di Pierro et al. linkage map. These changes were only made if they did not introduce additional double recombinations within the mapping populations and the pedigree-connected data set.

Genetic analysis of the ‘Honeycrisp’ pedigree

The pedigree-connected genetic data set used in the map construction described above was also used to elucidate the pedigree of ‘Honeycrisp’ by offering a wide germplasm set that might hold the unknown parent of ‘Honeycrisp’ or earlier ancestors of this unknown parent, and by allowing the reevaluation in each individual of the correct physical position information available and were within large blocks of SNPs that were inherited together were reassigned to haplblocks to make this linkage map more consistent with the Di Pierro et al. linkage map. These changes were only made if they did not introduce additional double recombinations within the mapping populations and the pedigree-connected data set.

SNP data from all of them could constitute the entirety of the phased SNP data. The average distance between SNPs in the genetic map is 1% (35 SNPs) of their average distance between SNPs in the genetic map is 1% (35 SNPs) of their 172 cM across 17 linkage groups. The original UMN selection records were evaluated to determine the likely identity of this unknown parent. Pedigree records of the UMN selections determined to share the unknown parent of ‘Honeycrisp’ were first evaluated and a likely parent was identified. Additional offspring of this likely parent were then identified and one was found to have been genotyped but not included in previous steps because both of its parents were not present in the pedigree-connected data set. The SNP calls for this individual and the imputed SNP calls for the unknown parent were evaluated for a parent-offspring relationship to validate the identity of the individual and its imputed SNP calls.

RESULTS

Integrated genetic map

The integrated genetic map created in this study includes 3632 SNPs from the apple 8 K Illumina Infinium SNP array v1 and spans a total length of 1 172 cM across 17 linkage groups (Complete genetic map and meta data for each SNP can be found in Supplementary Table 1). In the 413 individuals used for map development and scored for the 3632 SNPs, 231 individual SNP scores (0.0154% of the total data) that were either double recombinant singletons or inconsistent were recoded as missing data. The average distance between SNPs in the genetic map is 0.32 cM. The average size of haploblocks is 3.14 SNPs and the average distance between them is 1.03 cM. Approximately 13% (464) of the SNPs mapped to different linkage groups than what was assigned in the Malus domestica version 1.0 genome sequence assembly.
Candidate grandparents of ‘Honeycrisp’
The simple, manual unphased genotype-matching analysis of candidate grandparents of ‘Honeycrisp’ using the initial noncru- rated pedigree-connected data set indicated that ‘Duchess of Oldenburg’ and ‘Golden Delicious’ were the most likely candidates. This analysis suggested that SNP scores for ‘Duchess of Oldenburg’ and ‘Golden Delicious’ provided a complementary fit for the SNP haplotype of the unknown parent when compared alongside ‘Honeycrisp’ and its known parent ‘Keepsake’.

Validation of grandparents of ‘Honeycrisp’
The identity by descent analysis of phased SNP data supported ‘Keepsake’ as a parent of ‘Honeycrisp’. The haplotype contribution from the parents of ‘Keepsake’ to the haplotype composition of ‘Honeycrisp’ is represented in Figure 1 and Supplementary Table 2 by the colors dark and light green for the possible haplotypes from ‘Frostbite’ and ‘Northern Spy’ and by red for the haplotype from ‘Grimes Golden’ (recently reported as a parent of ‘Golden Delicious’)

Identification of siblings of ‘Honeycrisp’
Two extant UMN selections had ‘Duchess of Oldenburg’ and ‘Golden Delicious’ recorded as parents with SNP data supporting this parentage: MN1478 and ‘Red Baron’. However, both individuals were eliminated as possible parents of ‘Honeycrisp’ because of high numbers of Mendelian-inconsistent errors when tested as possible parents. Next, four UMN selections (MN1708, MN1789, MN1837 and MN1888) were observed to have one identified parent for which SNP data was available and one unknown parent.

Figure 1. Haplotype composition and areas of recombination for parental and grandparental gametes for all 17 pairs of linkage groups of ‘Honeycrisp’ color coded for grandparental contribution from ‘Frostbite’ and ‘Northern Spy’ through parent ‘Keepsake’, and from ‘Duchess of Oldenburg’ and ‘Golden Delicious’ through the previously unidentified parent MN1627. Marker organization between linkage groups for grandparents that have no known parents is arbitrary as no parental data was available to organize them. Regions of uncertainty between haplotypes due to haplotypes that are identical by state (IBS) are shown via regions with two colors. Regions of homozygosity in ‘Honeycrisp’ that are due to haplotypes that are likely identical by descent from the grandparental pair ‘Frostbite’ and ‘Duchess of Oldenburg’ or the grandparental pair ‘Northern Spy’ and ‘Golden Delicious’ (see Supplementary Table 2) are highlighted by a dashed box around the region. These regions share at least 25 SNPs and 8 cM between each pair of grandparents. SNP, single-nucleotide polymorphism.
that was consistent with itself being the offspring of a cross between 'Duchess of Oldenburg' and 'Golden Delicious'. The phased SNP data strongly suggested that these four selections and 'Honeycrisp' indeed share a common parent (Supplementary Table 3). Mendelian-consistent errors were observed in only 61 cases across 38 SNPs (< 1% of SNP scores per individual, depicted as yellow shaded areas in Supplementary Table 3) among the four selections and the new putative parentage. These SNPs were re-evaluated in GenomeStudio to identify causes of the discrepancies.

Four errors were due to missing parental SNP data that were incorrectly imputed by FlexQTL. Five errors were due to incorrect parental marker scores (one each for 'Golden Delicious', 'Keepseke' and 'Duchess of Oldenburg' and two for MN1691). The remaining 29 errors were due to poor SNP clustering, of which 12 were likely due to the presence of additional clusters other than AA, AB and BB, which confounded the SNP scores, and 3 were likely due to the presence of null alleles. These types and numbers of Mendelian-consistent errors were similar to those for other individuals in the pedigree-connected data set that had validated parent-child relationships. MN1708, MN1789, MN1837 and MN1888 were thus confirmed as siblings of 'Honeycrisp' via its unknown parent.

Identification of unknown parent of 'Honeycrisp'

MN1789 was recorded as an offspring from MN1736 × 'Beacon', but was determined to be an offspring from MN1691 × ('Duchess of Oldenburg' × 'Golden Delicious'). MN1708, like 'Honeycrisp', was originally recorded as 'Honeygold' × 'Macoun' but SSR markers examined by Cabe et al.16 suggested MN1708 was derived from 'Keepseke' × unknown parent, which was confirmed in this study. MN1837 and MN1888 were recorded as offspring from MN1691 ('Goodland' × 'Fireside') × MN1627. MN1691 was confirmed to be a parent of MN1837 and MN1888. MN1627 was recorded as an offspring from 'Duchess of Oldenburg' (as the sport 'Daniel's Red Duchess') × 'Golden Delicious' and was selected in 1951. Unfortunately, trees of this selection no longer exist in the UMN apple breeding program. The last recorded distribution of MN1627 was in 1965. We identified current contacts for recipients, where possible, and queried them about the presence of MN1627. All responding recipients indicated it was no longer present in their orchards or collections.

The confirmed breeding records for MN1837 and MN1888, coupled with the finding that these individuals are half-sibs of 'Honeycrisp' (Supplementary Table 3) suggests that the previously unknown parent of 'Honeycrisp' is the probably extinct UMN apple selection MN1627, resulting in the reconstructed pedigree shown in Figure 2.

Genetic characterization of MN1627 through haplotype and SNP imputation

The availability of SNP data for five siblings and both identified parents of MN1627 allowed for the imputation of 97.8% of its SNP scores across the 3 435 SNPs under consideration (columns D and G of Supplementary Table 3). There were about 100 cM of haplotypes across six linkage groups (8.5% of the genome) that were unable to be imputed due to lack of representation of either 'Duchess of Oldenburg' or 'Golden Delicious' from offspring of MN1627. However, SNPs that were homozygous in regions that did not have haplotype representation were still able to be imputed, which is what accounted for the discrepancy between the higher percentage of the SNPs imputed versus the lower percent coverage of the imputed haplotypes.

Imputed SNP scores of MN1627 were validated by examining the genotype of MN1839, which was recorded as an offspring from MN1627 × 'Prima'. SNP data for 'Prima' provided from the FruitBreedomics project61 was observed to not match as a parent of MN1839 despite this sample of 'Prima' having proven to be true to type.42 However, there were no Mendelian-inconsistent errors in a parent-offspring relationship evaluation between MN1839 and the imputed SNP data for MN1627, thus providing further confirming evidence that MN1839 is a half-sibling of 'Honeycrisp' and validating the imputed genotype of MN1627.

Homozygous genomic regions of 'Honeycrisp'

'Honeycrisp' was detected to have several large regions of homozygosity. The identity by descent analysis using phased SNP data revealed that most of this homozygosity is attributed to shared haplotypes between 'Frostbite' and 'Duchess of Oldenburg' and between 'Northern Spy' and 'Golden Delicious' (represented by shaded areas in Supplementary Table 2). The extended SNP haplotypes that are identical by state for > 25 SNPs and 8 cM between 'Golden Delicious' and 'Northern Spy' span ~ 21% of the phased marker data between 'Northern Spy' and 'Golden Delicious' and include regions up to 160 SNPs and 38 cM (represented by areas shaded by diagonal lines in 'Northern Spy' and 'Golden Delicious' columns in Supplementary Table 2). These extended SNP haplotypes can be found in either the phased SNP data from both 'Grimes Golden'10 or the unknown parent of 'Golden Delicious'. 'Frostbite' has extended SNP haplotypes that are identical by state with 'Duchess of Oldenburg' for ~ 29% of the genome. These identical by state SNP haplotypes span the entirety of one homolog of each of linkage groups 12 and 16 and large portions of other linkage groups (represented by areas shaded by small dots in 'Frostbite' and 'Duchess of Oldenburg' columns in Supplementary Table 2).

DISCUSSION

The pedigree of 'Honeycrisp'

The pedigree of 'Honeycrisp' (Figure 2) was deduced to be 'Keepseke' × MN1627 ('Duchess of Oldenburg' × 'Golden Delicious') (haplotype composition represented in graphically in Figure 1 and through phased marker data shown in Supplementary Table 2) through the use of a high-quality integrated genetic map and a large pedigree-connected data set. This study, based on 3435 SNPs, confirmed a previous report supporting 'Keepseke' as one parent of 'Honeycrisp'16 that was based on 11 SSR markers. The identification of 'Duchess of Oldenburg' and 'Golden Delicious' as grandparents is significant because they are of worldwide importance and this finding connects the pedigree of 'Honeycrisp' to the pedigrees of many
internationally important cultivars that descend from them. ‘Duchess of Oldenburg’, also known as ‘Borowitsky’, ‘Borovitsky’ and ‘Charlamowski’, was introduced into the United States from England in 1835, where it had been earlier brought from Russia in the early 1800s.23 ‘Duchess of Oldenburg’ was used extensively for breeding in the formative years of the UMN apple breeding program44 because of its extreme winter hardiness. ‘Golden Delicious’ originated around 1890 in West Virginia and was released commercially in 1916.45 ‘Golden Delicious’ is an ancestor of a multitude of important cultivars46 including ‘Gala’ (‘Kid’s Orange Red’ x ‘Golden Delicious’), ‘Jonagold’ (‘Golden Delicious’ x ‘Jonathan’) and ‘Cripps Pink’ (‘Golden Delicious’ x ‘Lady Williams’)19 and is famous in the scientific community for being the first sequenced apple genome.32

The previously unknown parent of ‘Honeycrisp’, MN1627, was indirectly identified through the analysis of phased SNP data of five UMN selections identified to be siblings of ‘Honeycrisp’, three of which had MN1627 listed as parents in the original selection records. MN1627 was recorded as being a cross between ‘Duchess of Oldenburg’ and ‘Golden Delicious’. Historical breeding records indicated that crosses between ‘Duchess of Oldenburg’ and ‘Golden Delicious’ were made numerous times in the UMN apple breeding program from the 1920s through the 1930s, and had resulted in several selections and the cultivar Red Baron,47 released in 1970. Many of these selections would have been available for breeding at the time of the cross that begat ‘Honeycrisp’.

Possible inbreeding within ‘Honeycrisp’ and genetic relatedness among ancestors

This study also revealed that many large regions of homozygosity in the ‘Honeycrisp’ genome (represented by dashed rectangles in Figure 1) are due to likely close genetic relationships between ‘Frostbite’ and ‘Duchess of Oldenburg’ and between ‘Northern Spy’ and ‘Golden Delicious’ (represented by shaded areas in Supplementary Table 2), indicating shared ancestry between the parents of ‘Honeycrisp’ and leading to some degree of inbreeding for ‘Honeycrisp’. The shared extended haplotypes between ‘Northern Spy’ and ‘Golden Delicious’ contain haplotypes from both the known parent, ‘Grimes Golden’,40 and the unknown parent of ‘Golden Delicious’. ‘Northern Spy’ originated in New York in the early 1800s,45 ‘Grimes Golden’ originated in West Virginia in the 1790s, and ‘Golden Delicious’ originated in West Virginia in the 1890s,45 making it chronologically and geographically possible that ‘Northern Spy’, ‘Grimes Golden’ and the unknown parent of ‘Golden Delicious’ share one or more recent common ancestors. The relatively large extended regions of shared SNP haplotypes between ‘Frostbite’ and ‘Duchess of Oldenburg’ suggest that ‘Frostbite’ is a grandchild of ‘Duchess of Oldenburg’. ‘Frostbite’ was released in 2008 but was originally selected in 1922.48 It is thought that the tree originated from open-pollinated seeds of ‘Malinda’ that were described by Dorsey,49 however ‘Malinda’ was determined to not be the parent of ‘Frostbite’.16 The time of the origin of ‘Frostbite’ coincides with the presence and use of ‘Duchess of Oldenburg’ in the UMN breeding program.44,49 That timing, in combination with the proportion of haplotype sharing, indicates it is a likely possibility that ‘Frostbite’ is a grandchild of ‘Duchess of Oldenburg’. Integrated linkage map quality

The quality of the integrated linkage map used in this study (found in Supplementary Table 1) was vital to the findings as high numbers of false marker orders would have prevented accurate marker phasing across the pedigree-connected data set, which would have impeded identification of pedigree relationships discovered and detailed in this study. The high quality of the current linkage map should make it useful to future studies that use data from the apple 8, 20 and 480 K SNP arrays.20–22 Both this map and the 20 K iGL map26 are useful because each has a unique SNP composition. Indeed, of the currently mapped 3632 SNPs, 1441 are unique to the current map and 2191 were in common with the 20 K iGL map.

The quality of the map was achieved because of intense data curation and the approach in map construction, which was similar to that proposed by Di Pierro et al.26 The methods used to construct these linkage maps differ from previous apple linkage maps made with data from apple SNP arrays26,50,51 by using graphical genotyping34 to avoid double recombinations along with the use of multiple families and the newly developed tool Haploblock Aggregator (http://www.wageningenur.nl/en/show/HaploblockAggregator.htm) to create an integrated genetic map that reduced cases of false marker order. The high quality of our current map and the 20 K iGL map is underlined by the low number of SNPs that are in discordant order (71 SNPs, 3.2%), the small size of the genetic segments in which these discordant orders occurred (usually < 0.5 cM, data not shown), and the similar small size of both genetic maps. The map created in this study is 76 cM smaller than that of Di Pierro et al.,26 which is likely a function of a lower representation of the chromosomal ends and the smaller numbers of families used here. The similarity of these maps in size and map order will be useful for the transferability of genetic data across studies using apple SNP array data.

CONCLUSION

This study provides a revised pedigree for ‘Honeycrisp’ that is consistent across a pedigree-connected data set using a new dense and high-quality integrated SNP map. This pedigree and the identification of relatedness between two pairs of ‘Honeycrisp’s grandparents will be useful in future genetic studies involving ‘Honeycrisp’. The haplotype and SNP data for the newly identified parent of ‘Honeycrisp’, MN1627, has been imputed and made available in this study (Supplementary Table 3). Though no longer available, the imputed haplotype and SNP data for MN1627 will enable accurate tracing of the grandparental allelic contributions inherited by ‘Honeycrisp’ at any given region of its genome. Identifying and using these types of relationships for pedigree-based quantitative trait locus analyses is an explicit approach of RosBREED and these results will be useful in this work. The discovery that ‘Duchess of Oldenburg’ and ‘Golden Delicious’ are grandparents of ‘Honeycrisp’ connects the pedigree of ‘Honeycrisp’ to many cultivars of worldwide significance. The ability to connect these pedigrees will result in more accurate results from pedigree-based quantitative trait locus analyses to understand the genetic underpinning of ‘Honeycrisp’s traits, such as its highly acclaimed crisp texture, its reported susceptibility to developing leaf chlorosis and soft scald and its reported apple scab resistance. The findings described in this paper are expected to help in the development of future superior apple cultivars related to ‘Honeycrisp’.

CONFLICT OF INTEREST

The University of Minnesota receives royalty payments related to the ‘Honeycrisp’ apple cultivar. J.L. and D.S., and the University of Minnesota have a royalty interest in this cultivar. These relationships have been reviewed and managed by the University of Minnesota in accordance with its Conflict of Interest policies. The remaining authors declare no conflict of interest.

ACKNOWLEDGEMENTS

This work was partially supported by the USDA National Institute of Food and Agriculture—Specialty Crop Research Initiative projects, ‘RosBREED: Enabling marker-assisted breeding in Rosaceae’ (2009-51181-05808) and ‘RosBREED: Combining disease resistance with horticultural quality in new rosaceous cultivars’ (2014-51181-22378). Some genetic data and technical expertise were provided by the FruitBreedomics project No 265582: Integrated approach for increasing breeding...
efficiency in fruit tree crops (www.FruitBreeders.com), which was co-funded by the EU seventh Framework Programme.

REFERENCES

1 Gallardo RK, Hannahan I, Hong YA, Luby JJ. Crop load management and the market profitability of ‘Honeycrisp’ apples. Hort Technol 2015; 25: 575–584.
2 Luby J, Bedford DS. Apple tree: Honeycrisp. Regents of the University of Minnesota, assignee. US patent, US PP197, 1990.
3 Mann H, Bedford D, Luby J, Vickers Z, Tong C. Relationship of instrumental and sensory texture measurements of fresh and stored apples to cell number and size. Horticscience 2005; 40: 1815–1820.
4 Tong C, Krueger D, Vickers Z, Bedford D, Luby J, El-Shiekh A et al. Comparison of softening-related changes during storage of ‘Honeycrisp’ apple, its parents, and a Delicieux. J Am Soc Hortic Sci 1999; 124: 407–415.
5 Rosenberger D, Schupp J, Watkins C, Iungerman K, Hoying S, Straub D et al. Honeycrisp: promising profit maker or just another problem child. NY Fruit Quarterly 2001; 9: 9–13.
6 Trujillo Di, Mann HS, Tong CB. Examination of expansin genes as related to apple fruit crispness. Tree Genet Genomes 2012; 8: 27–38.
7 Clark MD, Bus VG, Luby J, Braden JM. Characterization of the defensive response to Venturia inaequalis in ‘Honeycrisp’ apple, its ancestors, and progeny. Eur J Plant Pathol 2014; 140: 69–81.
8 Bedford DS, Luby J. Apple tree named ‘Minneiska’. Regents of the University of Minnesota, assignee. US patent, US PP18812, 2008.
9 Brown SK, Maloney K. Apple tree named ‘New York 1’. US patent, US PP22228, 2011.
10 Nystrom C. Apple tree. ‘CN 860’. US patent, US PP23862, 2013.
11 Nystrom C. Apple tree ‘CN 121’. US patent, US PP23777, 2013.
12 Shelefine D. Apple tree ‘DS 22’. US patent, US PP23933, 2013.
13 Evans KM, Barrett BH, Konishi BS, Brutzer LJ, Ross CF. ‘WA 38’ apple. Hortic science 2012; 47: 1177–1179.
14 Dodd W, Doud D, Lynd JM, Miller G. Apple tree named ‘MAIA1’. Midwest Apple Improvement Association, assignee. US patent, US PP24579, 2014.
15 Bedford D, Luby J. Apple tree named ‘MN55’. Regents of the University of Minnesota, assignee. US patent, US PP26412, 2016.
16 Cabe PR, Baumgarten A, Onan K, Luby JJ, Bedford DS. Using Microsatellite Analysis to Verify Breeding Records: A study of ‘Honeycrisp’ and Other Cold-hardy Apple Cultivars. Horticscience 2005; 40: 15–17.
17 Savolainen V, Corbaz R, Moncousin C, Spichiger R, Manen JF. Chloroplast DNA variation and parental analysis in 55 apples. Theor Appl Genet 1995; 90: 1138–1141.
18 Harada T, Matsukawa K, Sato T, Ishikawa R, Niiyuki M, Saito K. DNA-RAPDs detect genetic variation and parentage in Malus. Europhytica 1992; 65: 87–91.
19 Evans KM, Patocchi A, Rezzonico F, Mathis F, Durel CE, Fernández-Fernández F et al. Genotyping of pedigreed apple breeding material with a genome-covering set of SSRs: trueness-to-type of cultivars and their parentages. Mol Breed 2011; 28: 535–547.
20 Chagné D, Crowhurst RN, Troggio M, Davery MW, Gilmore B, Lawley C et al. Genome-wide SNP detection, validation, and development of an 8 K SNP array for apple. Plos ONE 2012; 7: e31745.
21 Bianco L, Cestaro A, Sargent DJ, Banchi E, Derdak S, Di Guardo M et al. Development and validation of a 20 K single nucleotide polymorphism (SNP) whole genome genotyping array for apple (Malus × domestica Borkh.). Plos ONE 2014; 9: e110377.
22 Bianco L, Cestaro A, Linsmich G, Murantsy H, Denancé C, Théron A et al. Development and validation of the Axiom Apple 480 K SNP genotyping array. Plant J 2016; 86: 72–84.
23 Pikunova A, Madduri M, Sedov E, Noordijk Y, Peil A, Troggio M et al. ‘Schmidt’s Antonovka’ is identical to ‘Common Antonovka’, an apple cultivar widely used in Russia in breeding for biotic and abiotic stresses. Tree Genet Genomes 2013; 10: 261–271.
24 Rosyara UR, Sebott AM, Peace C, Iezzoni AF. Identification of the Parental Parent of ‘Bing’ Sweet Cherry and Confirmation of Descendants Using Single Nucleotide Polymorphism Markers. J Am Soc Hortic Sci 2014; 139: 148–156.
25 Iezzoni AC, Wébéddade C, Luby J, Yue C, van de Weg E, Fazio G et al. RosBREED: enabling marker-assisted breeding in Rosaceae. Acta Hortic 2010; 859: 389–394.
26 Di Pierro AE, Gianfranceschi L, Di Guardo M, Koehorst-van Putten HJ, Kruisselbrink JW, Longhi S et al. A high-density, multi-parental SNP genetic map on apple validates a new mapping approach for outcrossing species. Hortic Res 2016; 3: 16057.
27 McKay SJ, Braden JM, Luby JJ. Prediction of genotypic values for apple fruit texture traits in a breeding population derived from ‘Honeycrisp’. J Am Soc Hortic Sci 2011; 136: 408–414.