Low Rate of Somatic Mutations in a Long-Lived Oak Tree

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SUMMARY

Because plants do not possess a proper germline, deleterious mutations that occur in the soma can be passed to gametes. It has generally been assumed that the large number of somatic cell divisions separating zygote from gamete formation in long-lived plants should lead to many mutations. However, a recent study showed that surprisingly few cell divisions separate apical stem cells from axillary stem cells in annual plants, challenging this view. To test this prediction, we generated and analysed the full genome sequence of two terminal branches of a 234-year-old oak tree and found very few fixed somatic single-nucleotide variants (SNVs), whose sequential appearance in the tree could reliably be traced back along nested sectors of younger branches. Our data indicate that the stem cells of shoot meristems in trees are robustly protected from accumulation of mutations, analogous to the germline in animals.

INTRODUCTION

Accumulation of deleterious mutations is a fundamental parameter in plant ageing and evolution [1, 2]. Because the pedigree of cell division that generates somatic tissue is poorly understood, the number of cell divisions that separate zygote from gamete formation is difficult to estimate; this number is expected to be particularly large in trees and could in theory lead to a large number of DNA replication errors [3-5]. Tree architecture is determined by the modular growth of apical meristems, which contain stem cells. These cells divide and produce progenitor cells that undergo division, elongation and differentiation to form a vegetative shoot, the branch. Axillary meristems are formed at the base of leaf axils and are

50 responsible for the emergence of side branches. They are separated from apical meristems by
51 elongating internodes. In oak, early and repeated growth cessation of terminal apical
52 meristems leads to a branching pattern originating from such axillary meristems. In turn,
53 axillary meristems grow out and produce secondary axillary meristems. This process is
54 reiterated indeterminately to produce highly ramified trees of large stature, resulting in
55 thousands of terminal ramets [6, 7].

56 Classical studies of shoot apical meristem organization have reported that the most
57 distal zone has a significantly lower rate of cell division than more basal regions of the apex,
58 and might therefore be relatively protected from replication errors [8, 9]. In a recent study
59 that followed the fate of dividing cells in the apical meristems of *Arabidopsis thaliana* and
60 tomato, Burian et al. [10] showed that an unexpectedly low number of divisions separate
61 apical from axillary meristems. In these herbaceous plants, axillary meristems are separated
62 from apical meristem stem cells by seven to nine cell divisions, with internode growth
63 occurring through the division of cells behind the meristem. The number of cell divisions
64 between early embryonic stem cells and terminal meristems thus depends more on the
65 number of branching events than on absolute plant size. Moreover, only three or four semi-
66 permanent apical stem cells give rise to independent sectors of the growing shoot, so that a
67 mutation in one apical stem cell may propagate and be fixed in a domain of the apical shoot
68 that contains an axillary meristem [10]. Alternatively, mutations that arise in sub-apical stem
69 cells may be partly fixed in axillary meristems and are either lost or fully fixed in secondary-
70 order axillary meristems.

71 In trees, because axillary meristems replace apical meristems iteratively, the
72 cumulative number of cell divisions separating meristems determines the rate of genetic
73 aging and the potential accumulation of somatic mutations. If the same growth pattern
74 described above for *A. thaliana* and tomato applies to trees, their somatic mutation rate might

be much lower than is commonly thought, and the majority of fixed mutations should be found in relatively small sectors as nested sets of mutations. To test these predictions, we sequenced the full genome of two terminal branches of an iconic old oak tree (*Quercus robur*).

RESULTS AND DISCUSSION

Napoleon Oak Genome Sequencing

We conducted our study on an oak tree known as the 'Napoleon Oak' by the academic community of the University of Lausanne. The tree was 22 years old when, on May 12, 1800, Napoleon Bonaparte and his troops crossed what is now the Lausanne University campus, on their way to conquer Italy. It was standing next to the road, or may have been transplanted in honour of the future emperor's passage, whence its campus nickname. At the time of sample harvest for our study, the dividing apical meristems of this magnificent tree (Figure 1, Figure S1) had been exposed for 234 years to potential environmental mutagens, such as UV and radioactive radiation.

To identify fixed somatic variants (i.e., those present in an entire sector of the Napoleon Oak) and to reconstruct their origin and distribution among branches, we collected 26 leaf samples from different locations on the tree. We first sequenced the genome from leaves sampled on terminal ramets of one lower and one upper branch of the tree. We then used a combination of short-read Illumina and single-molecule real-time (SMRT, Pacific Biosciences) sequencing to generate a *de novo* assembly of the oak genome. After removing contigs <1000bp, we established a draft sequence of ca. 720 megabases (Mb) at a coverage of ca. 70X, with 85,557 scaffolds and a N50 length of 17,014. Our sequence is thus in broad agreement with the published estimated genome size of 740 Mbp [11]. The oak genome encodes 49,444 predicted protein-coding loci (Table 1).

100 **Identification of Somatic Mutations Between Genomes from Two Branches**

101 We used two approaches to identify SNVs (single-nucleotide variants) between the
102 sequenced genomes of the two terminal branches of our initial sample, for regions of both
103 high and low coverage. In total, reads from ca. 650 Mb of non-Ns containing sequence could
104 be assessed. First, we aligned Illumina paired-reads on the repeat-masked genome in
105 combination with the GATK [12] variant caller. This allowed us to establish a list of 314,865
106 potential SNV candidates. On the basis of a confidence score ≥300 on the heterozygous sites
107 and ≥200 on homozygous sites, we further selected 1,536 putative SNVs for experimental
108 validation by both PCR-seq [13] and Sanger sequencing. Of the 1,536 candidates, only seven
109 could be confirmed (see Experimental Procedures).

110 Second, we used fetchGWI [14] to map read pairs to the entire non-masked genome.
111 We were able to call 5,330 potential SNVs from the mapped reads using a simple read pileup
112 process followed by detection of positions where the pileup differed from the reference
113 genome. We systematically browsed candidate positions to evaluate the quality of the
114 mapping in the surrounding region, and to discriminate between well-assembled high-quality
115 regions with two alleles per sample and potentially poorly assembled repeated regions. This
116 approach allowed us to select 82 putatively variable positions, including the seven already
117 identified using the repeat-masked genome analysis described above. Ten of the remaining 75
118 candidates identified using the second approach were confirmed by PCR-seq and Sanger
119 sequencing, increasing the total number of confirmed SNVs separating the two genomes to
120 17 (Figure 1, Table S1). Based on a conservative estimate, we are likely to have missed no
121 more than 17 further such sites (see Experimental Procedures). All confirmed SNVs were
122 heterozygous, as expected for novel somatic mutations. Intriguingly, two SNVs were found
123 on the same contig, separated by only 12 bp (Figure 1, Table S1).

124

125 **Nested Distribution of SNVs Throughout the Napoleon Oak**

126 Having confidently established 17 SNVs, we then assessed their occurrence throughout the
127 tree. We used Sanger sequencing to genotype the remaining 24 terminal branches sampled
128 from other parts of the tree and checked for the presence of each SNV. As might be expected,
129 the SNVs were found in different sectors of the tree in a nested hierarchy that clearly
130 indicates the accumulation of mutations along branches during development (Figure 1, Figure
131 S2). Specifically, SNV1 and SNV2 were located in a large sector of connected branches that
132 are distributed in the upper half of the tree (Figure 1). SNV3 was restricted to a portion of the
133 same sector, whereas SNV4 to SNV10 were found at the top of one of the two branches for
134 which the full genome had been sequenced. Similarly, SNV11 to SNV14 were restricted to
135 the terminal fork of a principle lower branch from which the other genome had been fully
136 sequenced, whereas SNV15 to SNV17 were present in only one sector arising from this fork
137 (Figure 1, Figure S2). These results both provide independent confirmation of the originally
138 identified SNVs, and demonstrate their gradual, nested appearance and fixation in
139 developmentally connected branches during growth of the oak tree. Thus, while the exact
140 ontogeny of the Napoleon Oak may be difficult to reconstruct, our SNV analysis generated a
141 nested set of lineages supported by derived mutations, analogous to a phylogenetic tree.

142

143 **Somatic Mutation Rate is Low in the Napoleon Oak**

144 The spontaneous mutation rate in plants has been estimated to range from 5×10^{-9} to 30×10^{-9}
145 substitutions/site/generation, based on mutations accumulated during divergence between
146 monocots and dicots [15] or divergence between independent lines of *A. thaliana* maintained
147 in the laboratory [16, 17]. *A. thaliana* is an annual plant that reaches approximately 30 cm in
148 height before producing seeds. In contrast, the physical distance traced along branches
149 between the terminal branches we sequenced for the Napoleon Oak is about 40 m (Figure 1).

150 Assuming similar cell sizes between oak and *A. thaliana*, there should have been about 133
151 (4,000 cm/ 30 cm) times more mitotic divisions separating the extremes of somatic lineages
152 in oaks than in *A. thaliana*. Under the assumption that the per-generation mutation rate is
153 correlated with the number of mitotic divisions from zygote to gametes of the next generation
154 [3, 8], the mitotic mutation rate for the Napoleon Oak should be between 6.6×10^{-7} and $4.0 \times$
155 10^{-6} substitution/site/generation. With such a somatic mutation rate, there should be between
156 433 and 2,600 SNVs across the 650 Mb sequenced between branch ends of the tree, or
157 conservatively between 305 and 1,832 SNVs across the 458,143,725 nucleotides with a read
158 coverage ≥8 in both samples. These values are much higher that the 17 SNVs we actually
159 found. Even under the conservative assumption that we missed 17 other SNVs from the list
160 of potential variants and between 12.9 and 79 false negatives (see Experimental Procedures),
161 a higher-end estimate of the total number of oak SNVs ranges from 46.9 to 113. Both values
162 are still substantially (and significantly) lower than the expected values (305 to 1,832)
163 (Fisher's exact test, both $P < 2.2E\text{-}16$). Our finding seems to imply either much lower
164 generational or mitotic mutation rates than generally assumed, or a different model for the
165 accumulation of somatic mutations in trees, such as that proposed by [10]. Although the oak
166 lineages sampled have not been separated by any meiosis events, which in yeast was found to
167 elevate the generational mutation rate [19], they have been exposed to the natural
168 environment, which in *A. thaliana* is known to significantly enhance mutation rate when
169 compared to a controlled lab environment [20].

170 Most of SNVs identified in the Napoleon Oak were found only in single branches.
171 Early sequestration of axillary meristems has been found in *A. thaliana* and tomato, two
172 herbaceous plants that differ markedly in the developmental fate of their apical meristems
173 [10]. Whereas *A. thaliana* forms a rosette of leaves and extends an inflorescence shoot at the
174 time of flowering, the tomato apical meristems are separated by elongated internodes. Oak

175 trees have apical meristems of similar diameters to those of tomato [10, 21, and Figure 2] and
176 show similar ontogeny. It thus seems reasonable to suppose that the growth pattern described
177 in *A. thaliana* and tomato is quite general in flowering plants and might also apply to long-
178 lived trees. If so, it would be consistent with the low number of SNVs we have identified in
179 the oak.

180 We found that G:C→A:T transitions were the most frequent class of SNVs observed
181 in the oak (Figure 3). Ultraviolet (UV) light causes G:C→A:T transitions at dipyrimidine
182 sites in plants [22]. Among the 11 G:C→A:T transitions that we observed, seven were in a
183 dipyrimidine context (Table S1). In addition, spontaneous deamination of methylated
184 cytosine leads to thymine change at CpG or CpNG sites [22]. However, there were only three
185 G:C→A:T transitions in such a context (Table S1). It thus seems plausible that UV light may
186 have caused most of the G:C→A:T transitions we observed, although other factors, such as
187 cytosine deamination and replication errors, may account for other SNVs.

188 Taken together, our results suggest that mutations due to replication errors in trees
189 may be less important than environmentally induced mutations, as hypothesized by Burian et
190 al. [10]. Mutations accumulate with age, irrespective of plant stature, and long-term exposure
191 to UV radiation contributes to such changes. However, oaks protect their meristems in buds
192 under multi-layered leaf-like structures (Figure 2), potentially reducing the incidence of UV
193 mutagenesis. If so, the surprisingly low somatic mutation rate implied by our data would be
194 consistent both with the pattern of cell division hypothesised by Burian et al. [10], as well as
195 with the protective nature of oak bud morphology. In this context, it is noteworthy that there
196 was no evidence for an expansion of DNA-repair genes in the oak genome compared to *A.*
197 *thaliana* (Table S2).

198 Sixteen of the 17 SNVs identified in the Napoleon Oak occurred in introns or non-
199 coding sequences that are probably neutral. The remaining one (SNV1), which occurred in a

200 large sector of the tree, generates an arginine-to-glycine conversion in a putative E3-ubiquitin
201 ligase (Table S1). The functional impact of exchanging a positively charged arginine with a
202 non-charged and smaller glycine residue is unknown and deserves further analysis.

203 To our knowledge, only two examples of functional mosaicism have been reported in
204 trees, a low incidence that might be attributable to the low somatic mutation rate implied by
205 our analysis. Although most non-neutral mutations should be maladaptive, eucalyptus trees
206 have been observed with a few branches that are biochemically distinct from the rest of the
207 canopy and have become resistant to Christmas beetle defoliation [23, 24]. Functionally
208 relevant somatic mutations, such as SNV1 in our study, may thus occasionally contribute to
209 adaptive evolution if transferred to the fruits, but will more typically increase the genetic load
210 of a population, with implications for inbreeding depression and mating-system evolution.

211 Our results throw new light on explanations proposed for differences in the
212 distribution of mating systems between short- and long-lived plants. While many annuals and
213 short-lived plants have undergone evolutionary transitions from outcrossing to selfing [25],
214 often involving a loss of self-incompatibility systems [26], long-lived woody species are
215 more likely to be fully outcrossing [27], including oaks [28]. Theoretical analysis indicates
216 that a high somatic mutation rate could account for this difference, because somatic
217 mutations would contribute to the genetic load of the population and thus to inbreeding
218 depression, disfavouring self-fertilization [3]. Inbreeding depression is indeed higher in long-
219 lived woody species than annuals [29], and the observation of higher inbreeding depression
220 caused by within-branch than between-branch selfing points to the accumulation of different
221 deleterious somatic mutations in different sectors of the plant [5]. However, our finding now
222 challenges the notion that the breeding system of long-lived trees is constrained by a high rate
223 of somatic mutations.

224 The results of our study, in conjunction with those of Burian et al. [10], have
225 important implications for how we should view one of the most fundamental ways in which
226 plants differ from animals – their absence of a germline. In oak, iterative growth of axillary
227 meristems produces terminal branches that carry stem cells. As in other plants, favourable
228 conditions induce stem cells to produce floral buds and ultimately the gametes of the next
229 generation. These stem cells are functionally analogous to germ cells in metazoans and result
230 from a limited number of divisions that prevent an accumulation of replicative errors.

231 Our data give an unprecedented view on the limited role played by somatic mutations
232 in long-lived plants, and support the view that stem cells in trees, although vulnerable to
233 environment-induced mutations, are probably quite well protected from them. Consistent
234 with this finding, a recent study in *A. thaliana* has shown that the number of cell divisions
235 from germination to gametogenesis is independent of life span and vegetative growth [30].
236 Our study also illustrates the potential for analyses of multiple genomes from single
237 individuals, which throw exciting new light on the rate, distribution and potential impact of
238 somatic mutations in both plant and animal tissues [31-34].

239

240 **SUPPLEMENTAL INFORMATION**

241 Supplemental Information includes five figures and seven tables.

242

243 **AUTHOR CONTRUBUTIONS**

244 L. F. sequenced the genome. E.S.-S., S.C., M.P. assembled and annotated the genome. N.S.,
245 E.S.-S., C.I. identified SNVs. C.G.-D., J.C. extracted DNA and confirmed SNVs. E.S.-S.,
246 M.R.-R. analyzed genome duplication. P.C. produced cross-sections of oak apical meristems.
247 M. S. established a list of DNA repair genes. F. S. provided statistical help with the analyses.

248 J.V., M.J. produced a 3D model of the oak tree. C.H., C.F., L.K., I.X., M.R.-R., J.P., A.R.,
249 P.R. conceived the project and wrote the manuscript.
250

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261 sequences have been deposited in GenBank under accession BioProject PRJNA327502.
262

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409

410 **FIGURE AND TABLE LEGENDS**

411

412 **Figure 1. Distribution of Somatic Mutations in the Napoleon Oak**

413 (**A**) The genome of two leaf samples (outlined dots) was sequenced to identify single-
414 nucleotide variants (SNV). 17 SNVs were confirmed and analysed in 26 other leaf samples to
415 map their origin. A reconstructed image of the Napoleon Oak shows similar location of two
416 SNVs (magenta dots) on the tree. Blue dots represent genotypes that are non-mutant for these
417 SNVs. Three non-mutant samples are not visible on this projection. Location of other SNVs
418 can be found in Fig. S1. (**B**) Location of all identified SNVs. Sectors of the tree containing
419 each group of SNVs are represented by different colours.

420

421 **Figure 2. Napoleon Oak Apical Meristem**

422 (**A**) Cross-section of an apical meristem. Stem cells are delineated. Surrounding cells belong
423 to leaf-like structures surrounding the meristem. Scale bar, 50 μm. (**B**) Longitudinal section
424 of an apical bud. Apical meristem (arrowhead) is surrounded by leaf-like structures (stars).
425 Scale bar, 500 μm.

426

427 **Figure 3. Spectrum of Somatic Mutations Between Two Napoleon Oak Genomes**

428 The type of substitution for 17 confirmed oak SNVs is shown.

429

430 **Table 1**. ***Quercus robur* Genome Statistics**

431

432 **EXPERIMENTAL PROCEDURES**

433 **Materials and Genome Sequencing**

434 Leaves were collected in April 2012 from the terminal part of a lower (sample 0) and an
435 upper branch (sample 66) of the Napoleon Oak (*Q. robur*) on the Lausanne University
436 Campus (Switzerland, 46°31'18.9"N 6°34'44.5"E). The age of the tree was estimated by a
437 tree ring analysis from a sample taken at the basis of the trunk (Laboratoire Romand de
438 Dendrochronologie, 1510 Moudon, Switzerland). DNA from the two samples was extracted
439 and the genome sequenced. Paired-end sequencing libraries with insert size of 400 bp were
440 constructed for each DNA sample according to the manufacturer's instructions. Then, 100 bp
441 paired-reads were generated on Illumina HiSEq 2000 at Fasteris (www.fasteris.com). In
442 addition, 3 kb mate-pair libraries were constructed and sequenced. Single-molecule real-time
443 (SMRT) sequencing (Pacific Biosciences) was performed on 25 SMRT cells according to the
444 manufacturer's instructions (University of Lausanne Genomics Technologies Platform).

445

446 **Genome Assembly**

447 For sample 0, a paired-end library generated 2 x 151,194,704 reads (coverage 40X) and a
448 mate-pair library generated 2 x 107,264,298 reads (coverage 29X). For sample 66, a paired-
449 end library generated 2 x 158,505,474 reads (coverage 42X) and a mate-pair library
450 generated 2 x 124,076,608 reads (coverage 33X). These reads were filtered and trimmed
451 prior assembly using Trimmomatic (v0.3; leading:3, trailing:3, slidingwindow:4:15,
452 minlen:36, custom adapter library) [35] and assembled using SOAPdenovo2 (v2.04.240,
453 kmer 49) [36]. In a second step the assembly was scaffolded with mate-pairs using the same
454 program. The assembly was further scaffolded with long single-molecule PacBio reads (25
455 smartcells, XL-C2 and P4-C2 chemistry) and the program AHA
456 (http://www.pacb.com/products-and-services/analytical-software/smrt-analysis/; SMRTPipe
457 2.0.1 manually driven, settings (5,2,50,70), no gap-filling). Assembled sequences <1000 bp
458 were removed to facilitate further analysis. The genome was extended with all paired-end
459 libraries and SSPACE [37] (v2.0, -x = 1,z = 0,-k = 5,-a = 0.7,-n = 15,-T = 20,-p = 0,-o = 20,-t
460 = 0,-m = 32,-r = 0.9) and gaps were filled using Gapfiller (v1.10, all paired-end libraries)
461 [38].

462 We screened the paired-end libraries for potential non-oak sequences using metaphlan
463 (v1.7.7) [39]. Based on metaphlan results, reference genomes were obtained for the non-oak
464 genomes and the oak scaffolds were filtered against these using blast (ncbi-blast v2.28, >90%
465 sequence identity and E-value <1e-5) [40]. The genome was next scaffolded again using the
466 PacBio reads and PBJelly (v14.1.14) [41]. If not further specified, programs were used with
467 their standard settings.

468

469 **Gene Prediction and Annotation**

470 Repetitive elements were analysed by first generating a specific repeat model using
471 RepeatModeler (http:/www.repeatmasker.org; v1.0.7, -engine wublast). Repetitive regions in
472 the genome were subsequently masked with the obtained model using RepeatMasker
473 (http:/www.repeatmasker.org; v4.0.3). Genes were predicted by generating a *Q. robur*
474 specific gene prediction model for Augustus (v3.0.1) [42], as described in Tran et al. [43].
475 Instead of RNAseq reads, we used the UniProtKB reference proteome of *Glycine max*
476 mapped with the splice aware mapper exonerate (V2.2.0, model protein2genome, geneseed
477 250 –minintron 20, --maxintron 20000) [44]. Using this model we predicted genes and
478 subsequently their encoded proteins for the hard-masked version of the genome (settings: no
479 hints, no UTR predicted, no alternative transcripts). Non-coding elements were annotated
480 using RFAM (v1.5; infernal 1.0.2; blast 2.2.26; hmmer 3.1b1) [45] in the genome with
481 coding regions masked but repetitive elements unmasked. The predicted proteome was
482 annotated based on homology using the FASTA toolkit
483 (http://www.ebi.ac.uk/Tools/sss/fasta/; v36.3.5e) as following: proteins from the *Glycine max*
484 proteome were first mapped with ggsearch (-b 1 -d 0 -E 1e-5 -m 8 -T 10); proteins that did
485 not map were mapped in a next step with glsearch (-b 1 -d 0 -E 1e-5 -m 8 -T 10) and finally
486 the rest with ssearch (-b 1 -d 0 -E 1e-5 -m 8 -T 10). The functional protein annotation was
487 overtaken from *Glycine max*. For proteins with unknown function in *Glycine max,* we
488 extended the annotation using the OMA database (www.omabrowser.org) and orthologous
489 proteins from *A. thaliana*. PFAM [46] was used additionally to obtain functional domain
490 annotations for the proteome and the concatenated proteome annotation was transferred onto
491 the oak genome.
492
493 **SNV Identification**

494 First, short Illumina paired-end sequencing reads (298,735,463 and 316,299,457 for sample 0
495 and 66, respectively) were aligned to the masked *de novo* assembly (RepeatMasker, v4.05)
496 with Bowtie2 (v2.2.2, https://sourceforge.net/projects/bowtie-bio/files/bowtie2/2.2.2) [47]
497 using default parameters. GATK [12] was used for local realignment and variant calling
498 using standard hard filtering parameters according to GATK Best Practices recommendations
499 [48, 49]. Prior to variant calling, each sample was screened for duplicates using PICARD
500 tools (http://broadinstitute.github.io/picard/). Variants with confidence score ≥50 were
501 retained further. We identified 1,832,554 heterozygous sites common to both samples, as
502 well as 314,865 putative differences between sample 0 and 66 (165,489 sites predicted to be
503 homozygous on sample 0 and heterozygous on sample 66 and 149,376 homozygous on
504 sample 66 and heterozygous on sample 0). The distribution of the confidence scores of the
505 1,832,554 heterozygous sites common to both samples was a superposition of a Gaussian
506 distribution, peaking at 910, and an exponential distribution, possibly representing true
507 positives, and the decreasing number of false positives with regard to increasing confidence
508 score, respectively. We thus hypothesized that sites that are truly different between samples
509 0 and 66 were unlikely to be present at sites with a confidence score below 300. We selected
510 1,536 putative SNVs out of 314,865 for validation, on the basis of a confidence score ≥300
511 on the heterozygous sites and ≥200 on homozygous sites. To validate putative differences
512 between both samples, we used PCR-seq, a modification of the published RT-PCR-seq
513 method [13]. Briefly, pairs of primers for 50-150 bp amplicons containing the targeted
514 sequence were designed using Primer3 [50]. Touchdown PCR amplification was performed
515 in a final volume of 12.5 ml with JumpStart REDTaq ReadyMix (Sigma-Aldrich), a primer
516 concentration of 0.4 mM and 2 ng of gDNA per reaction in 384-well plates. Equal volumes
517 of PCR products were pooled for each DNA template (sample 0 and 66). One ml of each pool
518 was then purified with the QIAquick PCR Purification Kit (Qiagen) following the

519 manufacturer's instructions. The KAPA LTP Library Preparation Kit (Kapa Biosystems) was
520 used, starting with 500 ng of purified PCR products, to create a library compatible with an
521 Illumina sequencing platform. Clean-ups between enzymatic steps were performed with
522 Nucleospin PCR Clean-up columns (Macherey-Nagel). After ligation of pentabase adapters,
523 libraries were run on a 2 % agarose gel and extracted using the MinElute Gel Extraction kit
524 (Qiagen). Libraries were sequenced on HiSeq 2000 after six cycles of amplification
525 (Lausanne Genomic Technologies Facility). Amplicon reads were aligned, with no
526 mismatches allowed, to a compendium of the expected amplimers that bore the reference
527 allele, the alternate allele identified in the heterozygote sample, as well as the remaining two
528 nucleotides at the variable position; this allowed an unbiased estimation of the error rate
529 generated by the sequencing itself. As this method might have missed *bona fide* changes
530 between the two sampled branches that present other heterozygous sites close by, we also
531 aligned amplicon sequencing reads directly to the reference genome, with mismatches
532 allowed. Only seven of the 1,536 candidates assessed were validated by PCR-seq. Sanger
533 sequencing further confirmed them.

534 Second, to identify potential differences between both samples including masked
535 sequences, Illumina reads of samples 0 and 66 were mapped against the non-masked oak
536 genome assembly. The genome was 719,779,348 bp long, but 69,130,634 (9.52%) of those
537 nucleotides were gaps and were discarded, leaving an actual search space of 650,648,714 bp.
538 Of the latter, 458,143,725 nucleotides with a read coverage ≥8 in both samples were analysed
539 further. The mapping process was performed at the read pair level by the genome mapping
540 tool, fetchGWI [14], followed by a detailed sequence alignment tool, align0 [51]. Potential
541 SNVs were called from the mapped reads by a simple read pileup process followed by
542 detection of positions where the pileup shows variations with respect to the reference
543 genome; this produced a list of 5,330 positions. Those positions were browsed through a

544 local adaptation of the samtools pileup browser [52] to evaluate the quality of the mapping in
545 the surrounding region and to discriminate between well-assembled high-quality regions with
546 two alleles per sample, or low complexity and possibly badly assembled repeated regions.
547 Criteria for selection were ≥8 reads in each orientation (see above); 100% homozygosity site
548 for one sample and at least 30% minor allele frequency for the other sample with variants in
549 both orientations; and coherent sequence ±50 bp from variant site. This manual process led to
550 the selection of 82 putative variable positions, including the seven already identified. Upon
551 experimental validation, 10 of the remaining 75 candidates were confirmed by PCR-seq and
552 Sanger sequencing. The Food and Drug Administration (FDA) has evaluated this approach in
553 an effort to assess, compare, and improve techniques used in DNA testing on human genome
554 variation analysis (https://precision.fda.gov/challenges/consistency). Within this frame, our
555 method reached a F-score (F-score evaluates precision and recall) over 95% comparable to
556 other identifiers like BWA coupled with GATK.
557
558 **Estimation of the Possible Missed SNVs.**
559
560 About half of the putative variable sites with confidence scores ≥200 were assessed
561 experimentally (1,536 out of 3,488 sites). Given the confidence scores of the tested sites, we
562 estimated that we missed fewer than six such sites not evaluated by PCR-seq. To evaluate the
563 number of true positives missed within candidates with confidence scores <200, we fitted a
564 mixture of two distributions modelled on the 1,832,554 sites that were predicted to be
565 heterozygous on both sequenced branches (Figure S3). This suggested that we had missed
566 fewer than eleven true SNVs. We thus estimate a total of 17 missed SNVs. Note that we did
567 not assess the presence of larger somatic changes such as copy number variants, small indels,
568 and transposition events.

569

570 **Estimation of the Possible False Negatives.**

571 We postulated that the false negative rate corresponds to the number of true SNVs that could
572 have been missed in the sites that were called homozygous in both samples due to random
573 sampling of both alleles. Assuming similar cell sizes between oak and *Arabidopsis*, there
574 should have been ca. 133 (4,000 cm/30 cm) more mitotic divisions separating the extremes of
575 somatic lineages in the analyzed oak, which were distant by 40 m, than in *Arabidopsis*, which
576 reaches approximately 30 cm in height. Under the assumption that the per-generation
577 mutation rate is correlated with the number of mitotic divisions from zygote to gametes of the
578 next generation, the mitotic mutation rate for the oak should be between 6.6×10^{-7} and $4.0 \times$
579 10^{-6} substitution/site/generation based on the estimated mutation rates in plants (5×10^{-9} to 30
580 $\times 10^{-9}$ substitutions/site/generation [15-17]). Since the fraction of the genome that we
581 analyzed consisted of ca. 458 Mb with ≥8 reads in each sample, the assumption is that there
582 should be between 305 and 1,832 SNVs. We thus calculated the probability of having missed
583 between 305 and 1,832 true SNVs in the ca. 458 Mb (read coverage ≥8) of sites considered
584 homozygous in both samples. Our selection criterion for calling a heterozygous site was that
585 it should contain ≥30% of the minor allele. Given the distribution of both alleles in an
586 heterozygous DNA sample, the probability of obtaining less than 30% of a given allele after
587 sequencing follows a binomial distribution, decreasing as the percentage of the minor allele
588 decreases. Thus, the added probability of obtaining less than 30% of the minor allele
589 decreases with the number of reads. We therefore analyzed the read coverage distribution for
590 both oak samples and sorted the data into bins. Sample 0 shows an even distribution of read
591 coverage between 8 and 70 whereas the coverage of sample 66 ranges from 8 to 50 (Figure
592 S4). For each coverage bin we computed the mean added probability of obtaining less than
593 30% of the minor allele, and we multiplied this value by the fraction of the genome

594 represented in this particular bin. We next used the higher and lower values of expected
595 SNVs (305 or 1,832) to calculate the number of SNVs possibly missed in each bin in each
596 sample for low and high mutation rates because of random sampling of both alleles (i.e., for
597 each bin we multiplied the added probability by either 305 or 1,832). The higher-end estimate
598 of false-negatives for both samples was 12.9 (4.0 + 8.9) for a low mutation rate, and 79.0
599 (24.1 + 54.9) for a high mutation rate (Table S3).
600

601 **SNV Genotyping**

602 Leaf DNA from different locations on the tree was prepared and amplified using primers
603 located 100-150 bp away from the 17 confirmed SNVs (Table S4). Amplicons were then
604 subjected to Sanger sequencing.
605

606 **Whole-Genome Duplication**

607 Simple clustering based on homology, (i.e., clustering the predicted proteins by identity, CD-
608 HIT, min 90% similarity), retrieved 1,098 proteins that have a >90% identity to another
609 protein, which is not suggestive of recent whole genome duplication. Whole genome
610 duplication should lead to an excess of relatively old paralogs, whereas small-scale duplicates
611 are expected to be enriched in very recent paralogs. This can be estimated from the
612 distribution of synonymous distances (dS) [53, 54]. We computed the dS on a stringent set of
613 4,777 paralog pairs with BLAST E-value <1e-10, removing large multigene families (more
614 than 20 members). The distribution of dS values is clearly unimodal, with an excess of low
615 dS values (i.e., young paralogs, Figure S5). This also does not support a recent whole genome
616 duplication in the oak lineage.

617 To address the possibility of a more ancient duplication event, we compared our oak
618 genome reference with itself using "BLAST all versus all" as suggested in Panchy et al. [55],

619 (i.e., similarity ≥30%, match length ≥150AA and E-value ≤1e-5). Following this procedure
620 we have 49,444 proteins, of which 3,650 are duplicated (7.4%), 2,070 are triplicated (4.1%)
621 and 23.7% are present in more copies with diminishing frequency. In summary, a total of
622 17,474 oak proteins out of 49,444 appear to be duplicated (35%), which is less than that
623 reported for closely related species (e.g. *Medicago sativa* has about 50,000 genes of which
624 >75% are duplicated, according to Panchy et al. [55]). We then assessed whether the
625 similarity identified above was local, properties of similar domains, or extended along the
626 entire protein, indicative of duplicated proteins. We found only 973 oak proteins that have
627 duplications extending over their entire lengths. In summary, it is possible that the oak
628 genome underwent duplication, as suggested by Panchy et al. [55], but this event appears to
629 be rather old, as we have very few (<3%) duplicated genes with very high similarity (>90%)
630 and no second peak in the dS distribution (Figure S5). It seems unlikely that such a
631 duplication event should compromise the identification of *bona fide* variants. Note that if the
632 duplication would have hindered the capacity to detect these variants, they would not be
633 found in nested sectors of the tree but rather in all 26 samples assessed.
634
635 **Analysis of DNA Repair Genes**
636 Orthologs between *A. thaliana*, *Prunus persica* (peach) and *Q. robur* were called using the
637 OMA database [56]. One-to-many orthologs, e.g., between *A. thaliana* and *Q. robur*,
638 represent duplication in the oak lineage since the divergence from *A. thaliana*; they are also
639 known as in-paralogs of oak. We classified these in-paralogs according to whether the
640 duplication was shared by *P. persica* and *Q. robur* (i.e., one copy in *A. thaliana* relative to
641 several copies in both the peach and oak genomes), or whether it was peach- or oak-specific
642 (i.e., one copy in *A. thaliana* and peach, relative to several copies in oak). The number of
643 duplicates was reported as the number of genes that could be called duplicate (i.e., the

644 number of orthologs between each tree genome and *A. thaliana*, Table S5). We then
645 manually compiled a list of *A. thaliana* genes involved in DNA repair from
646 SwissProt/UniProtKB annotations (Table S6). We then counted specifically the number of
647 duplicates for genes involved in DNA repair and reported this as the number of orthologs
648 associated with this function (Table S2 and S7).
649

650
651 **Table 1. *Quercus robur* Genome Statistics**
652

Genome	
Total genome length (bp)	719,779,348
Number of scaffolds	85,557
Maximum scaffold length (bp)	317,245
NG50 based on 740 Mbp (bp)	17,014
Gaps (%)	9.52
Masked (%)	39.84
Genes	
Average length (bp)	2,360
Maximum length (bp)	47,221
Average intron length (bp)	740
Average exon length (bp)	232
Proteome	
Total predicted proteins	49,444
Full proteins	44,096
Partial proteins	5,348
Nb proteins with orthologous in *Glycine max*	39,656
Nb orthologous in *Glycine max* + functional annotation	16,323
Nb orthologous in *Glycine max* + function via ATH	23,333

653

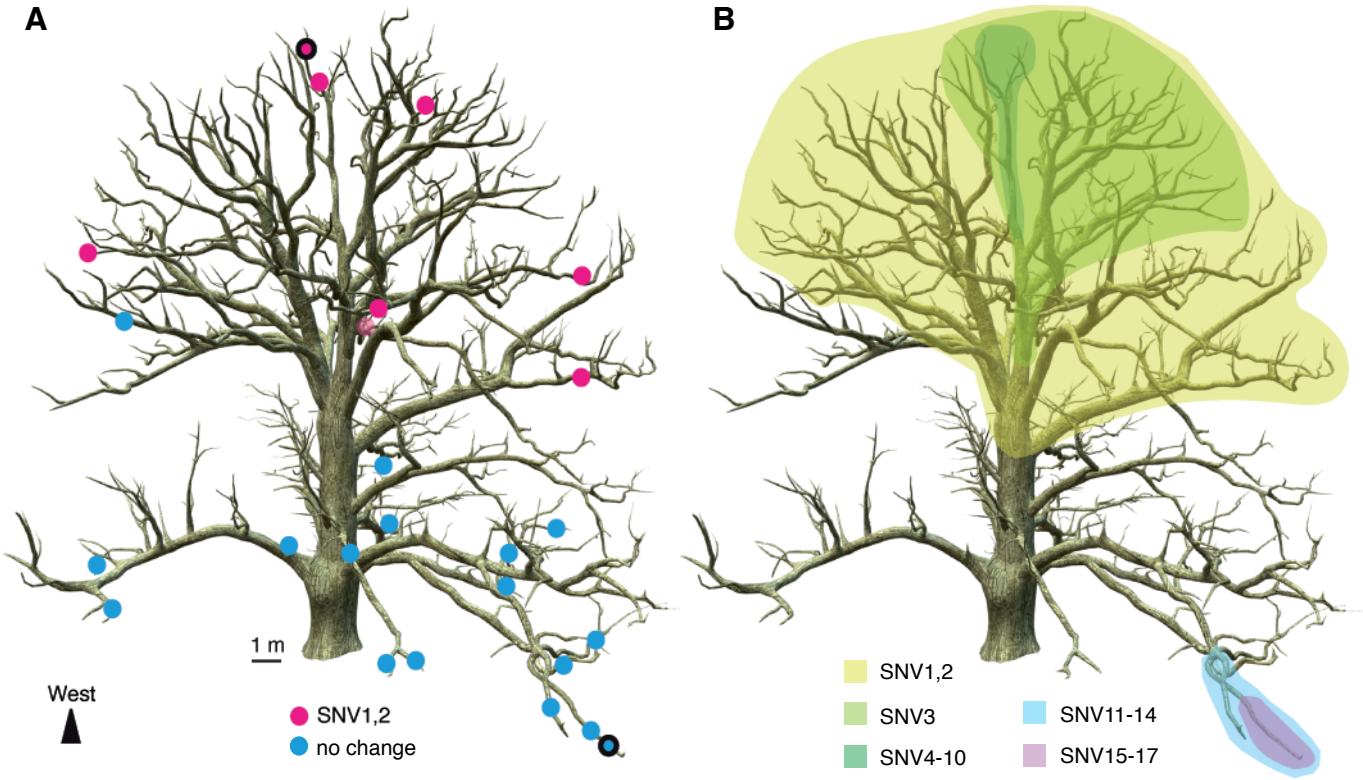

Figure 1. Distribution of Somatic Mutations in the Napoleon Oak

(A) The genome of two leaf samples (outlined dots) was sequenced to identify single-nucleotide variants (SNV). 17 SNVs were confirmed and analysed in 26 other leaf samples to map their origin. A reconstructed image of the Napoleon Oak shows similar location of two SNVs (magenta dots) on the tree. Blue dots represent genotypes that are non-mutant for these SNVs. Three non-mutant samples are not visible on this projection. Location of other SNVs can be found in Fig. S1. (**B**) Location of all identified SNVs. Sectors of the tree containing each group of SNVs are represented by different colours.

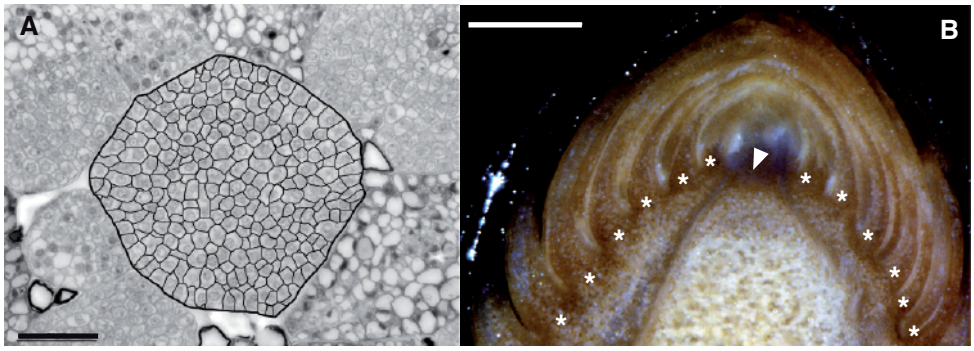

Figure 2. Napoleon Oak Apical Meristem

(**A**) Cross-section of an apical meristem. Stem cells are delineated. Surrounding cells belong to leaf-like structures surrounding the meristem. Scale bar, 50 μm. (**B**) Longitudinal section of an apical bud. Apical meristem (arrowhead) is surrounded by leaf-like structures (stars). Scale bar, 500 μm.

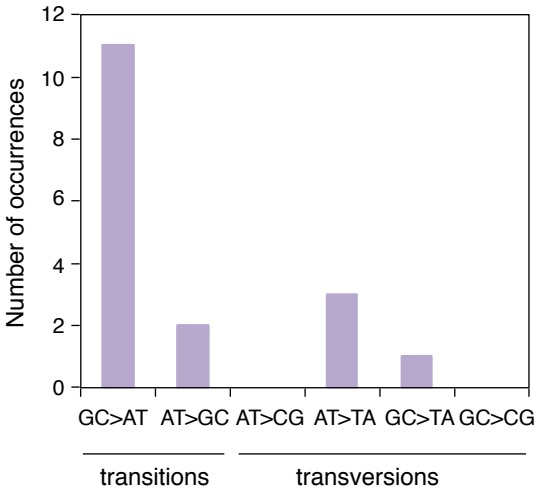

Figure 3. Spectrum of Somatic Mutations Between Two Napoleon Oak Genomes

The type of substitution for 17 confirmed oak SNVs is shown.