Geographic divergence and the genomic basis of reproductive diapause in *Drosophila triauraria*

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Abstract

Adjusting reproduction timing to environmental cues is essential for lifetime fitness. In many insects, reproductive diapause shows clinal variation along environmental gradients such as photoperiod and temperature. How such continuous trait variation may be encoded at the molecular level and maintained in the presence of gene flow remains largely elusive. The fruit fly *Drosophila triauraria* is distributed across a wide latitudinal range of the Japanese archipelago. Northern strains exhibit a strong photoperiodic reproductive diapause in females, whereas southern strains fail to arrest ovarian development even under short-day conditions at low temperatures. These distinct phenotypes and the presumable clinal variation in between, provide an ideal opportunity to examine the molecular basis of latitudinal divergence. We first investigated diapause induction in both females and males from previously reported and newly tested strains collected from the regions spanning ~26–43°N along the Japanese archipelago. The assessment revealed continuous geographic variation in sensitivity to photoperiod and temperature. We then analyzed the whole-genome sequences of 21 strains, including 14 newly sequenced, to identify genomic regions underlying this divergence. In addition to the conventional F_{ST} analysis, we applied a "monophyletic window" approach suitable for limited sample sizes. The analysis identified a candidate region containing putative E-box and TER-box sequence motifs of the *timeless* (*tim*) gene, which has been previously implicated in diapause regulation in multiple insect species. The quantitative PCR analysis further supported a partial association between the *tim* expression and the incidence of female diapause. These findings reinforce the growing evidence for a role of circadian clock genes in the adaptive regulation of reproductive diapause and demonstrate the utility of tree-based approaches for detecting genomic regions of geographic divergence.

Keywords: reproductive diapause, *timeless*, *Drosophila triauraria*, ovary, accessory gland

INTRODUCTION

Adjusting internal physiological states to environmental fluctuations is essential for survival and reproductive success. Traits related to the sensitivity to environmental cues or the magnitude of physiological responses often maintain polymorphisms due to fluctuating or unpredictable fitness outcomes (e.g., Johnson et al., 2023). Such traits may also exhibit intraspecific clinal variation when key environmental factors follow a continuous geographical gradient (reviewed in Hut et al., 2013; Mayekar et al., 2022). Sensitivity to photoperiod and temperature cues that induce diapause in insects is a well-documented example (reviewed in Bradshaw & Holzapfel, 2007; Denlinger, 2023). Despite decades of studies using various insect species, the molecular mechanisms that enable continuous variation in diapause induction along clinal environmental gradients, and the processes that maintain such variation in the presence of gene flow, remain elusive.

Many studies have attempted to identify loci involved in the photoperiodic regulation of diapause across clinal populations to tackle this question. In *Drosophila melanogaster*, specific genes with large effects have been identified, such as *ls-tim* in European populations (Tauber et al., 2007) and *couch potato* in North America (Schmitt et al., 2008). However, these associations appear inconsistent across different geographic regions (Lee et al., 2011; Zonato et al., 2016; 2018), suggesting a polygenic nature of the phenotype (Bradshaw et al., 2012; Laruson et al., 2020; Barghi et al., 2020). Recent genomic resequencing studies in Lepidoptera, comparing population differentiation or conducting large-scale phenotype-genotype association analyses, have identified additional candidate genes, many of which are related to circadian regulations (Kozak et al., 2019; Pruisscher et al., 2021; Lindestad et al., 2022; Yu et al., 2023; Zheng et al., 2025). Although single genetic variants rarely explain the full extent of phenotypic variation in many cases (e.g., Pruisscher et al., 2018; Lindestad et al., 2024), the association between the circadian clock and photoperiodic regulation is widely recognized Lepidoptera as well as in other insect species (Ikeno et al. 2010; Chang & Meuti, 2020; Hasebe & Shiga, 2025). Whether this association represents a consistent pattern across diverse insect species requires further investigation, as it has not been detected in some studies (e.g., Emerson et al., 2009; Lirakis et al., 2022). At the same time, despite advances in genomic technologies, collecting sufficiently large sample sizes across broad geographic ranges, alongside phenotypic assays and genome sequencing, continues to be a significant challenge.

Drosophila species, many of which likely to have originated in tropical regions, have expanded to occupy habitats spanning a wide latitudinal range (Throckmorton, 1975; Lemeunier et al., 1986; Markow & O'Grady, 2006). Their migratory ability has also facilitated the expansion of habitats within species (e.g., Sprengelmeyer et al., 2020), providing opportunities to investigate

both shared and convergent genetic bases of clinal variation. Because of the direct fitness consequences, clinal variation in reproductive diapause, in which reproduction is arrested under unfavorable environmental conditions, is documented in multiple *Drosophila* species inhabiting temperate to subarctic regions. The diapause incidence increases with latitude in many of these species, reflecting local adaptation despite ongoing gene flow. For example, diapause incidence varies with latitude between ~35–70°N in *D. montana* (Tyukmaeva et al., 2020; Lankinen et al., 2023) and *D. littoralis* (Lankinen, 1986), and between ~34–43°N in *D. auraria* (Minami & Kimura, 1980; Kimura, 1984; Pittendrigh & Takamura, 1987) and *D. lacertosa* (Ichijo, 1986). Similarly, clinal variation of diapause incidence has been intensively studied in *D. melanogaster* along the eastern coast of North America (~25–45°N) and Europe (e.g., Schmidt et al., 2007; Tauber et al., 2007).

In this study, we focus on *D. triauraria*, a member of the auraria complex, which inhabits wide latitudinal ranges (~26–43°N) across the Japanese archipelago (Kimura, 1987). In this species, a strong photoperiodic reproductive diapause has been reported in northern strains, whereas, notably, southern strains fail to arrest ovarian development even under short-day conditions at 15°C (Kimura, 1983; 1988; Yamada & Yamamoto, 2011). These distinct phenotypes, together with the presumable clinal variation in between, provide an ideal opportunity to examine the molecular basis of latitudinal divergence.

Here, we investigate the sensitivity to temperature and photoperiod in reproductive diapause induction in both females and males of *D. triauraria* from mid-latitude regions alongside previously reported and newly tested strains from high- and low-latitude populations. We then examined the degree of divergence from the distribution of a previously described polymorphism in genital morphology (Onuma et al., 2022), and also by a phylogenetic analysis using the whole-genome sequences of the 21 *D. triauraria* strains. Next, to finding signatures of regional divergence, we applied a "monophyletic window" approach, in addition to the conventional F_{ST} analysis. A candidate region contained the *timeless* (*tim*) gene; thus, we conducted quantitative PCR analysis to analyze the association between the *tim* expression and the female reproductive diapause incidence. We discuss the involvement of a circadian clock gene in the adaptive regulation of reproductive diapause in *D. triauraria* and demonstrate the utility of the monophyletic window approach for identifying genomic regions showing geographic divergence.

MATERIALS AND METHODS

Fly strains

The *Drosophila* strains used in this study are described in Table 1. The sampled locations on the map are shown in Figure 1. All strains were maintained at 20ºC under the 15 h light: 9 h dark cycle. All flies were fed with standard corn meal food mixed with yeast, glucose, and agar.

Female diapause assay

The flies were not exposed to the test conditions prior to eclosion, as exposure to low temperatures during embryonic and larval development results in high mortality. Ten virgin females collected within 6 h of eclosion were placed into the food vials and reared under an 8 h light: 16 h dark (8L:16D) or a 16 h light: 8 h dark (16L:8D) cycle, at 12°C, 15°C, and 18°C. The 15°C and 18°C conditions were adopted from the previous studies of this species (Kimura, 1983; Yamada & Yamamoto, 2011), and the 12°C condition was introduced in addition to those temperatures. The 16L:8D and 8L:16D testing light cycles were set to be slightly longer and shorter, respectively, than the natural day lengths (hours between sunrise and sunset) at the summer peak (~15.5 h) and winter peak (~9 h) at the collection sites of the high-latitude strains. Flies were dissected after 21 days at 12°C, 16 days at 15°C, and 14 days at 18°C, according to the timing of sexual maturation inferred from the previous studies (Kimura, 1983; Oguma et al., 1996). The females were dissected in phosphate-buffered saline (PBS), and the ovary images were taken by a CCD camera (DP73, Evident) attached to a microscope (SZX16, Evident). The developmental stages of eggs inside the ovarioles were determined according to King (1970). Diapaused ovaries were defined as those with egg stages 0 to 7 (Figure 2).

Measurements of Accessory gland (AG)

Ten non-mated males collected within 6 h of eclosion were dissected immediately or placed into the food vials and reared under an 8L:16D or 16L:8D light/dark cycle at 12°C for 21 days. The males were dissected in PBS and their accessory glands were fixed in 4% paraformaldehyde (PFA) in PBS for 30 min, followed by three washes in PBST (0.05% Tween 20). The samples were then transferred into PBS. For imaging, 7 µL VectorShield with DAPI (Vector Laboratories) was used for mounting on the slides. Images were taken by a CCD camera (DP73, Evident) attached to an inverted microscope (IX73, Evident). The obtained images were analyzed for area measurement using ImageJ (Schneider et al. 2012).

Male genitalia dissection

Genitalia from 10 males aged 7–10 days were dissected in glycerol after boiling whole bodies in

10% potassium hydroxide at 95°C for more than 10 min to digest soft internal tissues and facilitate clearing. Dissections were performed under a stereomicroscope (SZX7, Evident). Images were acquired using an inverted microscope (IX73, Evident) equipped with a CCD camera (DP73, Evident). Image stacks were processed with CellSens software (Evident) to generate depth-composited TIFF files. Terminology and identification of phallic structures followed Rice et al. (2019) and Onuma et al. (2022) for *D. triauraria*.

Genome sequencing

Genomic DNA was extracted from 40 individuals (20 males and 20 females) per strain for the nine *Drosophila triauraria* strains (SPR23-05, SPR23-09, TM15-38, TM15-57, TM15-67, TM15-92, T544, TTR010, and TMU23-02), along with one *D. biauraria* strain (SPR23-04) and one *D. subauraria* strain (ONM29). DNA extraction was performed using the QIAGEN Genomic-tip 20/G kit (QIAGEN), following the protocol described by Solares et al. (2018). DNA concentrations were quantified using a Qubit dsDNA Quantification Assay Kit (Invitrogen). For each sample, 1 µg of DNA was sent to Filgen, Inc. for library construction and sequencing using a NovaSeq6000 platform with 150 bp paired-end reads.
Additionally, genomic DNA was extracted separately from 10 females and 10 males from each of the five *D. triauraria* strains (ONM-15, K445, Jou, Yak2, and Yak3) using the Geno Plus Genomic DNA Extraction Miniprep System (Viogen). DNA samples (50–250 ng per sample) were used for library preparation with the Collibri PCR-free ES DNA Library Prep Kit for Illumina (Invitrogen). Quality assessment of the libraries was performed using an Agilent 2100 Bioanalyzer (Agilent Technologies). The libraries were then sent to Macrogen Inc., Korea, for sequencing by using a HiseqX with 150 bp paired-end reads. Read depth and quality information for each strain are listed in Table S1.

Quality control and variant calling of the genomic sequence data

Quality control of the sequencing reads was performed using FastQC (Andrews, 2010). Adapter trimming and quality filtering (QC > 30) were conducted using Trim Galore! (Krueger, 2021). Reads were then mapped to the *D. triauraria* reference genome (GCA_014170255.2, RU_Dtri_1.1, NCBI) using Bowtie2 (Langmead & Salzberg, 2012). The mapped reads were sorted using SAMtools (Li et al., 2009), and variant calling was performed using BCFtools v1.18 (Danecek et al., 2021). The quality of the variant calling process was assessed using MultiQC (Ewels et al., 2016) based on the BCFtools v1.18 output. Post-calling variant filtration was performed using BCFtools v1.18. Variants with QUAL ≤ 10, DP > 120, or MQBZ < -3

were filtered out, and the remaining variants were output in variant call format (VCF).

Maximum likelihood tree construction

A FASTA file for each strain was constructed by replacing the reference sequence with the single-nucleotide polymorphisms and deletions (replaced by "-") in the variant call format (VCF) file. The FASTA files from all strains were merged (alignment kept from the original VCF file) and converted to PHYLIP format. Maximum likelihood phylogenetic trees were constructed using IQ-TREE (Minh et al., 2013; 2020; Nguyen et al., 2015) with ultrafast bootstrap (UFBoot) analysis (1,000 replicates) and the GTR+G+I substitution model. Gaps were removed prior to running IQ-TREE. To construct trees from specific 5 kb windows, the focal regions were extracted from the merged FASTA file using SeqKit2 (Shen et al., 2024), in prior to PHYLIP conversion.

Monophyletic window analysis by maximum parsimony tree construction

To conduct a genome-wide sliding window analysis, VCF files from all strains were directly merged (without first constructing FASTA files). The merged VCF file was then divided into 5 kb windows with a 1 kb step size using BCFtools v1.18, and converted to PHYLIP format using vcf2phylip.py (Ortiz, 2019). MPBoot v1.1 (Hoang et al., 2018) was used to generate maximum parsimony phylogenetic trees from each window with 1,000 UFBoot replicates. Monophyly of a particular latitudinal group of strains was analyzed using ape 5.0 (Paradis & Schliep, 2019) and phangorn (Schliep, 2011) packages in R (R core team, 2025). Windows with trees containing monophyletic inner branches with UFBoot values ≥ 90 were considered as candidate genomic regions. The phylogenetic trees were visualized and examined using FigTree v1.4.4 (Rambaut, 2018). Other window sizes (10, 20, and 100 kb) were also analyzed for comparisons. Smaller window sizes provide higher resolution but reduced statistical power due to the limited number of variants. The window size of 5 kb was selected as the smallest size for which more than 90% of windows contained at least 100 variants. To identify genes within the candidate regions, a local BLASTN search (Altschul et al., 1990) using BLAST v2.15.0 (Camacho et al., 2009) was conducted against the *D. melanogaster* transcripts (GCF_000001215.4_Release_6_plus_ISO1_MT_rna.fna.gz), retrieving the hits with E-values < 0.01.

Genetic differentiation analysis

To assess genetic differentiation between groups, Weir and Cockerham's F_{ST} value (Weir and Cockerham, 1984) was calculated using VCFtools (Danecek et al., 2011) for each 5 kb window. The weighted F_{ST} statistic was used to account for varying sample sizes. The results were visualized in R using the ggplot2 package (Wickham, 2016).

Sanger sequencing of the two adjacent monophyletic windows (6 kb) including *tim*

Genomic DNA was extracted from a single female using the NucleoSpin DNA Extraction Kit (Macherey-Nagel). PCR amplification of the 6 kb region was performed using KAPA HiFi HotStart Ready Mix (KAPA Biosystems) or Takara Ex Premier DNA Polymerase (Takara Bio). Two sets of primer pairs were used: 1) 5'-CAGTGCTGATAAACCCCCTTACCTA- 3' or 5'-CACTTGGTTATGAAAGCCCTAACCT- 3' and 5'-GCCAGTTGTAGGTACTTCTCCTCCT- 3'; 2) 5'-AAATACCGGTTATGGACTGGTTACTAGC- 3' and 5'-AAGTCCTCCAAGAGGATGCCATAATAGT- 3'. PCR products were purified using AMPure XP beads (Beckman Coulter) or QIAquick Gel Extraction Kit (QIAGEN). Sanger sequencing was performed using BigDye Terminator v3.1 Cycle Sequencing Kit (Applied Biosystems, Thermo Fisher Scientific) and ABI 3130xl Genetic Analyzer (Applied Biosystems, Thermo Fisher Scientific). Sequence assembly was conducted using BioEdit (Hall, 1999), and the resulting FASTA files were compiled and aligned using MEGA7 (Kumar et al., 2016). The heterozygotes were replaced by the reference sequence manually or using Mitsucal (Suzuki et al., 2018).

Transcript models of *tim* were built by aligning a publicly available ovary transcripts (SRR11780982) to the reference genome (GCA_014170255.2, RU_Dtri_1.1, NCBI) using HISAT2 (Kim et al., 2019). Adapter trimming and quality filtering (QC > 30) were conducted using Trim Galore! in prior to alignment. The aligned reads were sorted into BAM files with SAMtools and assembled into transcripts using StringTie (Pertea et al., 2015). Open reading frames (ORFs) were predicted with TransDecoder (Haas et al. 2013) with a minimum length of 50 amino acids and subsequently filtered by BLASTP against *D. melanogaster* protein sequences (FlyBase dmel-all-translation-r6.36.fasta). BLASTP hits were used to retain only ORFs with significant matches (E-value < 1e-10).

3' Rapid amplification of cDNA ends (3' RACE) of *tim* isoforms

One hundred heads from *D. triauraria* females reared at 20°C under a 15L:9D light/dark cycle were flash-frozen in liquid nitrogen at Zeitgeber-time (ZT)4, corresponding to 4 h after lights on. Total RNA was extracted using the PureLink RNA Mini Kit with TRIzol Reagent (Thermo

254 Fisher Scientific). RNA concentration was measured using a NanoDrop 2000 spectrophotometer
255 (Thermo Fisher Scientific). cDNA synthesis was performed using PrimeScript III Reverse
256 Transcriptase (Takara Bio) with 1 μg of total RNA as a template. The oligo (dT) primer was
257 used at a final concentration of 100 pmol/μL. PCR amplification was carried out using DNA Ex
258 Premier Polymerase (Takara Bio) with 5'-
259 GAGCTCAAGCTTAATCTGTTAAAAGAGTTTACAGTGG-3' and 5'-
260 CCAGTGAGCAGAGTGACGAGGACTCGAGCTCAAGCTTTTTTTTTTTTTTTT-3'. PCR
261 products were analyzed by agarose gel electrophoresis, and target bands (800–1,000 bp and
262 3,000–3500 bp) were excised and purified using NucleoSpin Gel and PCR Clean-up Kit (Takara
263 Bio). The purified DNA fragments were cloned into the pBluescript II SK(+) vector (Agilent
264 Technologies). The vector and PCR products were digested by NotI and treated with shrimp
265 alkaline phosphatase (SAP) for dephosphorylation, followed by ligation using T4 DNA Ligase
266 (Takara Bio). The ligated plasmids were transformed into competent *E. coli* cells. Plasmid DNA
267 was extracted from colonies containing plasmids with a PCR product insertion using Cica
268 Geneus Plasmid Kit (Kanto Chemical). The inserted PCR products were then subjected to
269 Sanger sequencing as described above.
270
271 **Quantification of clock genes or *tim* isoforms transcription level**
272
273 Ten virgin females of ONMA20-3 were collected within 6 h of eclosion and reared in food vials
274 (10 individuals per vial) under an 8L:16D or 16L:8D light/dark cycle at 12°C. After 7 days, the
275 females were immediately frozen in liquid nitrogen every 4 h and stored at -80°C. The same
276 protocol was applied to 15 additional strains, except that the samples were collected at 8 h and
277 16 h after lights on under the respective 8L:16D or 16L:8D light/dark cycle.
278 To extract RNA, 10 frozen heads per sample were detached by vortexing for 5 seconds
279 and placed into 2 mL microtubes containing 400 μL TRIzol Reagent and 1.2 mm (diameter)
280 zirconia-silica beads. Tubes were shaken at 3,200 rpm for 2 min using a Beads Crusher μT-12
281 (Taitec). Chloroform (160 μL) was added, and total RNA was purified using the silica-gel-based
282 method of Boom et al. (1990). First-strand cDNA was synthesized from 70 ng total RNA using
283 the PrimeScript RT Reagent Kit with gDNA Eraser (Takara Bio).
284 Realtime reverse transcription quantitative PCR (RT-qPCR) was conducted using
285 TBGreen Premix Ex Taq II (Tli RNaseH Plus, Takara Bio) in a total reaction volume of 12.5
286 μL. Each reaction contained 6.25 μL of TBGreen Premix, 2 μL of the 3-fold diluted cDNA
287 sample, and 10 pmol each of forward and reverse primers (*tim-L*: 5'-
288 CCCGCATGTATGTAAGCGATG- 3' and 5'-AACTCGGATCTGGGATCTGCT- 3', *tim-sc*: 5'-
289 TGAACACTCCTCCAAAGTCACC- 3' and 5'-GCATCTTAATCCTTACCAAATGG- 3').

Reactions were performed using the Dice Real Time System II thermal cycler (Takara Bio). The standard curves generated from 5-fold serial dilutions of an arbitrarily selected sample (the third replicate of the OEB12 samples collected at ZT16 under 16L:8D light/dark cycle) were used. Each sample was analyzed in technical duplicate, with three biological replicates for each condition.

RESULTS

Geographic variation in female diapause induction

Previous studies have reported a strong photoperiodic induction of reproductive diapause in females of *D. triauraria* from subarctic regions (42–44°N) and the contrasting non-diapausing phenotype of those from subtropical regions (26–28°N) of the Japanese archipelago (Kimura, 1983; 1988; Kimura & Yoshida, 1995; Yamada & Yamamoto, 2011). Strains from the template regions in between exhibited various levels of photoperiodic induction of reproductive diapause at 15°C (Kimura, 1983; 1988). To investigate the geographic variation in photoperiodic responses across temperatures, we measured the proportion of ovaries in reproductive diapause at 12°C, 15°C, and 18°C under either an 8L:16D or 16L:8D light/dark cycle using 21 strains from high- to low-latitude localities (Table 1, Figure 3).

Consistent with the previous studies, the strains from low-latitude regions showed almost no diapause incidence under any condition, showing continuous ovarian development. In contrast, strains from high-latitude regions induced diapause under short-day conditions in a temperature-dependent manner but went into reproductive mode under the long-day photoperiod regardless of temperature. Reproducing under long-day conditions at low temperature may be an adaptive strategy to cope with short summers in high-latitude localities.

Mid-latitude strains showed photoperiod-dependent diapause induction at 15°C and 18°C, like high-latitude strains. However, at 12°C, approximately half of the females induced reproductive diapause under the long-day condition. These results suggest that although mid-latitude strains respond to photoperiods like high-latitude strains, their photoperiodic response at low temperature is reduced, indicating a higher sensitivity to temperature. Three strains from Yakushima Island, which is known for its unique climate including subtropical in the coastal area to near subarctic in the mountainous ranges > 1,800 m, exhibited variable extent of diapause induction under all temperature conditions.

Diapause induction in males

While reproductive diapause is more pronounced in females compared to males in *Drosophila* species, males also exhibit reduced reproductive activity under unfavorable conditions (Kimura, 1988; Kubrak et al., 2016; Ala-Honkola et al., 2020). The cost of reproduction typically differs between males and females (Bateman, 1948; Trivers, 1972); therefore, they may apply different criteria when allocating energy to reproduction. We investigated this possibility by examining male reproductive status under the 8L:16D or 16L:8D light/dark cycle at 12°C using 12 strains (four each from high-, mid-, and low-latitude populations). Yakushima strains were not included in the male accessory gland analysis because the diapause phenotypes of the females were variable and the variation was not associated with latitude, which is the primary focus of this study.

Reduction of testis and accessory gland size at low temperature and short photoperiod has been reported in *D. melanogaster* (Kubrak et al., 2016). However, unlike egg development in ovarioles, which has a checkpoint prior to the initiation of vitellogenesis, when environmental condition is assessed before investigating energy into egg production (Giorgi & Deri, 1976; Drummond-Barbosa & Spradling, 2001), there is no explicit point of arrest in male reproductive organs. Thus, we measured the size of accessory glands, where costly proteins are produced to be injected into the female reproductive tract during copulation.

The accessory gland sizes were measured from the males of all 12 strains kept 21 days after eclosion under the 8L:16D or 16L:8D light/dark cycle at 12°C (Figure 4A). For comparison, those of newly eclosed males within 6 h of eclosion were also measured and the 95% confidence interval (CI) was calculated from the measurement of all strains except T544 (Figure S1). Because the accessory glands of T544 males were significantly larger than those of Jou, OEB12, and OKNG12-6, the 95% CI was calculated separately for this strain. In this study, the males were conservatively classified as reproductively arrested if their accessory gland size was below the upper 95% CI limit of the newly eclosed males. Individuals with accessory gland sizes exceeding this threshold were classified as developing.

The proportion of males under reproductive arrest are shown in Figure 4B. Unlike females, no male in any of the 12 strains met the criteria of reproductive arrest under the 16L:8D light/dark cycle. Their accessory gland sizes not only exceeded the upper 95% CI limit of the newly eclosed males but also showed substantial growth in all strains (Figure 4A and Figure S1). Under the 8L:16D light/dark cycle, some individuals from the high- and mid-latitude strains went into reproductive arrest; however, the proportion did not exceed 60% in any strain, even under the condition where most of females from these regions entered reproductive diapause. These results suggest a weaker suppression of reproduction in males compared to females under unfavorable conditions. Consistent with the reproductive status of the females at

12°C, the males from low-latitude regions did not enter reproductive arrest under either photoperiod.

Intraspecific variation in male genital morphology

To assess the degree of divergence among the latitudinal groups within this species, we examined another polymorphic trait related to reproduction that is not strongly influenced by climatic adaptation. Unlike the diapause-related traits, genital morphology in general is insensitive to environmental factors and is often used for species identification. Thus, variation in this trait provides an independent dataset for evaluating the extent of genetic divergence and independent segregation of genomic regions. Different morphological forms of aedeagus appendages have raised considerable debate over species delimitation of *D. triauraria*. Bock & Wheeler (1972) initially described *D. quadraria* from Taiwan as a distinct species based on differences in male genital morphology, specifically the presence of smaller appendages (dorsolateral claws) compared to those of *D. triauraria* (type specimen from Tokyo, Japan). However, subsequent fertility assays of hybrids (Kimura, 1987; Kim et al., 1989) and molecular phylogenetic analyses (Miyake & Watada, 2007) led to the reclassification of *D. quadraria* as a junior synonym of *D. triauraria* (Watada et al., 2011). Additionally, individuals with similarly small appendages have been reported from the southern islands of Japan (Onuma et al., 2022), further supporting that the observed variation reflects intraspecific rather than interspecific differences.

The morphological variation in aedeagus appendages was classified into two types: Northern (N) and Southern (S) (Figure 5 upper panel). Type N is characterized by larger appendages with a narrower space between them compared to type S. Type N corresponds to the originally described form in *D. triauraria* (Bock & Wheeler, 1972), while type S matches the form from Nansei (Ryukyu) Islands (Onuma et al., 2022), corresponding to the low-latitude region in this study. Genital morphology was examined in 10 males per strain. The strains from southern Japan (low-latitude, Yakushima, and two mid-latitude strains) possessed only type S, whereas most mid- and high-latitude strains included both types (Figure 5 lower panel). Although weak differentiation between northern and southern populations was apparent in genital morphology, discrepancies between the genital morphology and the diapause phenotype suggest that these traits segregate independently, consistent with long-term gene flow and mixed genomic backgrounds across geographic regions.

Genomic phylogeny and geographic differentiation in *D. triauraria*

398 Whole-genome sequences were analyzed to further investigate the overall genetic differentiation
399 among *D. triauraria* strains and the relationship to three other species from the auraria complex.
400 Short-read sequencing data were generated from 14 *D. triauraria*, one *D. subauraria*, and one
401 *D. biauraria* strains, and additional data for seven *D. triauraria* and four *D. auraria* strains were
402 retrieved from the NCBI Sequence Read Archive (SRA) (Table 1). Phylogenetic analysis using
403 a maximum-likelihood tree based on the whole-genome sequences revealed that strains from *D.*
404 *triauraria* and *D. auraria* formed separate clades (Figure 6). Within *D. triauraria*, a weak north
405 to south clinal differentiation was observed, with southern population being closer to the other
406 three species of the auraria complex. The low-latitude strains formed a single cluster, whereas
407 strains within each of the high-, mid-latitude, and Yakushima regions did not.
408
409 **Identification of genomic regions differentiated among geographic populations**
410
411 The genital morphology polymorphism and the whole-genome phylogeny suggest that
412 divergence among latitudinal groups at loci regulating reproductive diapause is likely to be
413 maintained despite gene flow. Such loci should therefore exhibit signatures of divergence
414 among latitudinal groups, in contrast to the rest of the genome. To identify these regions, we
415 employed a tree-based method, focusing on strains from extremes of the species distribution
416 (high- and low-latitude groups), where diapause phenotypes differ most strongly. The genome
417 was partitioned into 5 kb windows with a 1 kb step size, and the windows were screened for
418 those in which high- and low-latitude strains formed monophyletic clusters with ≥ 90%
419 bootstrap (UFBoot) support. A window size of 5 kb was chosen after comparison with 10, 20,
420 and 100 kb windows, which produced largely consistent UFBoot profiles (Figure 7 and Figure
421 S2), indicating that the 5 kb window provided finer-scale resolution while retaining sufficient
422 phylogenetic signal.
423 For the high-latitude group, 55 monophyletic windows were detected on the X
424 chromosome, two windows on 2L, and a single window on 3R (Figure 7A and Table S2). The
425 clustered windows on the X chromosome, stretching discontinuously from 29.437 Mb to 30.287
426 Mb, included the region homologous to *D. melanogaster* Y chromosome (29.7–34.9 Mb, Chang
427 et al., 2023) and therefore almost no coding genes were found (Table S2). Notably, the two
428 windows on 2L included *timeless* (*tim*), which has been implicated for diapause regulation in
429 many insect species (Mathias et al., 2005; Tauber et al., 2007; Sandrelli et al., 2007; Pruisscher
430 et al., 2018; Lindestad et al., 2022; Vaze et al., 2024) and also suggested to be associated with
431 diapause induction in *D. triauraria* (Yamada & Yamamoto, 2011). Sanger resequencing of the
432 two consecutive windows spanning a 6 kb region confirmed the presence of two putative E-box
433 motifs and one TER-box motif (Figure 8), which are critical for the circadian gene regulation

434 (McDonald et al., 2001). The 11 polymorphic sites fixed in the high-latitude group were located
435 in intronic regions outside these motifs.
436 In the low-latitude group, which does not respond to either photoperiod or
437 temperature, a total of 188 monophyletic windows were located on chromosomes X, 2L, 2R,
438 and 3R (Figure 7B, Table S3). These regions included *eyes shut* (*eys*), known to be involved in
439 temperature entrainment of circadian activity (Sehadova et al., 2009); *nahoda*, which is
440 expressed in egg chambers (Manning et al., 2017); and *Sox100B*; which plays a role in male-
441 specific gonad development (Nanda et al., 2009). The involvement of these genes in the
442 regulation of reproductive diapause has not been implicated.
443 The genome-wide F_{ST} window comparisons are more commonly applied to detect
444 divergent genomic regions between populations. However, F_{ST} estimates can be biased when the
445 sample sizes are small or uneven among regional populations (Whitlock and McCauley, 1999;
446 Willing et al., 2012). To address this, we compared the windows with the highest F_{ST} values to
447 those identified using the tree-based approach (Figure S3 and Figure S4). These comparisons
448 revealed that 93.1% (54 out of 58) of the monophyletic windows in high-latitude strains
449 (including those with the *tim* locus) and 92.0% (173 out of 188) in low-latitude strains
450 overlapped with the top 5% F_{ST} windows. In contrast, only 0.09% (54 out of 5841) and 0.032%
451 (173 out of 5463) of the top 5% windows overlapped with the monophyletic windows in high-
452 and low-latitude strains, respectively. Thus, the monophyletic windows represent a stringently
453 defined subset of the highest F_{ST} windows, based on an additional criterion of strong bootstrap
454 support for monophyly.
455
456 **Association between the expression of *tim* isoform groups and diapause incidence**
457
458 Multiple *tim* isoforms are expressed in *D. melanogaster* and other species of the *melanogaster*
459 subgroup (Low et al., 2008; Anduaga et al., 2019). These isoforms can be categorized by size:
460 long isoforms (*tim-L*, *tim-cold*), and a short isoform (*tim-sc*). *tim-L* is the canonical isoform,
461 while *tim-cold* and *tim-sc* are more abundant at low temperatures. The roles of these isoforms
462 have been investigated in *D. melanogaster*, variants of the *tim-L* isoform (*ls-tim*- and *s-tim*) are
463 known to regulate diapause induction (Tauber et al., 2007; Sandrelli et al., 2007), and
464 accumulation of TIM-SC under low temperature, short-day condition is implicated in diapause
465 regulation by stabilizing Eyes absent (EYA) (Abrieux et al., 2020).
466 The isoform differences are mostly attributed to alternative splicing downstream of
467 exon 9. Thus, to investigate the presence of these isoforms in *D. triauraria*, we performed 3′
468 RACE using RNA extracted from the heads of females from two strains, ONMA20-3 (high-
469 latitude) and OEB12 (low-latitude). We were able to identify sequences corresponding to the

470 two common isoforms, *tim-L* and *tim-sc*, and designed primers within the terminal exons to
471 quantify the abundance of the long and short isoforms (hereafter referred to as *tim-L* and *tim-sc*
472 isoform groups, respectively) by a realtime RT-qPCR (Figure S5). Although *tim-cold* and *tim-M*
473 were not detected in our 3' RACE analysis, they may still be amplified by the primers targeting
474 the *tim-L* isoform group. It should be noted that other undetected isoforms may also be
475 amplified by the designed primer pairs.
476 The oscillation patterns of *tim-L* and *tim-sc* isoform groups in the heads of females
477 from the ONMA20-3 strain were analyzed under an 8L:16D or 16L:8D light/dark cycle at 12°C
478 (Figure S6). The temporal patterns of *tim-L* expression under both photoperiods largely
479 coincided with the nuclear accumulation of TIM in the lateral ventral neurons (LN_v) of *D.*
480 *melanogaster* brain (Shafer et al., 2004), including a possible phase advance at low temperature
481 (Majercak et al., 1999; Anduaga et al., 2019). The overall expression level of *tim-L* isoform
482 group (averaged across six timepoints) was significantly higher under the 16L:8D light/dark
483 cycle than under 8L:16D (*t*-test after hyperbolic arcsine transformation: $t = 14.94$, df = 2, $P <$
484 0.01), whereas no significant difference was observed between the two cycles in the *tim-sc*
485 isoform group ($t = 3.54$, df = 2, $P = 0.07$).
486 To investigate whether the differences between the two light conditions in expression
487 of the two isoform groups (particularly *tim-L*, which showed a significant light-dependent
488 difference in ONMA20-3) are associated with diapause incidence at 12°C, the *tim* mRNA
489 abundance was quantified at ZT8 and ZT20 under 8L:16D and 16L:8D in female heads from the
490 high-, mid-, and low-latitude strains (Figure S7A). Two-way ANOVA showed that the *tim-L*
491 expression in the low-latitude strains was significantly lower than in the high-latitude strains
492 under both light conditions and also significantly lower than in the mid-latitude strains under
493 8L:16D (Figure S7C), suggesting a distinct regulatory mechanism of this isoform group in the
494 low-latitude strains. For the *tim-sc* isoform group, no significant effects were observed except
495 for a difference between the high- and mid-latitude groups under the 8L:16D light/dark cycle
496 (Figure S7B and Figure S7C).
497 Because the low-latitude strains exhibited no reproductive diapause even under the
498 8L:16D short-day (SD) condition at 12°C and displayed distinct *tim-L* expression profiles, the
499 following association analysis was conducted using only the high- and mid-latitude strains,
500 which showed variable diapause incidence under the 16L:8D long-day (LD) condition at 12°C.
501 For simplicity, the abbreviations LD and SD are used in the model. To explain variation in
502 diapause incidence under LD, we considered the following model:
503 $\Delta_{\text{SD-LD}} P_{\text{diap}} = \beta_0 + \beta_1 \cdot tim\text{-}L_{\text{LD}} + \beta_2 \cdot tim\text{-}sc_{\text{LD}} + \beta_3 \cdot \Delta_{\text{LD-SD}}\, tim\text{-}L + \beta_4 \cdot \Delta_{\text{LD-SD}}\, tim\text{-}sc + \varepsilon$,
504 where $\Delta_{\text{SD-LD}} P_{\text{diap}}$ is the difference in the arcsine-transformed diapause proportions between the
505 SD (8L:16D) and LD (16L:8D) conditions. $tim\text{-}L_{\text{LD}}$ and $tim\text{-}sc_{\text{LD}}$ denote the hyperbolic arcsine-

transformed relative expression levels under LD, and $\Delta_{\text{LD-SD}}$ *tim-L* and $\Delta_{\text{LD-SD}}$ *tim-sc* represent the differences in expression between the two light conditions. The arcsine transformation was applied to normalize the diapause incidence, which ranges from 0 to 1, while the hyperbolic arcsine transformation was used to normalize the *tim* expression data, which are not restricted to this range . β_0 and $\beta_{1\text{–}4}$ denotes intercept and regression coefficients, respectively. This model aims to explain the variable $\Delta_{\text{SD-LD}}\, P_{\text{diap}}$, reflecting the increased reproduction (reduced diapause) under LD relative to SD, which is most pronounced in the high-latitude strains (Figure 3). It incorporates *tim-L* and *tim-sc* isoform group expression under LD ($tim\text{-}L_{\text{LD}}$ and $tim\text{-}sc_{\text{LD}}$), as well as their expression differences between LD and SD ($\Delta_{\text{LD-SD}}$ *tim-L* and $\beta_4 \cdot \Delta_{\text{LD-SD}}$ *tim-sc*), to account for the relationship between isoform-specific expression and photoperiodic reproductive response.

We then performed stepwise model selection using BIC, which identified the following model as the best-fit model:

$$\Delta_{\text{SD-LD}}\, P_{\text{diap}} = \beta_0 + \beta_3 \cdot \Delta_{\text{LD-SD}}\, tim\text{-}L + \varepsilon,$$

with the coefficient estimates shown in Table 2. The result indicates that the differences in *tim-L* expression between the two light conditions are significantly associated with the differences in diapause incidence at 12°C. The positive regression coefficient indicates that strains with relatively higher *tim-L* expression under the long-day condition (LD: 16L:8D) show reduced diapause incidence, suggesting an enhanced reproductive activity at low temperature.

DISCUSSION

Initiating or arresting reproduction is a critical life-history choice with major consequences for lifetime fitness. Like many other insects, *D. triauraria* respond to environmental cues such as temperature and photoperiod to make the choice. We conducted a comprehensive analysis of the female reproductive diapause induction in 21 strains of this species, including both newly tested and previously reported strains collected from across the Japanese archipelago (26.2–43.1°N). Our results revealed that a key difference between the high- and mid-latitude strains lies in their temperature sensitivity under the long-day condition (16L:8D). At 12°C, females from the mid-latitude strains exhibited a higher incidence of reproductive diapause compared to those from the high-latitude strains (Figure 3). This reduced sensitivity to low temperature (i.e., stronger photoperiodic induction of diapause) in the high-latitude strains likely reflects adaptation to northern environments, where reproducing under cooler and shorter summer seasons is essential.

Although direct comparisons between sexes are challenging, our results suggest that

542 females and males from the high- and mid-latitude regions differ in how reproduction activity is
543 modulated by photoperiod and temperature (Figure 3 and Figure 4). This implies that the
544 thresholds for reproductive suppression vary between sexes, potentially reflecting sex-specific
545 life history strategies. In particular, males may maintain investment in reproduction under
546 suboptimal conditions, consistent with the relatively lower energetic cost of reproduction
547 compared to females (Bateman, 1948; Trivers, 1972). Future work should examine the extent to
548 which shared versus sex-specific neuroendocrine pathways and sensory circuits contribute to
549 these differences. Moreover, assessing traits beyond accessory gland development, such as
550 spermatogenesis status and courtship behavior, will be essential for a comprehensive
551 understanding of intersexual variation in reproductive status under unfavorable environmental
552 conditions.

553 Our whole-genome phylogeny revealed only weak geographic divergence (Figure 6),
554 and the observed discrepancies between genital morphology and diapause phenotype (Figure 5)
555 further suggest that long-term gene flow across geographic regions has generated sufficient
556 recombination to decouple genomic regions associated with different traits. Such genomic
557 decoupling provides an opportunity to identify geographically divergent regions associated with
558 specific phenotypes. To investigate the genetic basis underlying the observed differences in
559 female diapause response, we applied a monophyletic window approach, which imposes a
560 stricter criterion for identifying genomic regions than the standard F_{ST} scans. Although Weir and
561 Cockerham's weighted F_{ST} estimation corrects for sample sizes of the populations (Weir and
562 Cockerham 1984), small and unbalanced samples, as in this study, can introduce false signals of
563 differentiation (Whitlock and McCauley, 1999; Willing et al., 2012). By focusing on genomic
564 windows where the focal group forms a well-supported monophyletic cluster, this approach
565 helps mitigate such biases.

566 For the high-latitude strain group (against all other groups), only 54 5-kb windows
567 showed both ≥ 90% bootstrap support for monophyly and F_{ST} values within the top 5%,
568 representing <1% of all top 5% F_{ST} windows (Figure S4A). These windows were located in two
569 separate genomic regions (one additional window on 3R met the monophyly criterion but fell
570 outside the top 5% F_{ST} threshold) (Figure 7A). The two windows on 2L contained *tim*, and a
571 cluster of windows on the X chromosome included few genes (Table S1). For the low-latitude
572 strain group, 173 windows met both the ≥ 90% bootstrap support and top 5% F_{ST} criteria,
573 representing approximately 3% of all top 5% F_{ST} windows (Figure S4B). These were distributed
574 across more than 20 separate genomic regions (Figure 7B). The smaller number of candidate
575 windows in the low-latitude groups could be due to multiple factors: a smaller number of
576 strains, a higher number of regions under selection, inflated F_{ST} threshold in the high-latitude
577 strains due to a dense cluster of high-F_{ST} windows on the X chromosome, or a combination of

578 these factors. We were unable to examine specific candidate regions within the low-latitude
579 group due to these complexities.
580 Our monophyletic window approach does not directly target diapause-associated loci
581 and may capture divergent regions associated with other locally adapted traits, including non-
582 reproductive traits such as the recently reported midgut remodeling response during diapause in
583 this species (Adachi et al. 2025), as well as more general metabolic or stress-tolerance
584 adaptations. Nevertheless, among the windows showing strong signals of high-latitude group
585 monophyly, we found a candidate region encompassing the E-box and T-box regulatory motifs
586 of *tim*. Given the implicated role of *tim* in regulating diapause across multiple insect species,
587 including *D. triauraria*, we further investigated the association between *tim* expression levels
588 and reproductive diapause incidence. Using RT-qPCR, the mRNA levels of the long and short
589 isoform groups were quantified. We detected a significant association across strains between the
590 differences in diapause incidence under the long- and short-day photoperiods and the
591 differences of *tim-L* isoform group expression between those light conditions at 12°C. The
592 analysis focused on the high- and mid-latitude strains, as the low-latitude strain exhibited
593 distinct diapause regulation patterns. Finally, it would be informative in future studies to
594 quantify other non-reproductive stress-response traits under these conditions, as they may also
595 be regulated by *tim*.
596 As in many organisms, circadian rhythms in *Drosophila* are influenced by light,
597 implicating a link between clock genes and photoperiodic regulation (e.g., Denlinger, 2022). *tim*
598 is a core circadian gene whose product, TIM, is bound by the photoreceptor CRYPTOCHROME
599 (CRY) upon light exposure and subsequently degraded by ubiquitination, resulting in light-
600 induced resetting of the circadian clock (Hunter-Ensor et al., 1996; Ceriani et al., 1999; Busza et
601 al., 2004). The primary light-sensitive isoform, *tim-L*, is included in the isoform group for which
602 we observed an association with diapause incidence. The light-insensitive isoforms, *tim-cold*
603 and *tim-sc*, are induced by low temperature (Montelli et al., 2015; Shakhmantsir et al., 2018;
604 Anduaga et al., 2019; Abrieux et al., 2020). Among these isoforms, TIM-SC contributes to the
605 stabilization of EYA, a key seasonal sensor, suggesting that the relative abundances of *tim-L* and
606 *tim-sc* may play a role in diapause induction in females of *D. melanogaster* (Abrieux et al.,
607 2020). There is no evidence from these *D. melanogaster* studies, however, demonstrating a
608 direct effect of *tim-L* on reproductive diapause. Thus, the mechanisms underlying the observed
609 association in our study, where higher *tim-L* expression associates with lower diapause
610 incidence at low temperature, remains unclear at this point. It is also important to note that the
611 TIM protein abundance was not quantified in our study, and the increased mRNA expression
612 observed under the long-day condition could reflect either an enhanced transcription or
613 compensatory response to light-driven protein degradation. Interestingly, unlike *D.*

614 *melanogaster* and related species such as *D. simulans, D. yakuba,* and *D. virilis*, whose *tim*
615 splicing is temperature-sensitive (Anduaga et al., 2019), the cold-tolerant northern species, *D.*
616 *montana*, exhibits photoperiod-sensitive *tim* splicing (Tapanainen et al., 2018). This suggests
617 that the splicing regulation of *tim* isoforms and their functional roles in circadian and diapause
618 pathways may vary considerably across species.

619 In *D. triauraria*, Kimura and Yoshida (1995) analyzed recombinant inbred lines derived
620 from hybrids between a diapausing strain (ONMA20-3) and a non-diapausing strain from
621 Kametoku (28°N), and estimated that three or four loci underly the difference in the photoperiodic
622 response, with at least one located on the X chromosome. More recently, Yamada and Yamamoto
623 (2011) conducted a genetic analysis and reported an association between reproductive diapause
624 incidence and the genetic marker variants at *tim* and *cry*. This analysis was based on genotyping
625 five clock genes (*per*, *tim*, *clk*, *cyc*, and *cry*) in 329 backcrossed individuals derived from a cross
626 between a diapausing strain (ONMA20-3) and a non-diapausing strain (OEB12). The association
627 with *tim* is consistent with our results, further supporting a potential role for this gene in diapause
628 regulation of *D. triauraria*. However, the low marker density (only five loci across the entire
629 genome) limits their mapping resolution. As they also noted, the observed associations could be
630 due to linkage with nearby genes rather than direct effects of *tim* or *cry*. Our higher-resolution
631 approach allows a more targeted investigation of this region and together with the expression
632 analysis, strengthens the case for *tim* as a candidate gene involved in photoperiodic diapause
633 regulation.

634 Consistent with the previous report (Yamada & Yamamoto, 2011), females of low-
635 latitude strains did not exhibit reproductive diapause under any of the tested conditions (Figure
636 3). Our experimental design differed from that of Yamada and Yamamoto (2011) in that flies
637 were transferred to the test conditions immediately after eclosion, whereas in the earlier study
638 flies were exposed to experimental conditions from the embryonic stage. Despite this difference,
639 we observed qualitatively similar phenotypes in the low-latitude strains. We further showed that
640 males of these strains also failed to arrest reproduction (Figure 4) and displayed reduced
641 expression of *tim-L* isoform group (Figure S7A). Taken together with the earlier finding that the
642 diapausing phenotype is completely dominant over the non-diapausing type (Yamada &
643 Yamamoto, 2011), these results suggest that the low-latitude strains may carry impaired
644 signaling pathways required for diapause induction. An intriguing evolutionary question that
645 remains unresolved is the ancestry of the phenotype; whether the absence of diapause in the
646 low-latitude strains represents a derived loss of the trait, or alternatively, whether the ability to
647 enter reproductive diapause was an adaptation acquired in the high-latitude populations.

648 Many *Drosophila* species are likely to have originated in tropical region and later
649 expanded into temperate and subarctic regions (Throckmorton, 1975; Lemeunier et al., 1986;

Markow & O'Grady, 2006). In our whole-genome maximum likelihood tree, the low-latitude and Yakushima strains of *D. triauraria* form the basal lineages (Figure 6), consistent with a tropical origin. However, Kimura (1988) argued that adaptation to cool-temperate climates likely preceded speciation within the *auraria* complex. This view was based on the observation that species within the complex do not differ markedly in cold-hardiness. Supporting this hypothesis, three other species in the complex exhibit reproductive diapause phenotypes similar to that of the northern strains of *D. triauraria* (Kimura, 1984; Kimura, 1990). Kimura (1988) further proposed that the current subtropical populations of *D. triauraria* may have established through reinvasion from northern, cool-temperate populations, as these subtropical flies are significantly more cold-hardy than sympatric populations of the subtropical or warm-temperate species like *D. rufa* and *D. lutescens*. These competing hypotheses, tropical origin with independent acquisition of diapause in the north versus ancestral diapause with secondary loss in the south, remain difficult to reconcile.

However, the phylogenetic analysis of the *tim* genomic region, including other species of the auraria complex (Figure S8), does not support a scenario in which the low- and mid-latitude alleles are derived from the high-latitude allele, nor the reverse. Instead, the tree suggests that these alleles have diverged independently from a basal state. Given the likelihood of frequent introgression and incomplete lineage sorting within the *auraria* complex (Miyake & Watada, 2007; Conner et al., 2021), it is plausible that two alleles of early origin associated with diapause regulation have persisted in different geographic regions within *D. triauraria*. Although our analysis is currently confined to a single locus, the results raise the possibility that key diapause-related alleles originated and diverged close to the time of speciation and subsequently underwent differentiation along latitudinal gradients. In light of the polygenic basis of diapause regulation, information from additional loci will be essential to further test and refine this scenario, thereby providing deeper insights into the evolutionary dynamics of adaptive traits evolving across heterogeneous environments.

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AUTHOR CONTRIBUTIONS

TF and AT conceived this work. YA and TF analyzed accessory gland. MO and TF analyzed genital morphology. MN obtained genome sequences of five *D. triauraria* strains. TF and AT analyzed data and wrote the manuscript.

DATA AVAILABILITY STATEMENT

Raw sequence reads have been deposited in the SRA under BioProject PRJDB20728, with individual run accession numbers provided in Table 1. Sequences of *tim* isoform groups are available in DDBJ (accession numbers LC882409–LC882412). Sequencing data for the 6 kb *tim* region are deposited in DDBJ (accession numbers LC884490–LC884507)

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Table 1 Strains of *D. triauraria*, *D. auraria*, *D. biauraria*, and *D. subauraria* used in this study.

Species	Strain name	Latitude group	Collection site	Coordinates	Year	Source (fly stock)	Genome accession #
D. triauraria	SPR23-05	High-latitude	Sapporo	43.1°N, 141.2°E	2023	Gift from Masahito T. Kimura.	DRR720568 [g]
D. triauraria	SPR23-09	High-latitude	Sapporo	43.1°N, 141.2°E	2023	Gift from Masahito T. Kimura.	DRR720569 [g]
D. triauraria	TM15-38	High-latitude	Tomakomai	42.6°N, 141.6°E	2015	KYORIN-Fly stock center	DRR720564 [g]
D. triauraria	TM15-57	High-latitude	Tomakomai	42.6°N, 141.6°E	2015	KYOTO *Drosophila* stock center	DRR720565 [g]
D. triauraria	TM15-67	High-latitude	Tomakomai	42.6°N, 141.6°E	2015	KYOTO *Drosophila* stock center	DRR720566 [g]
D. triauraria	TM15-92	High-latitude	Tomakomai	42.6°N, 141.6°E	2015	KYORIN-Fly stock center	DRR720567 [g]
D. triauraria	ONMA20-3	High-latitude	Onuma [b]	42.0°N, 140.4°E	1981	Gift from Shin G. Goto.	DRX055244 [g]
D. triauraria	ONM-15	High-latitude	Onuma [b]	42.0°N, 140.4°E	1984	TMU stock [e]	DRR720577 [g] DRR720578 [g]
D. triauraria	TTR010	Mid-latitude	Tsuchiura	36.1°N, 140.2°E	2017	Collected by M. Onuma (author)	DRR720571 [g]
D. triauraria	T544	Mid-latitude	Tsukuba	36.0°N, 140.0°E	1980	KYORIN-Fly stock center	DRR720570 [g]
D. triauraria	TMU23-02	Mid-latitude	Hachioji	35.6°N, 139.3°E	2023	Collected by T. Fujichika (author)	DRR720572 [g]
D. triauraria	K445	Mid-latitude	Oiso	35.3°N, 139.3°E	1980s [d]	TMU stock [e]	DRR720575 [g] DRR720576 [g]
D. triauraria	Jou	Mid-latitude	Mishima	35.1°N, 138.9°E	1986	TMU stock [e]	DRR720573 [g] DRR720574 [g]
D. triauraria	T748	Mid-latitude	Miyazaki	31.7–32.0°N, 131.2–131.3°E [c]	1982	KYORIN-Fly stock center	SRR13188919
D. triauraria	Yak2	- [a]	Yakushima	30.3°N, 130.6°E	1982	TMU stock [e]	DRR720579 [g] DRR720580 [g]
D. triauraria	Yak3	- [a]	Yakushima	30.3°N, 130.6°E	1982	TMU stock [e]	DRR720581 [g] DRR720582 [g]
D. triauraria	YKS-MTK	- [a]	Yakushima	30.3°N, 130.6°E	1982	KYORIN-Fly stock center	SRR13188918
D. triauraria	OEB12	Low-latitude	Okinoerabu	27.2°N, 128.3°E	2005	KYORIN-Fly stock center	SRR13188921
D. triauraria	OKNG12-6	Low-latitude	Nago	26.7°N, 128.1°E	2012	KYORIN-Fly stock center	SRR13188920
D. triauraria	KMJ1	Low-latitude	Kumejima	26.2°N, 126.5°E	2002	KYORIN-Fly stock center	SRR13188923
D. triauraria	KMJD2	Low-latitude	Kumejima	26.2°N, 126.5°E	2003	KYORIN-Fly stock center	SRR13188922
D. auraria	14028-0471.01	-	Nopporo	43.0°N, 141.5°E	1965	- [f]	SRR9997924
D. auraria	L5	-	Tomakomai	42.6°N, 141.6°E	2011	- [f]	SRR13188915
D. auraria	L8	-	Matsuyama	33.8°N, 132.7°E	2014	- [f]	SRR13188913
D. auraria	L11	-	Matsuyama	33.8°N, 132.7°E	2016	- [f]	SRR13188937

D. biauraria	SPR23-04	-	Sapporo	43.1°N, 141.2°E	2023	Gift from Masahito T. Kimura.	DRR720583 [g]
D. subauraria	ONM-29	-	Onuma [b]	42.0°N, 140.4°E	1982	KYORIN-Fly stock center	DRR720584 [g]

[a] Strains from Yakushima are not assigned to any latitude group.
[b] Referred to "Ohnuma" in Onuma et al. (2022).
[c] Exact location unknown.
[d] Exact year of collection unknown.
[e] Stock kept at Tokyo Metropolitan University.
[f] Live flies not used; genomic data only.
[g] Genome sequence data obtained in this study.

Table 2 Results of the linear regression model selected by stepwise BIC for explaining the differences in diapause incidence between light conditions.

Predictor	Estimate (β)	Std. Error	t	P
Intercept	0.813	0.095	8.55	<0.0001
$\Delta_{16L8D\text{-}8L16D}$ *timL*	0.948	0.383	2.47	0.0293

1064 Figure legends
1065
1066 **FIGURE 1 Collection sites of *D. triauraria* strains from Japanese archipelago used in this**
1067 **study**
1068 A total of 21 isofemale lines of *D. triauraria* that were established from natural populations
1069 were used. Circles indicate collection sites: blue, gray, and red denote high-, mid-, and low-
1070 latitude regions, respectively, while orange represents Yakushima Island, which has a unique
1071 mixed climate distinct from the other regions.
1072
1073 **FIGURE 2 Reproductively diapaused and non-diapaused ovaries of *D. triauraria***
1074 (A) Schematic illustration of a pair of *Drosophila* ovaries, modified from King (1970). Each
1075 ovary consists of multiple ovarioles, where oogenesis progresses from stage 0 to 14 (mature
1076 egg). (B) Diapaused ovaries, lacking eggs at ≥ stage 8 (vitellogenic stages). (C) Non-diapaused
1077 ovary with nine eggs at ≥ stage 8. (D) Fully developed ovary.
1078
1079 **FIGURE 3 Effects of temperature and photoperiod on reproductive diapause incidence**
1080 **across regional populations of *D. triauraria***
1081 The proportion (%) of female individuals in reproductive diapause under different temperatures
1082 (12ºC, 15ºC, and 18ºC) and photoperiods (8L:16D or 16L:8D light/dark cycle). The colors
1083 indicate different latitudinal regions: blue, grey, orange, and red indicate high-latitude, mid-
1084 latitude, Yakushima, and low-latitude regions, respectively. Thick solid line connects the mean
1085 at each temperature.
1086
1087 **FIGURE. 4 Effects of temperature and photoperiod on accessory gland (AG) growth**
1088 **across regional populations of *D. triauraria***
1089 (A) Sizes of AGs after 21 days under different photoperiods (8L:16D or 16L:8D) at 12ºC. Two
1090 representative images of AGs are shown above the graph. Orange dashed lines indicate the
1091 upper limit of the 95% CI calculated within strain for T544, and for the remaining strains, from
1092 the pooled data excluding T544. The separate calculation for T544 was performed due to its
1093 significant difference from other strains (see Figure S1). (B) Proportion (%) of males with AG
1094 sizes below the 95% CI upper limit of day 0 after 21 days under 8L:16D or 16L:8D at 12ºC.
1095 Colors indicate latitudinal regions: blue, grey, and red indicate high-latitude, mid-latitude, and
1096 low-latitude regions, respectively. Thick solid line connects the means at each temperature.
1097
1098 **FIGURE 5 Polymorphism of the aedeagus appendages (dorsolateral claws) compared with**
1099 **female reproductive diapause phenotype in *D. triauraria***

The upper panel shows the schematic images of the size polymorphism of aedeagus appendages (after Onuma et al. 2022), classified as Northern (N) and Southern (S) types. Scale bar indicates 50 μm. Genital morphology was examined in 10 males per strain and compared with the female reproductive diapause phenotype at 12ºC (lower panel). The colors of the strain names represent their latitudinal regions of origin: blue, grey, orange, and red indicate high-latitude, mid-latitude, Yakushima, and low-latitude regions, respectively.

FIGURE 6 Maximum likelihood tree constructed from the whole-genome sequences of *D. triauraria, D. auraria, D. biauraria,* and *D. subauraria* strains used in this study.
Maximum likelihood tree using IQ-TREE with the GTR+G+I model. Nodes with UFBoot value = 100 , estimated from 1,000 pseudo-replicates are highlighted in orange. The colors of *D. triauraria* strain names represent their latitudinal regions of origin: blue, grey, orange, and red indicate high-latitude, mid-latitude, Yakushima, and low-latitude regions, respectively. Asterisks indicate strains whose genomic sequences were obtained in this study.

FIGURE 7 Monophyletic window analyses of the high- and low-latitudinal groups.
(A) Sliding window profile of bootstrap (UFBoot) support (%) for monophyly of the high-latitude strain group, based on maximum parsimony trees (window size = 5 kb, step size = 1 kb). Red dots mark the midpoints of windows where the high-latitude strains formed monophyletic clusters with ≥ 90% bootstrap support (1,000 pseudo-replicates). The upper graph zooms in on the region containing the *timeless* (*tim*) gene (brown horizontal bar), which coincides with two consecutive windows above this threshold (midpoints in red). The maximum likelihood tree of one of these windows (highlighted by a pink stripe) is shown, with nodes having UFBoot ≥ 90% highlighted in orange.
(B) Sliding-window profile of bootstrap (UFBoot) support (%) for monophyly of the low-latitude strain group, based on maximum parsimony trees (window size = 5 kb; step size = 1 kb). Red dots mark the midpoints of windows where low-latitude strains formed monophyletic clusters with ≥ 90% bootstrap support (1,000 pseudo-replicates). The maximum likelihood trees of the sampled windows are drawn above the graph, with nodes having UFBoot ≥ 90% highlighted in orange. The genome coordinates are based on the *D. triauraria* reference genome (GCA_014170255.2_RU_Dtri_1.1_genomic.fna). The colors of *D. triauraria* strain names represent their latitudinal origin: blue, grey, orange, and red indicate high-latitude, mid-latitude, Yakushima, and low-latitude regions, respectively.

FIGURE 8 Putative E-box and TER-box sequence motifs within the 6 kb region covering the two consecutive monophyletic windows of the high-latitude strains.

The two consecutive monophyletic 5 kb windows are shown in a red horizontal arrow. Gray boxes indicate predicted exons of *tim-L* isoform. Red vertical arrows mark the positions of SNPs that are fixed only in high-latitude populations (positions in bp: 4,337,946, 4,338,013, 4,338,442, 4,338,876, 4,338,994, 4,338,995, 4,339,687, 4,339,715, 4,339,759, 4,341,078, 4,341,209). Putative E-box and TER-box motifs are shown, with the positions corresponding to the indicated sites. The genome coordinates are based on the *D. triauraria* reference genome (GCA_014170255.2_RU_Dtri_1.1_genomic.fna).

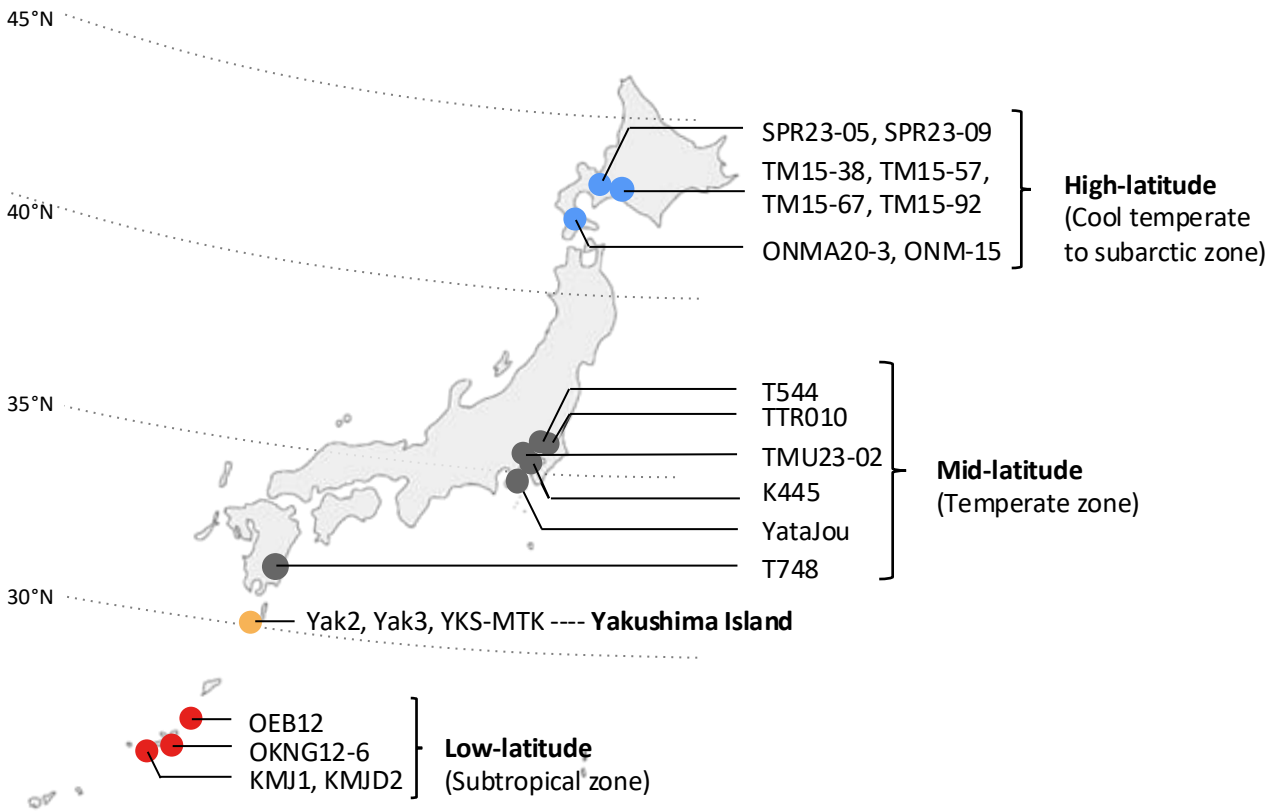

45°N
40°N
35°N
30°N
SPR23-05, SPR23-09
TM15-38, TM15-57,
TM15-67, TM15-92
ONMA20-3, ONM-15
High-latitude
(Cool temperate
to subarctic zone)
T544
TTR010
TMU23-02
K445
YataJou
T748
Mid-latitude
(Temperate zone)
Yak2, Yak3, YKS-MTK ---- Yakushima Island
OEB12
OKNG12-6
KMJ1, KMJD2
Low-latitude
(Subtropical zone)

FIGURE 1

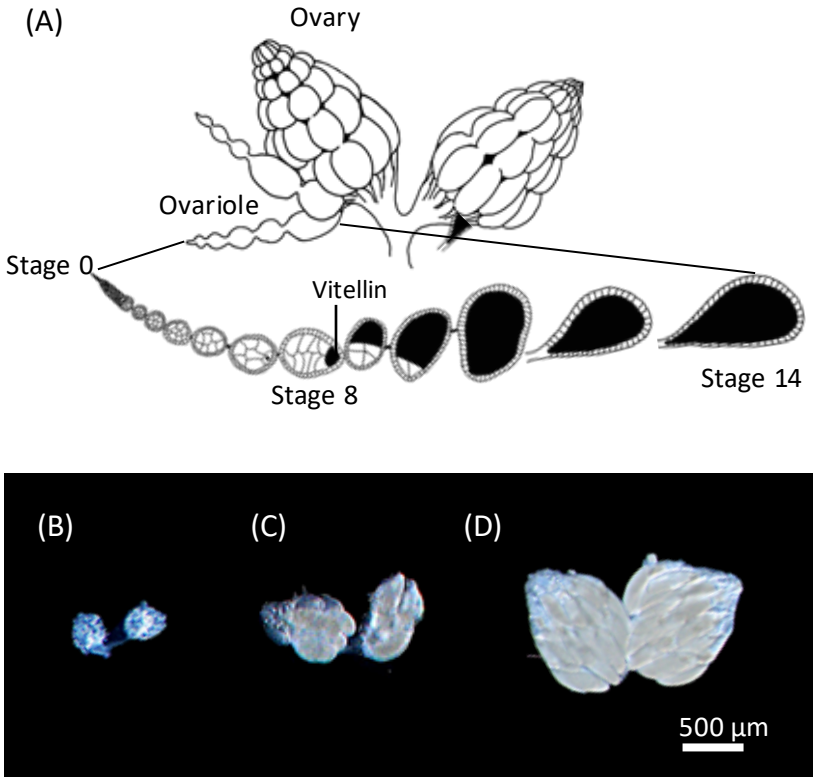


FIGURE 2

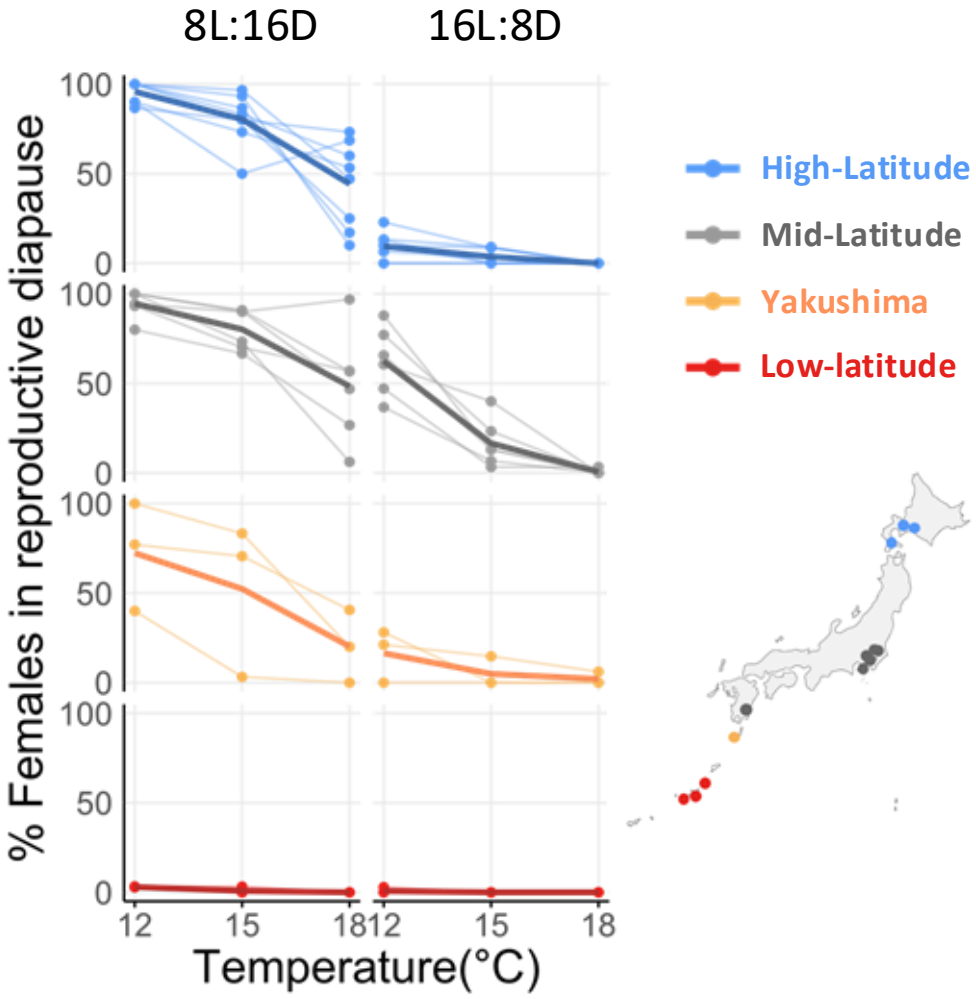

8L:16D
16L:8D
% Females in reproductive diapause
100
50
0
12
15
18
Temperature(°C)
High-Latitude
Mid-Latitude
Yakushima
Low-latitude

FIGURE 3

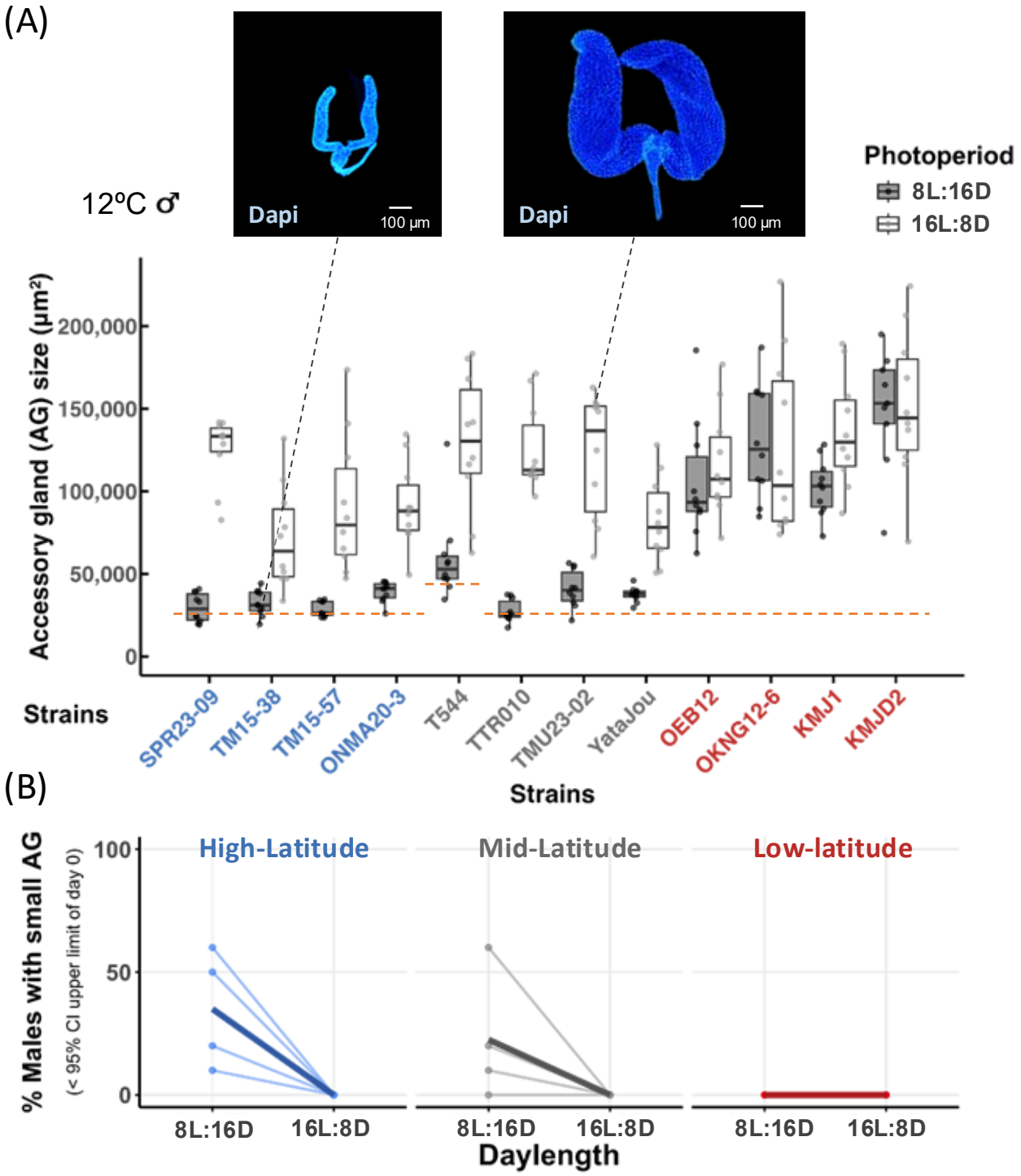
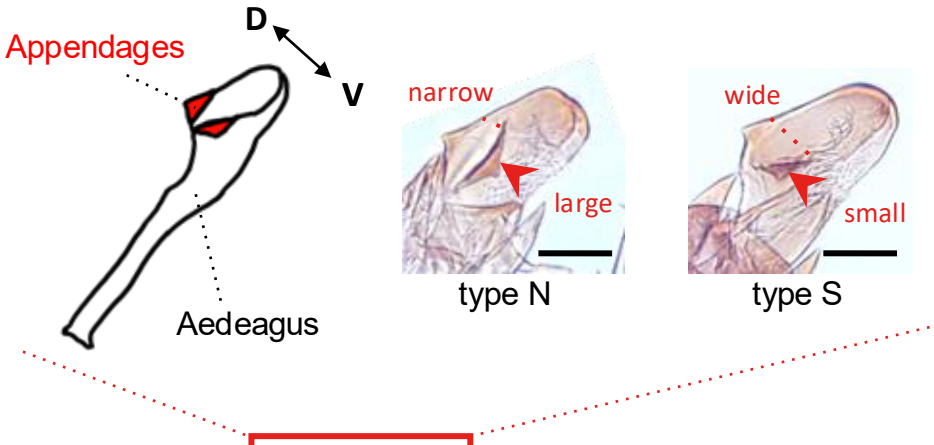

(A)
12ºC ♂
Dapi
100 µm
Dapi
100 µm
Photoperiod
8L:16D
16L:8D
Accessory gland (AG) size (µm²)
200,000
150,000
100,000
50,000
0
Strains
SPR23-09
TM15-38
TM15-57
ONMA20-3
T544
TTR010
TMU23-02
YataJou
OEB12
OKNG12-6
KMJ1
KMJD2
Strains
(B)
% Males with small AG
(< 95% CI upper limit of day 0)
100
50
0
High-Latitude
Mid-Latitude
Low-latitude
8L:16D
16L:8D
8L:16D
16L:8D
8L:16D
16L:8D
Daylength

FIGURE. 4



	Strain	Aedeagus appendages (N = 10)	Reproductive diapause (%) at 12°C (N = 30–35) 8L16D	16L8D
High-Latitude	SPR23-05	type N & S	90	10
	SPR23-09	type N & S	86.7	0
	TM15-38	type N & S	100	6.5
	TM15-57	type N & S	100	10
	TM15-67	type N & S	100	22.9
	TM15-92	type N & S	100	13.3
	ONMA20-3	type N & S	100	12.9
	ONM-15	type N & S	90	0
Mid-Latitude	T544	type N & S	100	60.6
	TTR010	type S	94.3	77.1
	TMU23-02	type N & S	100	47.1
	K445	type N & S	80	36.7
	Jou	type N & S	100	65.7
	T748	type S	93.3	87.9
Yakushima	Yak2	type S	40	0
	Yak3	type S	100	28.1
	YKS-MTK	type S	77.1	21.2
Low-latitude	OEB12	type S	2.9	0
	OKNG12-6	type S	3.3	0
	KMJ1	type S	2.9	2.9
	KMJD2	type S	2.9	0

100%

0%

FIGURE 5

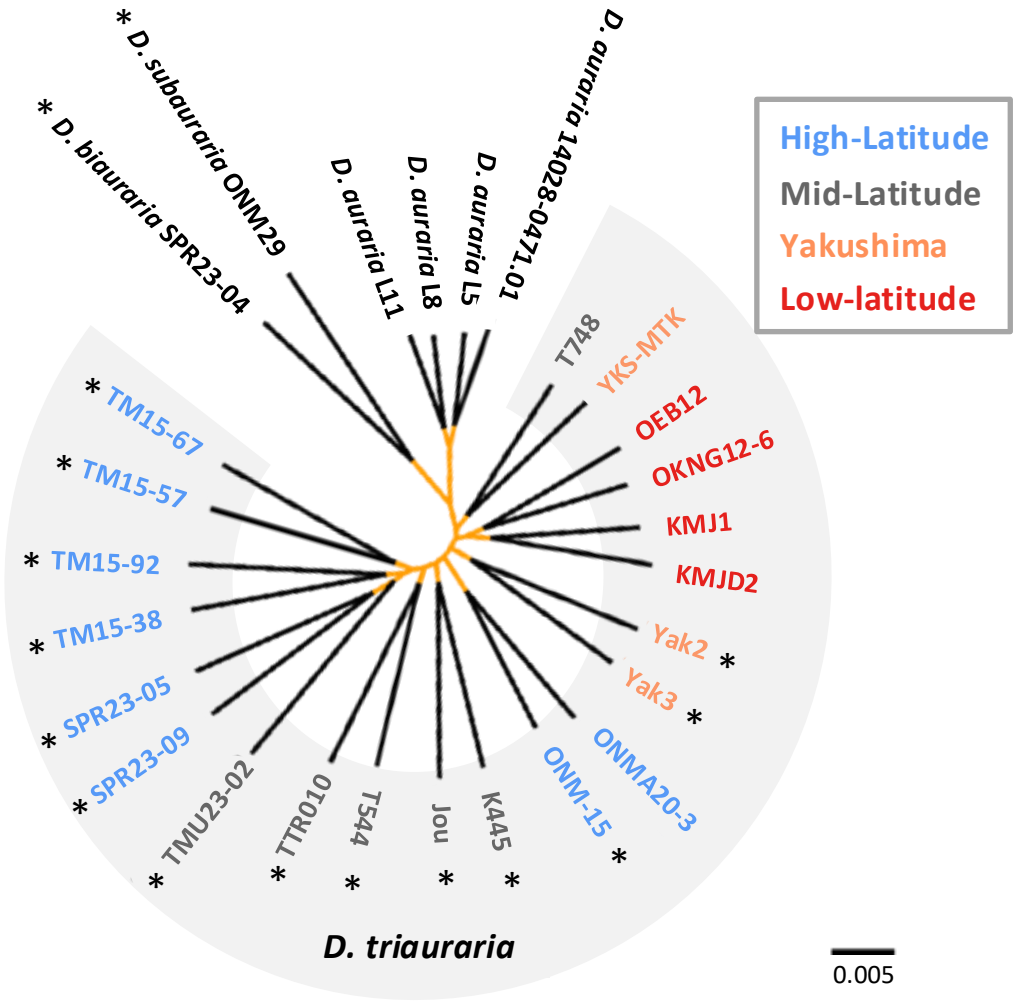
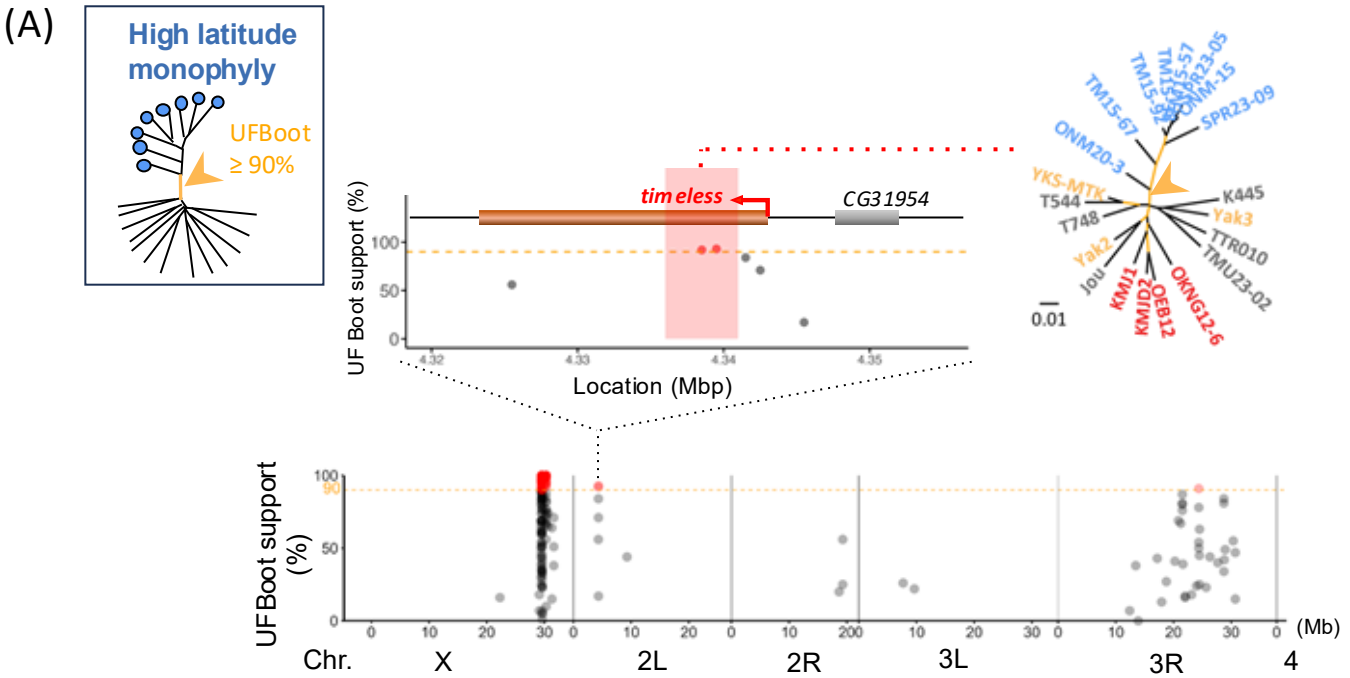

High-Latitude
Mid-Latitude
Yakushima
Low-latitude
D. auraria L402B-0471.01
D. auraria L5
D. auraria L8
D. auraria L11
D. subauraria ONM29
D. biauraria SPR23-04
T748
YKS-MTK
OEB12
OKNG12-6
KMJ1
KMJD2
Yak2
Yak3
ONMA20-3
ONM-15
K445
Jou
T544
TTR010
TMU23-02
SPR23-09
SPR23-05
TM15-38
TM15-92
TM15-57
TM15-67
D. triauraria
0.005

FIGURE 6


(A)
High latitude monophyly
UFBoot ≥ 90%
timeless
CG31954
UF Boot support (%)
Location (Mbp)
0.01
UFBoot support (%)
Chr.
X
2L
2R
3L
3R
4
(Mb)

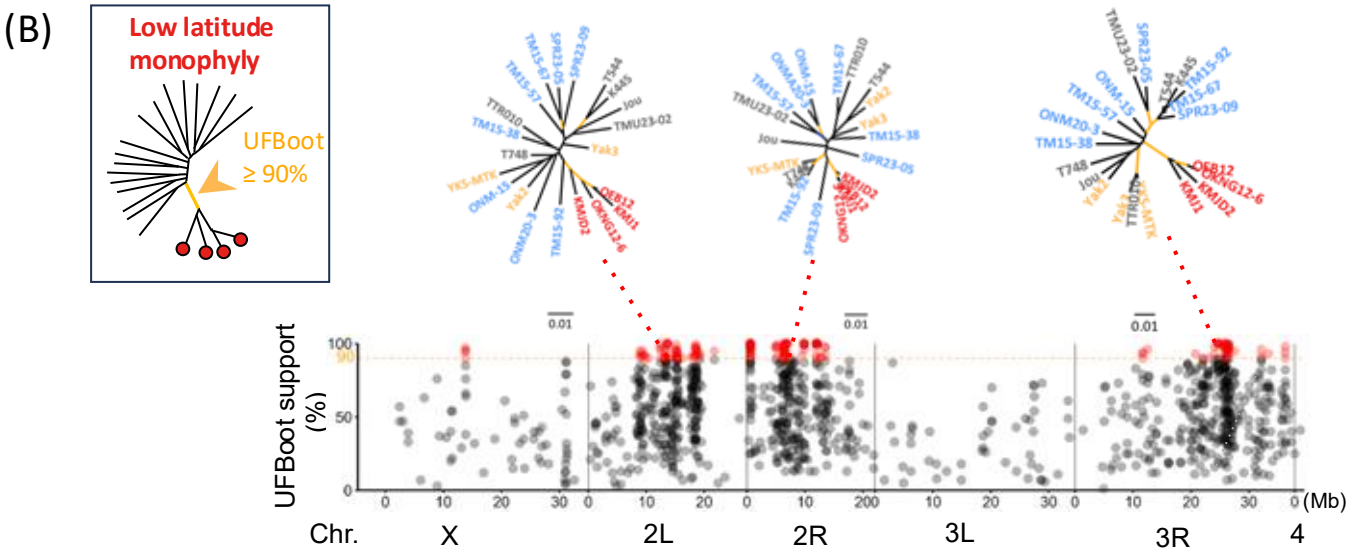

(B)
Low latitude monophyly
UFBoot ≥ 90%
0.01
UFBoot support (%)
Chr.
X
2L
2R
3L
3R
4
(Mb)

FIGURE 7

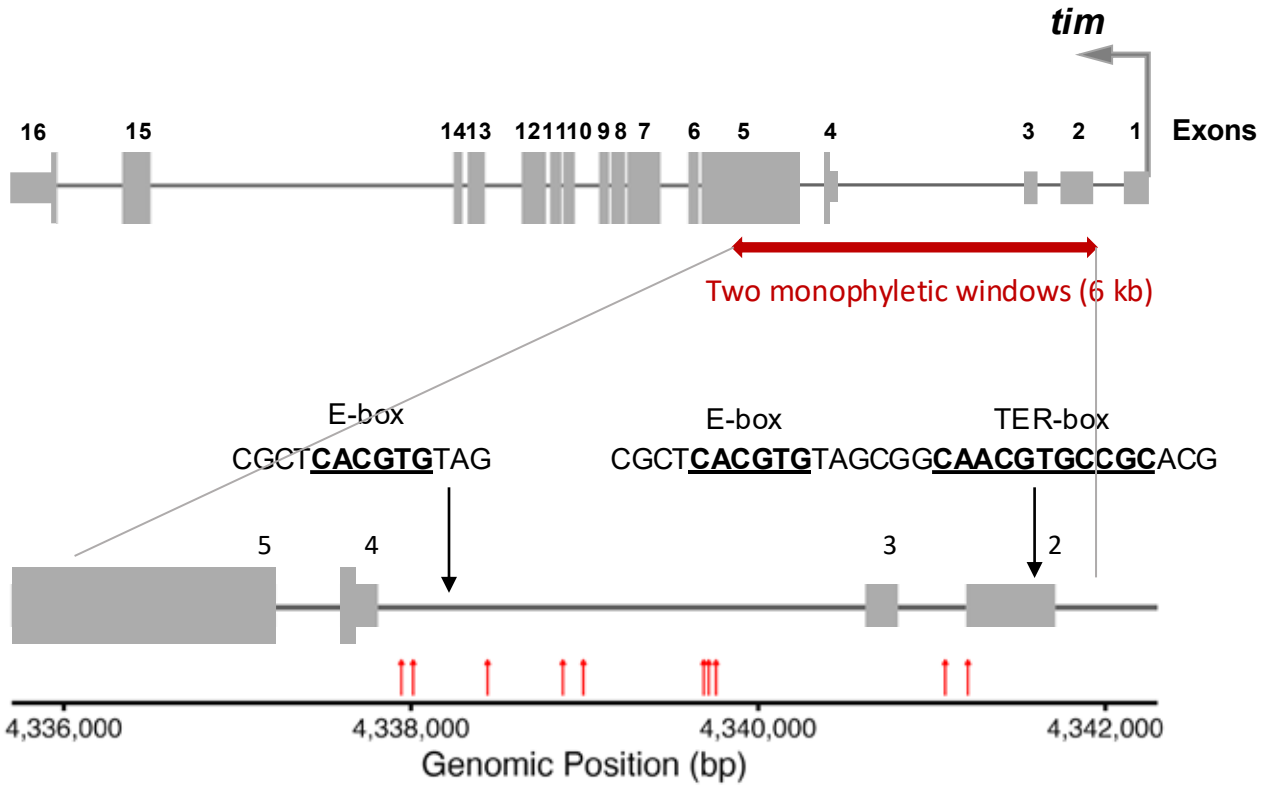

tim
16
15
1413
121110 9 8
7
6
5
4
3
2
1
Exons
Two monophyletic windows (6 kb)
E-box
CGCTCACGTGTAG
E-box
CGCTCACGTGTAGCGGCAACGTGCCGCACG
TER-box
5
4
3
2
4,336,000
4,338,000
4,340,000
4,342,000
Genomic Position (bp)

FIGURE 8