Title

Circadian-period variation underlies the local adaptation of photoperiodism in the short-day plant *Lemna aequinoctialis.*

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Summary

Phenotypic variation is the basis for trait adaptation via evolutionary selection.[1, 2, 3] However, the driving forces behind the quantitative trait variations remain unclear owing to their complexity at the molecular level.[4, 5, 6] This study focused on the natural variation of the free-running period (FRP) of the circadian clock because FRP is a determining factor of the internal clock phase (chronotype), which is responsible for physiological timing during a day.[7] Although natural variations in FRP have been widely reported,[8, 9, 10, 11] few studies have shown the association between FRP and adaptive temporal traits. As a clock-dependent physiological process, photoperiodism is a typical target of local adaptation.[12, 13] *Lemna aequinoctialis* in Japan is a paddy-field duckweed exhibiting a latitudinal cline of critical day-lengths (CDLs) for short-day flowering.[14] To investigate the relationship between FRP and CDL, we collected 72 strains of *L. aequinoctialis* within a latitudinal range between 31.5°N to 43.8°N. We found a significant correlation (P = 7.5E-8) between FRPs and locally adaptive CDLs, confirming that the variation in FRP-dependent chronotypes underlies geographically differentiated photoperiodism. Diel transcriptome analysis revealed that the induction timing of a florigen gene is key for connecting chronotypes to photoperiodism at the molecular level. Based on these results, we propose a fundamental rule concerning the "chronotype effect" in evolution: the variation of FRP functions as a resource for the variation of temporal traits. This study highlights the adaptive significance of FRP variation and provides a reason for the maintenance of FRP variation in natural populations.

Results and discussions.

We investigated the influence of natural variations in circadian clock properties on the temporal phenotype of clock-dependent physiology. The circadian clock is an endogenous timing system that generates a self-sustained daily oscillation entrained to day-night cycles via environmental cues.[15] The eukaryotic circadian clock consists of feedback loops of multiple clock genes.[16] The free-running period (FRP) of the circadian clock is a polygenic trait that exhibits natural variation.[8, 9, 10, 11, 12, 17] These circadian clocks with different periods are entrained to 24 h day-night cycles.[18, 19] The peak timing (phase) of an entrained rhythm also shows natural variation. This phase phenotype is termed the chronotype.[7] In this study, we define the "chronotype effect" as the phenotypic effects on physiological traits originating from variations in chronotype. Previous studies suggest that chronotype determination is related to the FRP.[20, 21, 22, 23, 24, 25, 26] We hypothesized that FRP variation is associated with local adaptation of a clock-dependent physiology.

Lemna aequinoctialis in Japan is a paddy-field duckweed with a latitudinal cline of critical day-lengths (CDLs) for short-day flowering.[14] To investigate the relationship between FRP and CDL, we collected 72 strains of *L. aequinoctialis* from 20 populations located between latitudes 31.5°N and 43.8°N (Figure 1A and Table S1). To estimate both intra-population and inter-population variation, 11–12 strains were collected from each of four populations (N32Ka, N35Ht, N35So, and N44Ha). The strains were aseptically maintained by clonal growth. Laboratory experiments using a clonal plant enabled the precise determination of multiple phenotypic traits of the natural genotype. The frond size showed intra-population and inter-population variation, suggesting heterogeneous genotypes, even within a population (Figure S1). The estimated genome sizes of all the strains were similar (Figure S2).

These strains recognized day lengths with a resolution of 0.5 h and their CDLs ranged from 11.2 to 14.2 h (Figures 1B, 1C and 1D). As previously reported,[14] a latitudinal cline was observed in CDLs: 11.2–12.6 h in the south, 12.4–14.2 h in the north, and a large variation of CDLs was observed at approximately 35°N (Figure 1E). The longer CDL at higher latitudes is consistent with other short-day flowering species.[27, 28, 29] Intra-population differences of 1–1.5 h in CDLs were observed in each population of N32Ka, N35Ht, N35So, and N44Ha (Figure 1F). The significant differences between these populations suggest geographical differentiation of CDLs. The difference in CDL between the two 35°N populations, N35Ht and N35So suggests that the adaptive CDL at each site may differ even at the same latitude (Figure 1F). The flooding period of the paddy fields differed between the sampling sites depending on the cultivation schedule of the different rice cultivars. The longer CDL of N35So, corresponding to earlier flowering, is consistent with the earlier cessation of flooding at this site than that at the N35Ht site (Figure 1G). The CDL of the N32Ka population was shorter than that of the N35 population (Figure 1F). The CDLs of the three populations appeared to be linked to the cultivation schedule at each site (Figure 1G). Complete drainage of paddy fields during and after rice harvesting

is a potential selection pressure for duckweed.[30, 31] Although the rice-harvesting time at the N44Ha site was comparable to that at the N35Ht site, the CDL of N44Ha was longer than that of N35Ht. At the N44Ha site, the low-temperature season (<15 °C: lower limit for *L. aequinoctialis* growth)[32] began before the rice harvest time, suggesting that low temperature, rather than rice harvest time, may be a potential selection pressure. Overall, the CDLs of the four populations were likely to fit a suitable season for reproduction at each site.

The natural variation in circadian rhythms was assessed using a luciferase reporter assay.[33] Using particle bombardment, a luminescent reporter, *AtCCA1::LUC*,[34] was semi-transiently introduced into plants grown under long-day conditions (15L9D; 15-h light / 9-h dark). The plants were placed on an automatic luminescent monitoring system and released into constant light (LL) after two days of 15L9D (Figure 2A). All strains showed clear diel luminescence rhythms with morning peaks at 15L9D. Among the four populations, the peak time of N32Ka was significantly later than that of the other three populations (Figure 2B). To estimate FRP under LL, fast Fourier transform-nonlinear least squares (FFT-NLLS) analysis[35] was used (Figure 2C), in which the rhythm significance was estimated by a relative amplitude error (RAE) that increased from 0 to 1 as the rhythm neared statistical insignificance. Seven strains with a high RAE value (>0.1) or a high standard deviation (SD) of FRP (>1.5 h) were excluded from the following analysis (Figure S3). The FRP of N32Ka was significantly longer than that of the other populations, corresponding to its late peak time (Figures 2B and 2D). This is consistent with the concept of chronotype: a positive correlation between FRP and peak time.[24]

Correlation analysis using data from all 72 strains (20 populations) suggested a chronotype effect on photoperiodism (Figure 3A). A positive correlation between FRP and peak time was confirmed at the genotypic level. In addition, CDL showed a negative correlation with both FRP and the peak time. These results suggest that the variation in FRP-dependent chronotypes underlies the variation in the CDL. The CDL shift can be explained as the chronotype effect on the florigen (floral inducer), which responds to night-length (Figure 3B).[36] In this model, the activation of the florigen is assumed to be gated by the circadian clock and permitted in the dark. A longer FRP causes a phase delay in the gate timing and, consequently, a shorter CDL, resulting in a negative correlation between FRP and CDL.[37]

To explore florigen genes, we obtained diel transcriptomes of *L. aequnictialis* pure line (Nd strain[33]) under three photoperiod conditions. Five florigen homologues were detected by *de novo* assembly and were named *LaFTh1–5* (Figures S4A and S4B). *LaFTh1* was induced before the end of the night, and its expression level increased during longer-night conditions (Figures 3C and S4C). The transgenic *Arabidopsis thaliana* carrying an *LaFTh1* overexpression construct showed an early flowering phenotype, suggesting its florigen activity (Figure S4D). *LaFTh1* was induced even in extended dark following a non-flowering long-day condition, suggesting that *LaFTh1* expression directly responds to night lengthening. The timing of *LaFTh1* induction differed among the three

109 strains with different CDLs and the variation in induction timing appears to be responsible for the
110 CDL variation (Figures 3D and 3E). Thus, the induction timing of *LaFTh1* is key for connecting
111 chronotype to photoperiodism at the molecular level. Notably, the *LaFTh1* expression levels showed
112 a large difference. The *LaFTh1* expression in the N44Ha08 strain was 10-fold higher than that in the
113 other two strains (Figure 3E). This high basal level may have caused an extremely long CDL of 14.2
114 h (Figure 1F).

115 Our study demonstrated the chronotype effect on locally adapted traits: CDL variation is
116 tightly coupled with FRP variation, even in natural populations. Diel transcriptome analysis suggests
117 that florigen induction timing, which is likely to be related to the FRP-dependent chronotype, is a
118 determining factor for CDL and consequently for the flowering season. These results indicate the
119 importance of circadian phenotypes in the natural selection of seasonal phenotypes. This study also
120 provides new insights into the local adaptation of CDLs to the paddy-field environment. Consistent
121 with previous studies using short-day plants,[27, 28, 29] the populations of *L. aequnictialis* in Japan showed
122 a latitudinal cline in their CDLs, suggesting that the flowering season of this plant adapted to the local
123 climate, exhibiting a latitudinal cline in temperature.[12] Furthermore, their CDLs appeared to adapt to
124 the flooding season at each sampling site (Figure 1G). The improved drainage systems associated with
125 the agricultural modernization of Japan that began in the 1950s have resulted in dry paddy-field
126 environments in winter and consequently altered the weed flora.[38] The natural variation of the FRPs
127 possibly contributed to the adaptive evolution of the flowering season in response to the rapid artificial
128 shift of the flooding season. In addition to inter-population variations, CDLs also showed intra-
129 population variations (Figure 1F). The flooding period of paddy fields is highly dependent on the rice
130 cultivar grown. Such artificial fluctuations may promote intra-population variations in CDLs. In *A.*
131 *thaliana*, the recombinant inbred lines of two accessions with similar FPRs showed variation as
132 substantial as that observed among the global collection (22.0 to 28.5 h).[39] Such transgressive
133 segregation of FPR is caused by the complex interference among many quantitative loci,[40] and may
134 play an important role in providing the phenotypic variations for rapid evolutionary adaptation to
135 irregular environmental changes.[41] Interestingly, the estimated genome sizes of all *L. aequinoctialis*
136 strains used in this study were ~800 Mbp and considered to be tetraploid (Figure S2).[42, 43] Polyploidy
137 may generate phenotypic variations by increasing the rates of evolution and number of components in
138 gene regulatory networks.[44, 45]

139 Because the circadian clock regulates various physiologies,[7, 46] FRP variation potentially
140 contributes to the fine-tuning of their temporal traits in the process of local adaptation. Conversely,
141 selection pressure on the temporal traits of such clock-dependent physiologies may favor mutations in
142 clock-related genes that alter the FRP and, consequently, the chronotype (Figure 4). This is a possible
143 reason for the maintenance of FRP variation with standing genetic variations in clock-related genes in
144 natural populations.[8, 11, 12] Thus, the adaptive significance of FRP variation should be considered in

relation to the phase phenotype under day-night conditions.[7, 21, 25] Interestingly, a latitudinal cline of FRP was reported in the linden bug, *Pyrrhocoris apterus*,[10] in which circadian clock genes are responsible for the photoperiodic response of the reproductive diapause.[47] The circadian clock was acquired for adaptation to day-night cycles and has evolved as a hub of environmental response systems involving multiple input pathways.[48] As a result, in the process of adaptive evolution, the circadian system can function as a source of variation for temporal traits through the chronotype effect integrating many quantitative loci for FRP.[4, 39, 49, 50]

Data availability

The RNA-seq raw sequences (PRJDB12719) and LaFTh1 CDS (LC662606) were deposited at DDBJ.

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Author contributions

T.M. and T.O. designed the study and wrote and revised the manuscript. T.M. performed the experiments using *L. aequinoctialis* and all the analyses. S.I. performed the experiments using *A. thaliana* and contributed to the particle bombardment experiments. H.K. contributed to RNA-seq experiments and revised the manuscript. All authors have contributed to the text.

Competing interests

The authors declare no competing interests.

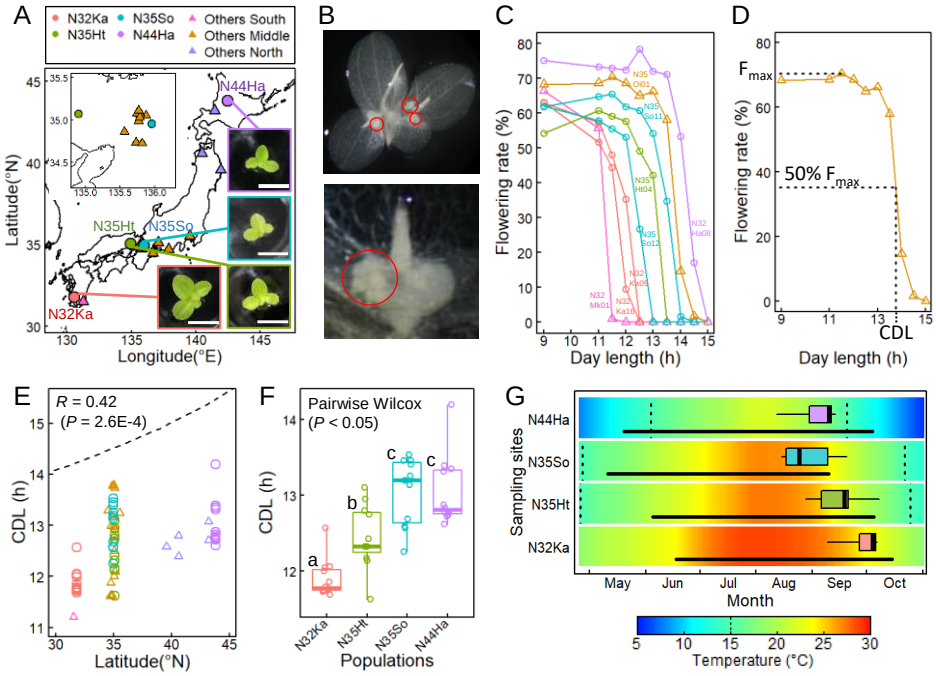

Figure 1 Local adaptation of critical day-length (CDL) in *Lemna aequinoctialis* strains isolated in Japan. A, The locations from which 11–12 strains (circles) and 1–3 strains (triangles) were isolated. The same colors and symbols apply to other panels. Examples of the strains in the four populations are shown. Scale bars: 5 mm. **B**, A colony with floral buds (top). Colony of N35Oi03 strain bleached by EtOH after one week of short-day (9L15D) treatment and imaged from the underside. Close-up underside view around the meristematic tissue. Red circles indicate floral buds. **C,** Continuous variation of photoperiodic response on flowering. Flowering rate after one week of photoperiodic treatment is plotted against treated day-length. Eight strains in six populations are shown. **D**, Critical day length (CDL) was determined as the day-length where 50% of the maximum flowering rate (Fmax) is expected. See Methods for more detail. **E**, Latitudinal cline of CDL. The Pearson's correlation coefficient and *P* value are shown. Dashed line represents day-length of summer solstice. **F,** CDL variation among the four populations. Boxplots with points representing individual strains are shown. **G,** Timing of CDLs in the year at four sampling sites. The dates for CDLs shown in panel c are represented as a box plot at each site. Black horizontal lines represent the flooding period. The background colors represent 30-year (1990–2019) mean of daily temperature. Vertical dotted lines represent 15 °C.

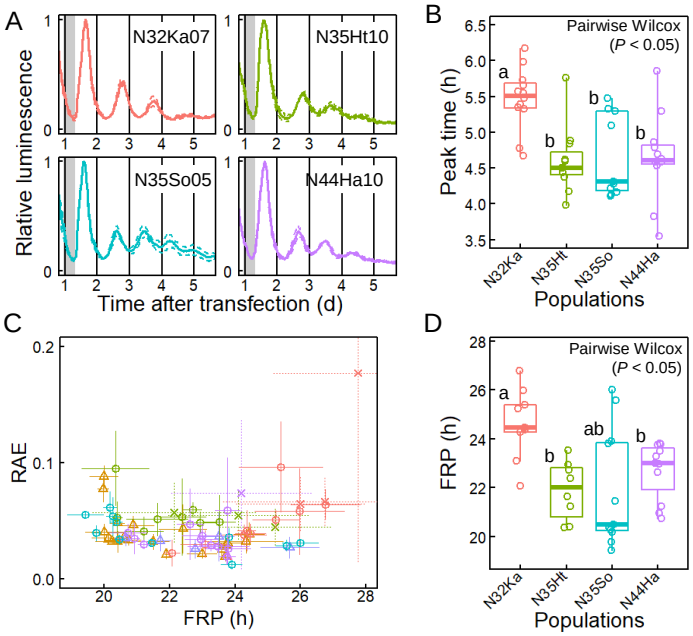

Figure 2 Natural variation of circadian rhythms in *Lemna aequinoctialis* strains. A, Examples of luminescence rhythms of *AtCCA1::LUC*. Solid and dashed lines represent mean and ± SD of three replications, respectively. Gray boxes indicate dark period. The strain name is indicated in each plot. **B,** Variation of the timing of the first peak in constant light (LL) among the four populations. Boxplots with points for individual strains are shown. **C**, Relative amplitude error (RAE) of each strain plotted against its free running period (FRP). Mean values of three replications are shown. Error bars = SD. The crosses represent seven strains that showed unstable rhythms (SD of FRP > 1.5 h, Figure S3). Population names are represented in the graph legend. **D,** Variation of the free-running period (FRP) in LL among the four populations. Boxplots with points for individual strains are shown. Seven strains with unstable rhythms (SD of FRP > 1.5 h) were excluded from the plot.

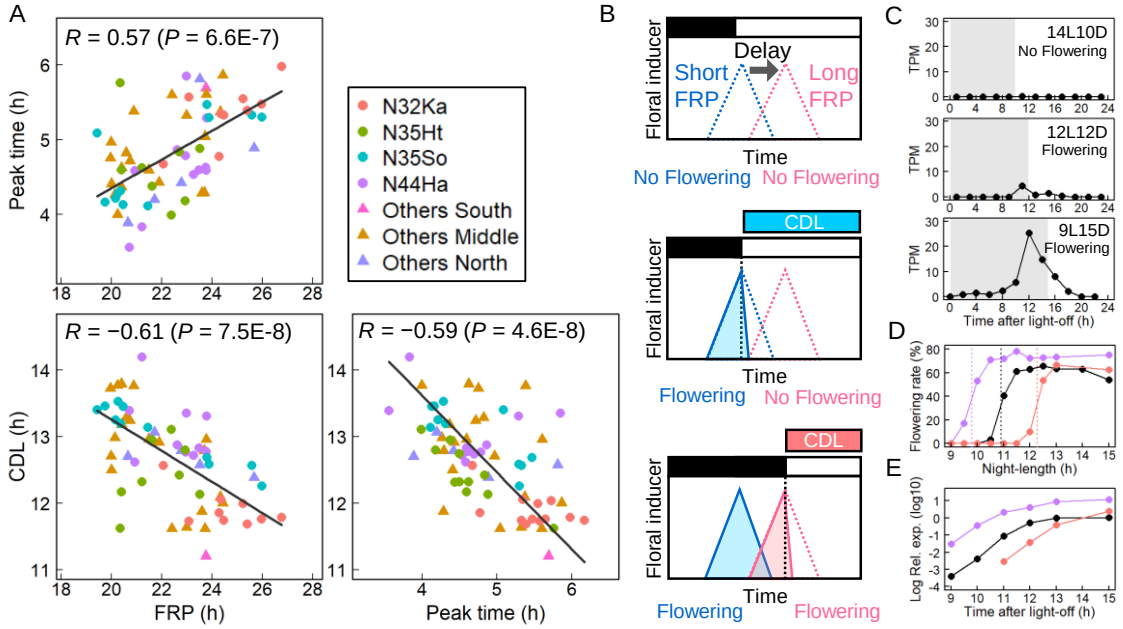

Figure 3 Chronotype effect on photoperiodic flowering. A, The correlations between FRP, peak time, and CDL of *L. aequinoctialis* strains. The Pearson's correlation coefficient and *P* value are shown in each graph. Black lines represent Deming regression lines. Plots of seven strains with unstable rhythms (SD of FRP > 1.5 h) are excluded from graphs that include FRP. **B,** The hypothetical mechanism for the negative correlation between FRP and CDL. The activation of the floral inducer is assumed to be gated by the circadian clock and permitted in the dark. The dotted lines and filled triangles schematically represent gate timing and activity of a floral inducer, respectively. The blue and red colors correspond to strains with a short and long FRP, respectively. **C,** A photoperiodic response of the *LaFTh1* expression. Means of four or two RNA-seq experiments are plotted. Gray box indicates a dark period. **D,** Photoperiodic responses of flowering for three strains (purple, N44Ha08; black, Nd; red, N32Ka06). The flowering rates are plotted against the night length of each photoperiod. The critical night length (24 – CDL) of each strain is shown as dashed line. **E,** *LaFTh1* induction in the three strains during constant dark following 15L9D. The mRNA accumulation quantified by qPCR is plotted. The mRNA expression in N32Ka06 at 9 and 10 h were undetected. Colors are the same as in panel d.

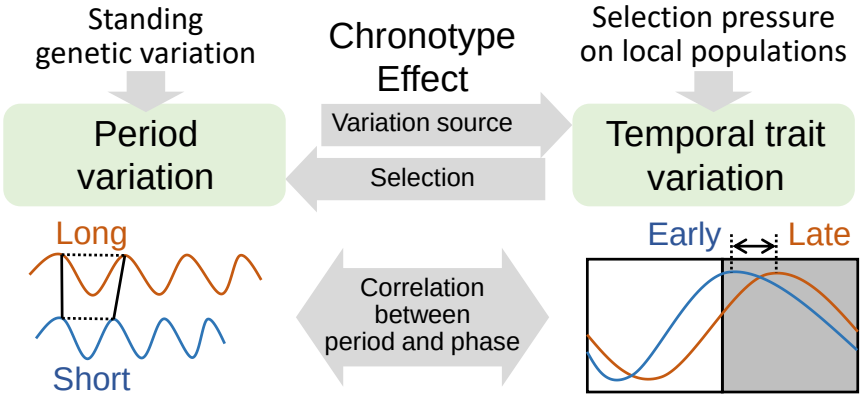

Figure 4. The chronotype effect on local adaptation of clock-dependent temporal traits. FRP variation functions as a resource for the variation of temporal traits in the process of local adaptation. Genetic variations in many quantitative loci for FRP are selected based on their phenotypic effect on temporal traits under day-night conditions. In *L. aequinoctialis*, the selection pressure for early-flowering phenotype appeared to select a short-FRP genotype related to its early induction timing of a florigen gene.

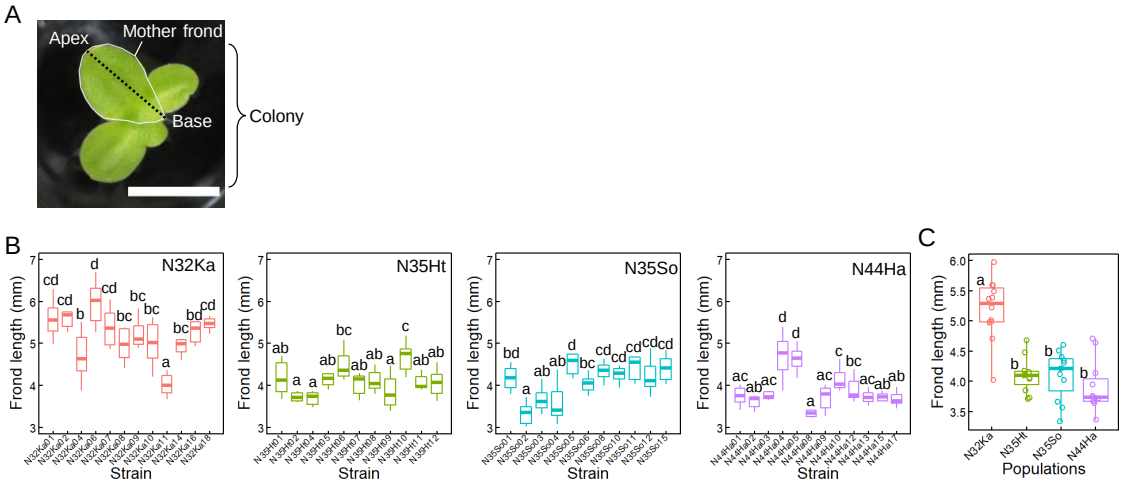

Figure S1. Intra- and inter-population variation of frond length in *L. aequinoctialis* strains. a, Definition of a frond length. The length of the mother frond (from base to apex, dotted black line) of eight colonies were measured for each strain of four populations (N32Ka, N35Ht, N35So, and N44Ha). Scale bar indicates 5 mm. **b,** Intra-population variation of frond length of the four populations are shown as boxplots. Different letters indicate significant differences based on Tukey's HSD test ($P < 0.05$). **c,** Inter-population variation of frond length among the four populations. Different letters indicate significant differences based on pairwise Wilcoxon test ($P < 0.05$). Boxplots display a median line, interquartile range boxes, min/max whiskers.

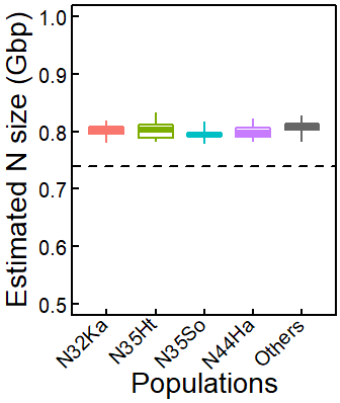

Figure S2. Similar genome sizes among 72 strains in different populations. Box plot displays a median line, interquartile range boxes, min/max whiskers of estimated genome sizes of the strains in a population (N32Ka, N35Ht, N35So, and N44Ha). "Others" includes 16 populations, which are indicated by triangles in Figure 1A. The genome size of a strain was estimated by flow cytometer. A dashed line represents the estimated genome size of *L. aequinoctialis* 6746 strain[33] isolated in California, USA. No significant difference was detected based on pairwise Wilcoxon test.

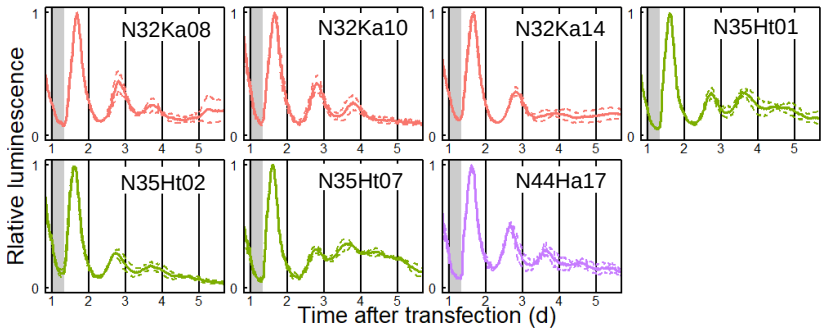

Figure S3. Luminescence rhythms of the seven strains excluded from the analysis. Luminescence intensity at each time point was normalized by the maximum intensity (first peak value). Solid and dashed lines represent mean and SD of three replications, respectively. Same populations are represented by the same colors.

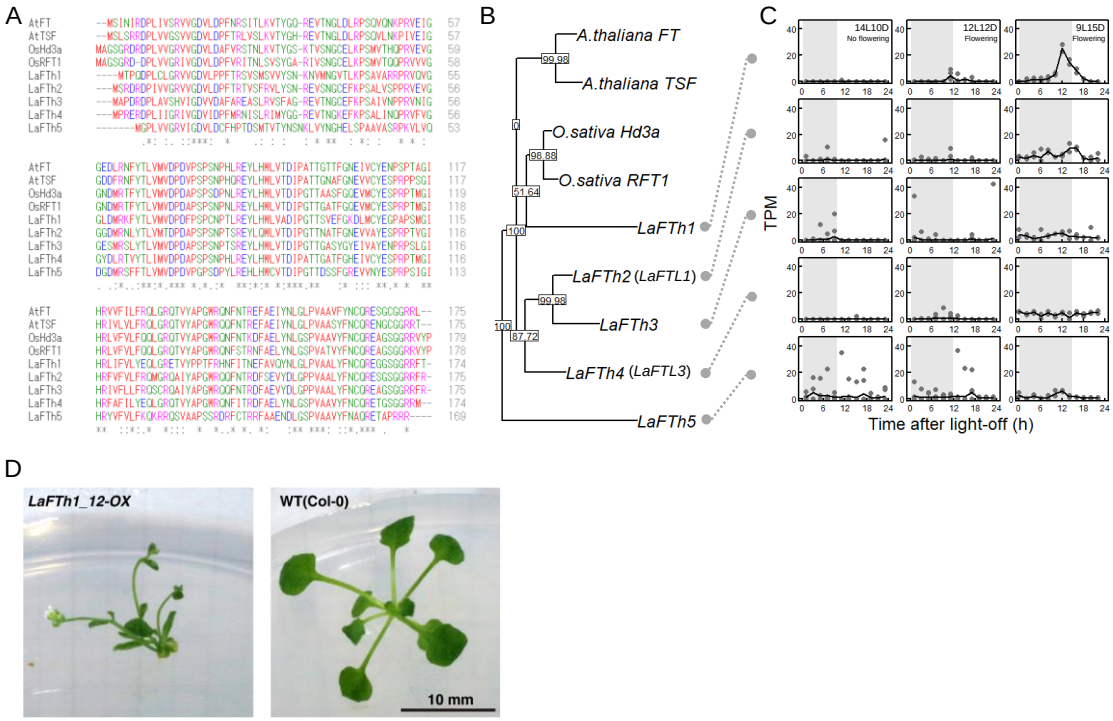

Figure S4. FT homologues of *L. aequinoctialis* Nd strain. **A,** Multiple amino acid sequence alignment of the five FT homologues (LaFTh1-5) with the florigen of *Arabidopsis thaliana* (AtFT and AtTSF) and *Oryza sativa* (OsHd3a and OsRFT1). Colors represent physicochemical properties of residues. **B,** Maximum likelihood phylogenetic tree constructed with PhyML algorithm using full-length amino acid sequences. **C,** The expression patterns of five FT homologues (LaFTh1 to LaFTh5 from top to bottom) under three photoperiods (14L10D, 12L12D, 9L15D from right to left). The transcripts per kilobase million (TPM) values are plotted. Two (9L15D) or four (12L12D and 14L10D) experiments were performed for each photoperiodic condition. Black lines represent the mean values at each time point. Gray boxes indicate dark period. **D**, Early flowering phenotype of *Arabidopsis thaliana* carrying an *LaFTh1* overexpression construct. Plants of an *LaFTh1* overexpression line (T2 generation) (left) and Col-0 wild type (right) on an agar plate at 22 °C and 24 days (10L14D) after sowing.

#	Population name	Symbol in Figs	Sampling site	Water system	Latitude	Longitude	Number of isolated strains
1	N44Ha	N44Ha	Asahikawa, Hokkaido	Paddy field	43.80468	142.45088	12
2	N43Hi	Others North	Ishikari, Hokkaido	Paddy field	43.1943	141.45465	2
3	N41Ac	Others North	Hirosaki castle, Aomori	Castle moat	40.60337	140.46717	2
4	N40Im	Others North	Miyako, Iwate	Paddy field	39.56776	141.93836	1
5	N36Ky	Others Middle	Yokohama, Kanagawa	Paddy field	35.52783	139.52045	1
6	N35At	Others Middle	Togo, Aichi	Paddy field	35.11062	137.083	1
7	N35Ki	Others Middle	Iwakura, Kyoto	Paddy field	35.07706	135.78781	2
8	N35Ht	N35Ht	Taka, Hyogo	Paddy field	35.07304	134.90231	11
9	N35Kk	Others Middle	Kyoto, Kyoto	Paddy field	35.07206	135.74302	1
10	N35Sb	Others Middle	Biwako, Shiga	Lake	35.04908	135.87446	3
11	N35Kn	Others Middle	Nougaku, Kyoto	Paddy field	35.03259	135.7836	3
12	N35Kr	Others Middle	Kamogawa river, Kyoto	Rivier	34.9896	135.76769	1
13	N35So	N35So	Otsu, Shiga	Paddy field	34.95615	135.95493	11
14	N35Oi	Others Middle	Ibaraki, Osaka	Paddy field	34.85884	135.56461	3
15	N35Nn	Others Middle	NAIST, Nara	Paddy field	34.7317	135.73142	2
16	N35Nk	Others Middle	Kizugawa, Nara	Paddy field	34.7242	135.8158	1
17	N35Si	Others Middle	Iwata, Shizuoka	Paddy field	34.72128	137.89284	1
18	N34Mi	Others Middle	Ise, Mie	Paddy field	34.49805	136.67711	1
19	N32Ka	N32Ka	Aira, Kagoshima	Paddy field	31.77734	130.56278	12
20	N32Mk	Others South	Kushimoto, Miyazaki	Paddy field	31.51068	131.25419	1

Table S1. Summary of twenty sampling sites.

Methods

Plant materials and growth conditions. Seventy-two *L. aequinoctialis* strains were collected from 20 sites in Japan (Table S1). The collected plants were sterilized by washing with 5% sodium hypochlorite for several minutes, followed by washing with sterilized water. From the successfully sterilized plants, a single colony was isolated. Only one strain was isolated from a paddy field, and a maximum of 12 paddy fields were selected at each site. These strains were maintained aseptically in a growth medium (NF medium containing 1% sucrose[33]) under long-day conditions (15L9D; approximately 50 μmol m^{-2} s^{-1}) in an incubator (LH350-SP, NK system, Japan) at 25 ± 1 °C. *L. aequinoctialis* 6746 [33] and *Lemna gibba* p8L [33] strains were maintained in the same conditions. Before the experiments, the plants were grown in a flask or 6-well plastic plate filled with 30 mL or 8 mL of growth medium, respectively.

Genome size estimation. The relative genome sizes of *L. aequinoctialis* strains were estimated based on 4',6-diamidino-2-phenylindole diacetate dye flow cytometry (DAPI-FCM) using a Partec CyStain UV Precise P reagent kit (Sysmex Partec GmbH, Germany) and a flow cytometer (Partec Ploidy Analyzer PA-I, Sysmex Partec GmbH). *Lemna gibba* p8L[33] was used as the standard. The relative genome sizes of th*e L. aequinoctialis* strains were calculated as the relative peak positions. The genome size of *L. gibba* has been estimated to be 486 Mbp.[43]

Frond-length measurements. The top view image of the plants was captured using a digital camera (EOS 5D mark3 [Canon, Japan] with SP 90 mm Di MACRO [Tamron, Japan] or EOS Kiss X5 with EF-S55-250 mm [Canon]). The frond length was manually measured as the length from the base to the apex of the mother frond using ImageJ 1.53c software (Figure S1A).[51] The frond lengths of the eight colonies were measured for each strain.

Measurement of the critical day length in photoperiodic flowering. A colony consisting of three or four visible fronds was placed in each well of a 24-well plastic plate filled with 2 mL of growth medium. These plants were subjected to a one-week photoperiodic treatment with day lengths of 9, 11, 11.5, 12, 12.5, 13, 13.5, 14, 14.5, and 15 h in an eight-chamber incubator (LH30-8-CT, NK system, Japan). The temperature was maintained at 25 ± 1 °C and the light intensity was approximately 30 μmol m^{-2} s^{-1}. After treatment, the plants were bleached with 70% ethanol. The number of flowering and non-flowering fronds was counted for each colony under a stereoscopic microscope. Flowering rate was calculated as the percentage of flowering fronds to the total number of fronds in at least two replicates. The critical day length was determined as the day length where 50% of the maximum flowering rate (Fmax) was expected in a piecewise linear function for the obtained flowering rate (Figure 1D).

321

322 **Meteorological data**

323 Temperature data at each site were obtained from the Automated Meteorological Data Acquisition
324 System (AMeDAS) data download service (https://www.data.jma.go.jp/risk/obsdl/index.php). Day
325 lengths were calculated using the online service of the National Astronomical Observatory of Japan
326 (https://eco.mtk.nao.ac.jp/cgi-bin/koyomi/koyomix_en.cgi).

327

328 **Monitoring luminescence rhythms.** Luminescence monitoring using a circadian luminescent
329 reporter was performed as previously described[33]. Plasmid DNA carrying the luciferase reporter gene
330 *pUC-AtCCA1::LUC+* (*AtCCA1::LUC*[34]) was coated on 0.48 mg of gold particles (1.0 mm diameter,
331 Bio-Rad) and introduced into plants laid on a 60-mm plastic dish using a particle bombardment system
332 (PDS-1000/He, Bio-Rad) according to the manufacturer's instructions (vacuum, 27 mmHg; helium
333 pressure, 450 psi). After particle bombardment, the plants were divided into three 35-mm dishes
334 (approximately four colonies per dish) filled with 4 mL of growth medium containing D-luciferin (0.2
335 mM potassium salt, Wako). A luminescence dish-monitoring system with photomultiplier tubes
336 (H7360-01; Hamamatsu Photonics K.K., Japan) was used for the luminescence measurements. To
337 reduce the background chlorophyll fluorescence, a short-pass filter (SVO630; Asahi Spectra, Japan)
338 was set at the detection site of the photomultiplier tubes. Each dish was subjected to 30 s of
339 measurements every 20 min. The monitoring system was placed in an incubator (KCLP-1000I-CT;
340 NK System, Japan) with fluorescent lamps (FL20SSW/18; Mitsubishi Electric Co., Japan). The
341 temperature was maintained at 25 ± 1 °C and the light intensity was approximately 30 μmol m^{-2} s^{-1}.

342

343 **Time-series analysis.** Peak detection and period estimation were performed as previously described.[33,
344 52] The peak positions were estimated by local quadratic curve fitting. For period estimation, the
345 obtained luminescence time series were detrended by subtracting the 24-h moving average. Thereafter,
346 the amplitude was normalized by dividing by the 24-h moving standard deviation. The normalized
347 time series of 60 to 132 h was analyzed using fast Fourier transform-nonlinear least squares (FFT-
348 NLLS) to determine the period.[35] FFT-NLLS was based on a multicomponent cosine fit. Rhythm
349 significance was estimated by a relative amplitude error (RAE) that increases from 0 to 1 as the rhythm
350 approached statistical insignificance. These analyses were performed using R scripts developed and
351 run with R 3.6.3 (http://r-project.org/).[53]

352

353 **RNA-seq analysis.** Th*e L. aequinoctialis* Nd strain (6th generation of self-fertilization of the N35Kn04
354 strain)[33] was used for RNA-seq analysis. Plants were maintained under 15L9D conditions
355 (approximately 50 μmol m^{-2} s^{-1}, white LED T5LT20W, Beamtec, Japan) in an incubator (HCLP-880,
356 NK system, Japan) at 25 ± 1 °C. For the 14L10D and 12L12D experiments, the plants were divided

357 into 48 x 35-mm dishes (four colonies per dish) with 4 mL growth medium per dish. After one week
358 of photoperiodic treatment (14L10D or 12L12D), plants in each dish were collected every 2 h for 24
359 h (four replicates per sampling time). For the 9L15D experiment, plants were pre-cultured under
360 9L15D conditions for one week. Thereafter, these plants were divided into 24 x 35-mm dishes (six
361 colonies per dish) with 4 mL of growth medium per dish. After one week of photoperiodic treatment
362 (9L15D), plants in each dish were collected every 2 h for 24 h (two replicates at each sampling time).
363 The collected plants were wiped of moisture with paper, then immediately immersed in RNAlater
364 solution (Sigma Aldrich) at each time point and stored at -20 °C before RNA extraction. RNA-seq
365 library preparation was performed based on the BrAD-seq protocol, as follows.[54] Plants were
366 homogenized with a lysate buffer using a multi-bead shocker (MB755U, Yasui Kikai, Japan). mRNA
367 was extracted from the lysate using magnetic streptavidin beads (New England Biolabs) with a biotin-
368 20nt-20T oligo. The mRNA was subjected to heat fragmentation (94 °C for 1.5 min) and converted to
369 cDNA using RevertAid Reverse Transcriptase (Thermo Fisher) with a 3-prime priming adapter with
370 a random octamer sequence. The 5-prime adapter was then added to the cDNA and captured by the
371 terminus of the RNA-cDNA hybrid. Its incorporation into a complete library molecule was catalyzed
372 by DNA polymerase I (Thermo Fisher). The library was prepared using 16 (9L15D samples) or 18
373 (14L10D and 12L12D samples) PCR cycles with KAPA HiFi HS ReadyMix (Kapa Biosystems). The
374 fragment size was selected to range from 300 bp to 600 bp using Ampure magnetic beads (Beckman
375 Coulter). The quality of the library was checked using a bioanalyzer (Agilent). Paired-end 150 bp
376 sequencing was conducted using the HiSeq system (Illumina). The obtained sequences (total 554
377 million reads for the 120 samples) were filtered using Trimmomatic v0.39 with option "LEADING:24
378 TRAILING:24 SLIDINGWINDOW:30:20 AVGQUAL:20 MINLEN:100".[55] The filtered sequences
379 were assembled *de novo* into 322,899 contigs (isoforms of 186,102 genes) using Trinity v2.8.4.[56] The
380 183,102 contigs (isoforms of 84,206 genes) that were longer than 400 bp were used as a reference
381 sequence for mapping and read counting using RSEM v1.3.1 with bowtie2 v2.4.2.[57, 58] The mapped
382 reads were 3.46 ± 1.22 million reads / sample (mean ± SD).
383
384 **Detection of *FT* homologues**. *FT* homologues in the reference sequence (183,102 contigs) were
385 searched using tblastn 2.11.0+ [59] with a query for the OsHd3a amino acid sequence (UniProt-ID:
386 Q93WI9). The top five *FT* homologues were named as *LaFTh1-5* based on their position in the
387 maximum likelihood phylogenetic tree with their estimated amino acid sequences and AtFT (UniProt-
388 ID: Q9SXZ2), AtTSF (UniProt-ID: Q9S7R5), OsHd3a (UniProt-ID: Q93WI9), and OsRFT1(UniProt-
389 ID: Q8VWH2) (Figure S4B). LaFTh2 and LaFTh4 have the same sequence as previously reported FT
390 homologues, LaFTL1 and LaFTL3, respectively.[60] A phylogenetic tree was constructed using the
391 online tool ClustalW (https://www.genome.jp/tools-bin/clustalw) using the PhyML algorithm.
392 Colored multiple amino acid sequence alignments were generated using the online tool Clustal Omega

393 (https://www.ebi.ac.uk/Tools/msa/clustalo/).
394
395 **qPCR analysis.** Eight to 12 colonies grown under 15L9D conditions were placed in a 35-mm dish
396 with 4 mL of growth medium and maintained under the same conditions for a day, after which they
397 were released to constant darkness at the end of 15 h of light and sampled every hour from 9 to 15 h
398 after the light-off. The collected plants were wiped of moisture with paper, then immediately immersed
399 in RNAlater solution (Sigma Aldrich) at each time point and stored at -20 °C before RNA extraction.
400 Total RNA was extracted using the NucleoSpin RNA Plant (MACHEREY-NAGEL GmbH & Co.) and
401 converted to cDNA using ReverTra Ace qPCR RT Master Mix (TOYOBO). qPCR was performed
402 using the StepOnePlus Real-Time PCR System (Applied Biosystems) with THUNDERBIRD SYBR
403 qPCR Mix (TOYOBO). An *ACT2* homologue in *de novo* assembled sequences was determined using
404 tblastn 2.11.0+ with a query of the OsACT2 amino acid sequence (UniProt-ID: A3C6D7) and used as
405 a reference gene for the delta-delta Ct method. Primers for qPCR analysis were designed according to
406 the *de novo* assembled sequences as follows: LaFTh1_fwd, 5'-
407 ACCCTACCCTTAGAGAATATCTGC-3'; LaFTh1_rev, 5'-TAGGTGCTGGGCCTTCATAG-3',
408 LaACT2_fwd, 5'-ACACAGTGCCCATCTATGAAGG-3'; LaACT2_rev, 5'-
409 AGTAGCCTCGTTCGGTTAGGATC-3'.
410
411 ***LaFTh1* overexpression in *Arabidopsis thaliana.*** To generate *LaFTh1* overexpressing transgenic
412 *Arabidopsis* plants, the coding region of *LaFTh1* was amplified from cDNA derived from *L.*
413 *aequinoctialis* Nd using the following primers: 5'-
414 CGCGGCCGCCACCATGACACCTCAGGATCCCTTGTG-3', and 5'-
415 CGGCGCGCCCTAGGTAAACCGCCTTCCACCAG-3'. The amplified PCR fragment was digested
416 with *Not*I and *Asc*I restriction enzymes and integrated into the pENTR-MCS cloning vector [pENTR-
417 D/TOPO vector (Invitrogen) containing the pBluescript II multi-cloning sites] using the conventional
418 linker ligation method. The sequence of *LaFTh1* CDS was transferred into the pK7WG2
419 overexpression binary vector,[61] which contained the *CaMV35S* promoter-driven expression cassette,
420 using Gateway LR clonase II (Invitrogen). This construct was introduced into *Arabidopsis* wild-type
421 plants Col-0 by the *Agrobacterium tumefaciens*-mediated floral dipping method.[62] Primary
422 transformants (T1) were selected on 1x Murashige and Skoog culture media containing 1% sucrose,
423 0.8% agar, and 25 μg mL^{-1} kanamycin sulfate. Seeds were sterilized using chlorine gas, stratified for
424 3 days at 4 °C, and then grown under short-day (10L14D) conditions to analyze the flowering
425 phenotype in parallel with the selection process. Seedlings developing relatively long primary and
426 lateral roots were regarded as kanamycin-resistant transgenic plants and transferred to a 1:1 mixture
427 of vermiculite and soil (Nihon Hiryo Co., Ltd.). Several independent lines ($N > 10$) were isolated for
428 further analysis of their morphological and flowering phenotypes. Most primary transformants could

429 not produce mature siliques or seeds; however, some transgenic plants produced T2 seeds. Flowering
430 phenotypes were also observed in the T2 generation.
431
432 **Statistics.** All boxplots in this manuscript display median lines, interquartile range boxes, and
433 min/max whiskers. Different letters indicate significant differences based on the pairwise Wilcoxon
434 test ($p < 0.05$). The pairwise Wilcoxon test was performed using the R built-in function
435 "pairwise.wilcox.test" with *P* value adjustment using the Holm method. In correlation analysis, the
436 Pearson's correlation coefficient and *P* value was calculated by the R-built-in function "cor.test".
437
438

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