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Winter flowering phenology of Japanese apricot *Prunus mume* reflects climate change across Japan

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ABSTRACT: Although it is likely that winter flowering of various plant species has been influenced by recent climate change, previous phenological analyses have not focused on flowering phenology in winter. In Japan, the Japanese apricot *Prunus mume* historically flowers during the cold months of winter from January to March. I used a continuous dataset of the flowering date at 32 sites in various regions of Japan from 1953 to 2005. Over the course of this period, the flowering date of apricots has advanced, with a notable shift in regimes between 1953–1989 and 1990–2005. The correlation results show that mean winter air temperature significantly affected the flowering date of the apricots at all of the sites, but snowfall was not correlated with the flowering date at 30 out of 32 sites. The difference between the mean flowering dates of 1953–1989 and 1990–2005 was correlated with the correlation coefficient between the flowering date and air temperature. Winter flowering of Japanese apricot has been influenced by recent climate change, especially by drastic climate-related shifts in the timing of key processes.

KEY WORDS: Climate change · Snowfall · Air temperature · Regime shift · Dynamic factor analysis

1. INTRODUCTION

Recent effects of climate change, such as temperature rises, have been found to affect species' phenological events. Many studies have concurrently documented a progressively earlier start for vegetation activity in the spring (e.g. IPCC 2001, Walther et al. 2002, Parmesan & Yohe 2003, Root et al. 2003, Gordo & Sanz 2005, Menzel et al. 2006).

From meta-analysis of the various phenology papers, Root et al. (2003) showed that these plant phenological shifts make up a consistent fingerprint of global change, with mean changes of -2.3 d decade^{-1}. Most published literature suggests that the timing of spring phenological events in many species is occurring earlier than in past decades (e.g. Post & Stenseth 1999, Walther et al. 2002, Root et al. 2003, Winder & Schindler 2004a,b, Gordo & Sanz 2005, Menzel et al. 2006). For instance, in the northeastern United States, changes in lilac, apple, and grape phenology suggest that spring flowering has advanced by 2 to 8 d over the last 3 or 4 decades, consistent with patterns across North America as a whole (Schwartz & Reiter 2000, Wolfe et al. 2005).

Analysis of winter-flowering plants allows an assessment of biotic influences on the evolution of flowering time because temperature is unlikely to select directly for this uncommon reproductive behavior (Aizen 2003). The timing of winter flowering influences the reproductive success and behavior of insect pollinators (Alonso 2004). Winter flowering is likely influenced by recent climate changes in a similar way that spring-flowering plants are affected. However, very few phenological analyses have focused on flowering phenology in winter (but see Menzel et al. 2001, Schaber & Badeck 2005). In addition, the relationships between phenological events and climate changes have been principally studied in North America and Europe, while studies connecting phenology to climate change in Asian regions are very limited (Chen & Pan 2002, Matsumoto et al. 2003). Tryjanowski et al. (2006) suggested that phenological reaction to temperature is

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not always the same across continents, thus the phenological dataset at different regions with similar latitude (i.e. Europe and Northeast Asia) will be important. The present study focused on the winter flowering phenology of the Japanese apricot *Prunus mume* across Japan in relation to recent climate changes; it also contributes to the understanding of trends in phenological change in Asia more generally.

The aim of the present study was to estimate the influence of recent climate changes over Japan on the winter flowering phenology of the Japanese apricot. I used a dataset of the flowering date of the Japanese apricot at 32 sites throughout Japan from 1953 to 2005. For analysis of this time-series dataset, we used a recent statistical approach for multivariate time series, dynamic factor analysis (DFA, Zuur et al. 2003a,b) and chronological clustering (Legendre et al. 1985, Bell & Legendre 1987). DFA is a dimension-reduction technique for time series (DFA is used to estimate common trends in various sites across Japan), and chronological clustering can detect the regime shifts of the time-series dataset statistically. Using these statistical approaches, I estimated the influence of abrupt climate change on the winter flowering phenology across Japan.

2. MATERIAL AND METHODS

2.1. Phenology dataset

The present study used datasets of the flowering of the Japanese apricot *Prunus mume* as observed by the Japan Meteorological Agency (JMA). The JMA recorded flowering as the date when the first flowers were observed (i.e. when 5 to 6 buds on the tree have flowered) at each JMA observation station from 1953 to 2005. The 32 stations across Japan (JMA site codes between 409 and 837; 30.4–44.0° N, 129.5–144.2° E; elevation: 0.5–610 m above sea level, Table 1) were selected according to the consistency of data collection over 40 yr, in order to ensure a continuous dataset across all sites.

2.2. Climate dataset

I used the autumn and winter air temperature (October to March) calculated by the JMA from 1961 to 2005 at the 32 stations to evaluate the impact of climate on timing of apricot flowering. For statistical analysis, I used mean air temperature data for autumn (October to December) and winter (January to March). I also used the mean snowfall between January and March at each of the 32 JMA stations from 1961 to 2005.

Table 1. Location, altitude, mean temperature (Temp.) and mean snowfall (Snow) from January to March. The sites are ordered by latitude

Stn	Latitude (°N)	Longitude (°E)	Altitude (m)	Temp. (°C)	Snow (cm d^{-1})
409	44.0	144.2	37.6	–5.0	3.30
581	40.3	141.3	27.1	2.5	3.13
585	39.4	141.6	42.5	1.4	0.63
587	38.5	139.5	3.1	4.2	0.85
590	38.2	140.5	38.9	4.0	0.15
602	38.0	138.1	5.5	0.8	0.30
604	37.5	139.0	1.9	3.0	0.81
597	37.1	140.1	355.0	3.4	0.25
612	37.1	138.2	12.9	–0.2	3.48
598	36.6	140.5	3.2	3.6	0.03
607	36.4	137.1	8.6	4.1	1.57
624	36.2	139.0	112.1	4.2	0.18
629	36.2	140.3	29.3	5.6	0.04
618	36.1	137.6	610.0	5.1	1.10
617	36.1	137.2	560.1	4.5	1.61
616	36.0	136.1	8.8	0.8	4.68
648	35.4	140.5	20.1	6.9	0.01
662	35.4	139.5	6.5	10.9	0.01
747	35.3	134.5	3.4	5.8	0.47
632	35.2	136.5	12.7	5.6	0.04
636	35.1	136.6	51.1	7.1	0.05
780	34.4	135.5	104.4	5.3	0.01
765	34.2	132.3	3.6	6.2	0.79
807	33.3	130.2	2.5	7.8	0.01
893	33.3	133.3	0.5	12.6	0.01
813	33.3	130.2	3.6	7.3	0.01
778	33.3	135.5	73.0	9.0	0.01
678	33.1	139.5	79.2	4.2	0.01
817	32.4	129.5	26.9	7.4	0.01
822	32.3	131.4	19.2	8.4	0.00
827	31.3	130.3	3.9	7.9	0.01
837	30.4	130.6	17.0	9.6	0.00

2.3. Statistical analysis

In order to analyze temporal changes on the flowering date, dynamic factor analysis (DFA) was performed using the software package Brodgar 2.5.2 with R 2.2.1. DFA is multivariate time-series analysis technique used to estimate underlying common patterns in a set of time series, i.e. a dimension-reduction technique for time-series datasets such as principal component analysis. Details of the mathematical basis of this statistical model are presented in Zuur et al. (2003a,b). The time-series datasets of flowering dates are modeled in terms of a linear combination of M common trends and a noise component. Time-series data can be expressed with the following mathematical formulation:

$$\mathbf{D} = \mathrm{Z\ M\ common\ trend(s)} + \mathrm{noise} \quad (1)$$

where **D** is a sites-years matrix of the flowering date among the 32 stations and 52 yr, and Z is the factor loading for the M common trend(s), the estimated slope of the explanatory variables of the data. Factor loadings (Z) determine how important a particular common trend is for each flowering date of the site (Table 2). Noise was fitted to a symmetric non-diagonal covariate matrix in all analyses. The model was performed with 999 iterations, and 10 trials of starting model variations.

DFA analysis was performed to search for common temporal patterns in the flowering date of the 32 sites. I estimated that the models contained 1, 2, and 3 common trends, and the optimal number of common trends was selected using Bayesian information criterion (BIC). The lowest BIC values indicate the optimal model. As the results of the comparison models, the 1 common trend model is optimal for the first appearance (BIC = 10 950), compared with 2 and 3 common trend models (BIC = 11 209 and 14 500, respectively).

In order to analyze the regime shift related to the flowering date, the winter temperature, and snowfall, chronological clustering was performed using the software package Brodgar 2.5.2 with $\alpha = 0.05$ (for further details, see Legendre et al. 1985, Bell & Legendre 1987). For the clustering, I used the data on flowering date, winter temperature, and snowfall at the 32 sites as each variable for the analysis.

Pearson's correlation coefficients and linear regression analyses were performed for the climate changes trend and for the relationships between each climate variable and the common trend and the dataset of flowering timing. Although flowering timing has been observed since 1953, temperature and precipitation data for 1953–1960 at these sites were not available from JMA, thus correlation analysis included only data from 1961 to 2005.

3. RESULTS

3.1. Trends in flowering date

The mean flowering dates of Japanese apricot *Prunus mume* were related to latitude ($r = 0.850$, $p < 0.001$, slope = 8.09 d per degree of latitude), but not related to altitude ($r = 0.001$, $p = 0.96$). Over the study period, the flowering of the Japanese apricot *Prunus mume* has tended towards earlier dates, especially since 1989, and can be separated into 2 distinct regimes: 1961–1989 and 1990–2005 (chronological clustering, $\alpha = 0.05$) (Fig. 1). Common trend of the flowering date by dynamic factor analysis (DFA) was negative, showing that flowering date has become progressively earlier over time (Fig. 1). Factor loading (Z) of common trend at all sites was positive (Table 2).

Table 2. *Prunus mume*. Mean flowering date of Japanese apricot from 1953 to 2005, and factor loading (Z) for common trend by dynamic factor analysis (DFA)

Stn	Mean date	Factor loading (Z)
409	3 May	3.16
581	11 Apr	6.18
585	3 Apr	8.18
587	3 Apr	8.34
590	8 Mar	13.22
602	16 Feb	11.05
604	13 Mar	13.11
597	19 Mar	13.80
612	4 Mar	17.60
598	20 Mar	12.82
607	20 Feb	17.68
624	5 Apr	10.40
629	25 Mar	11.04
618	18 Feb	17.75
617	13 Feb	10.97
616	24 Feb	23.25
648	7 Feb	16.27
662	1 Mar	13.78
747	3 Feb	13.73
632	2 Feb	6.35
636	14 Feb	18.55
780	22 Feb	14.28
765	10 Feb	13.84
807	8 Feb	15.46
893	31 Jan	13.15
813	1 Feb	13.22
778	31 Jan	12.59
678	1 Feb	12.61
817	29 Jan	3.44
822	23 Jan	8.01
827	1 Feb	9.52
837	4 Feb	9.74

3.2. Changes in climate factors

Mean winter temperature from January to March at the 32 stations ranged from 2.5 to 7.3°C (Fig. 2), and can be separated into 4 regimes: 1961–1970, 1971–1984, 1984–1989 and 1990–2005 (chronological clustering, $\alpha = 0.05$) (Fig. 2). The mean snowfall ranged from 0.07 to 0.62 cm d^{-1}, and can be separated into 3 regimes: 1961–1971, 1972–1992 and 1992–2005 (Fig. 2). Mean snowfall was significantly positively correlated with winter temperature ($r = -0.771$, $p < 0.001$, $n = 45$).

3.3. Relationships between timing of flowering and climate factors

The correlation between flowering date of Japanese apricot and temperature in winter was significantly negative at all of the sites ($r = -0.38$ to -0.84, $p < 0.05$) (Table 3), but there was no significant relationship between temperature in autumn and flowering date at 29 of 32 stations (Table 3). There was also no sig-

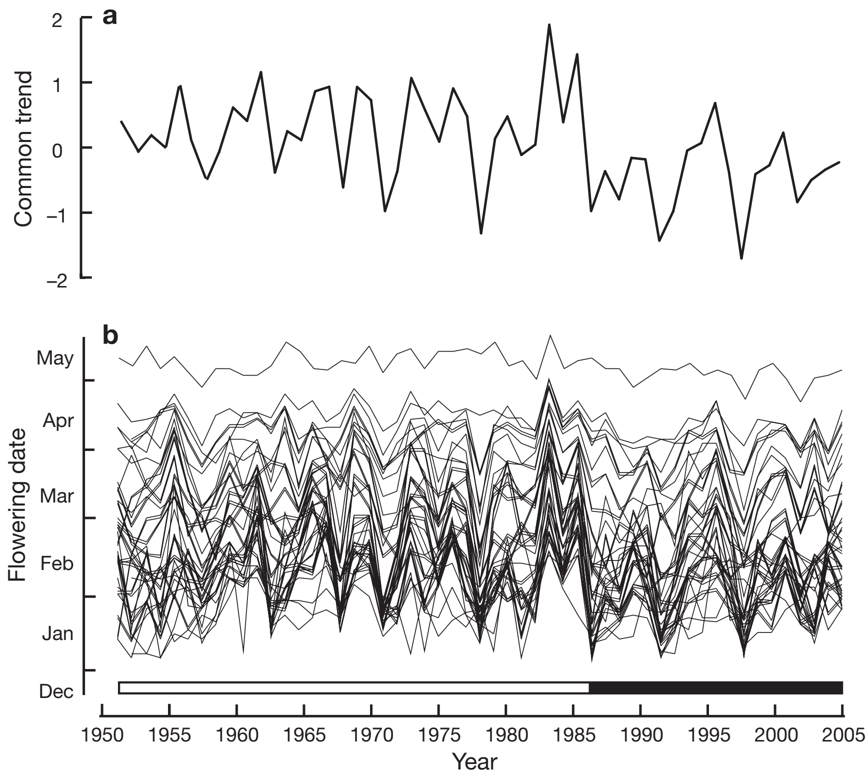

Fig. 1. *Prunus mume.* (a) Common trend of dynamic factor analysis and (b) temporal changes in flowering date of apricot from 1953 to 2005. Lines in (b): observation stations. Black/white bar shows chronological clustering (α = 0.05), and indicates change in regime over the study period

nificant relationship between snowfall and flowering date at 30 of 32 stations (Table 3). The correlation between the common trend of flowering date and temperature was significantly negative ($r = -0.873$, $p < 0.001$, $n = 45$).

The difference in mean flowering date between 1953–1989 and 1990–2005 ranged from –22.8 to 8.0 d at 32 sites (Table 3). The differences between regimes from 1961–1989 and from 1990–2005 were –7.0 ± 7.1 d (mean ± 1 SD), and these regimes were significantly different (*t*-test, $t = -5.55$, $p < 0.001$). There was a significant negative correlation between differences in flowering dates and correlation coefficients of flowering date and air temperature ($r = 0.717$. $p < 0.001$, $n = 32$) (Fig. 3). However, there were no significant correlations between flowering date difference and latitude ($r = -0.172$. $p = 0.345$) ($n = 32$) and between flowering date difference and mean winter temperature ($r = 0.330$, $p = 0.07$, $n = 32$) (Fig. 3).

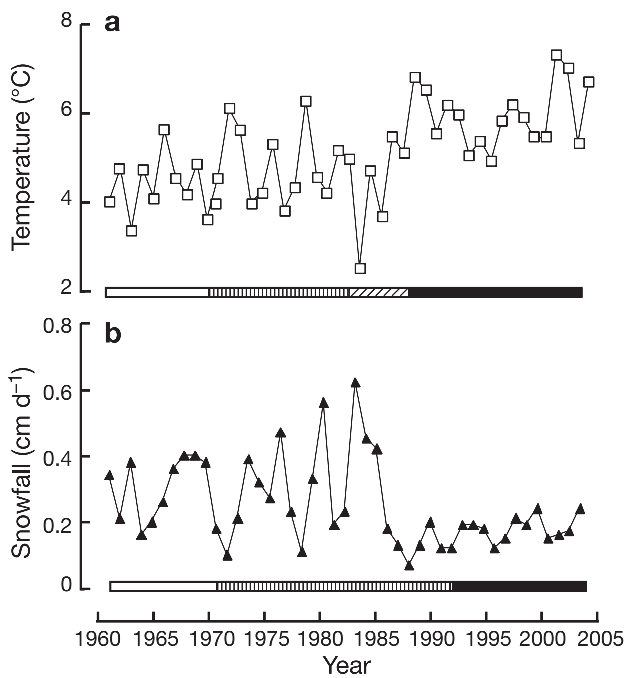

Fig. 2. (a) Mean air temperature and (b) mean snowfall, (1961–2005), of 32 observation stations from January to March. Bars at bottom of graph show chronological clustering (α = 0.05), and different shadings indicate change in regime over the study period

4. DISCUSSION

Between 1953 and 2005, the flowering date of apricots at 32 stations in Japan has occurred progressively earlier, with 2 significantly distinct regimes (1953–

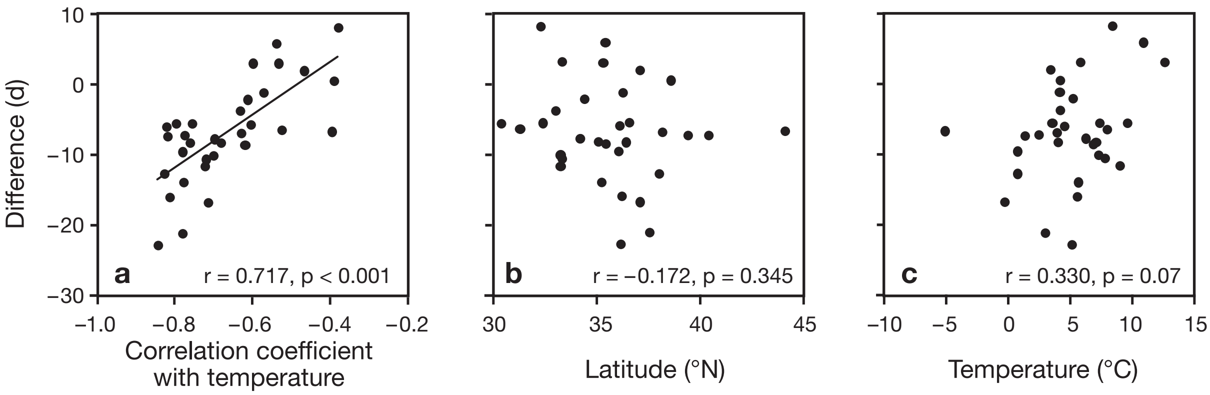

Fig. 3. *Prunus mume.* Difference (d) between mean flowering dates of 1953–1989 and 1990–2005 and (a) correlation coefficient between flowering date and temperature, (b) latitude of the stations, and (c) mean air temperature of stations. r and p values are from Pearson's correlation coefficients

Table 3. *Prunus mume.* Pearson's correlation coefficients (r) and linear regression slopes (d °C^{-1}) between the flowering date of apricot and mean air temperature, and snowfall (snow) of the stations. **Bold**: significant correlation ($\alpha = 0.05$). Difference (d): difference in mean flowering date between the periods 1953–1989 and 1990–2005

Stn	Temperature (Oct–Dec)		Temperature (Jan–Mar)		Snow (Jan–Mar)		Difference (d)
	r	Slope	r	Slope	r	Slope	
409	−0.22	−1.40	**−0.39**	**−1.8**	0.21	0.51	−6.8
581	**−0.39**	**−2.93**	**−0.77**	**−5.6**	0.07	0.07	−7.3
585	−0.22	−2.46	**−0.82**	**−7.8**	0.30	0.29	−7.4
587	−0.26	−2.66	**−0.39**	**−3.9**	−0.05	−0.04	0.4
590	**−0.47**	**−8.47**	**−0.63**	**−11.6**	0.19	0.02	−6.9
602	−0.17	−3.28	**−0.82**	**−7.7**	0.00	0.02	−12.8
604	0.10	0.44	**−0.78**	**−9.4**	−0.02	0.01	−21.1
597	−0.07	−0.58	**−0.47**	**−10.3**	0.11	0.00	1.9
612	−0.04	−0.41	**−0.71**	**−12.9**	−0.19	−0.01	−16.8
598	0.21	1.14	**−0.79**	**−9.3**	0.16	−0.10	−5.6
607	0.09	0.66	**−0.76**	**−10.1**	−0.07	−0.47	−8.4
624	−0.01	−0.04	**−0.57**	**−7.3**	−0.03	1.19	−1.3
629	0.23	0.84	**−0.81**	**−9.6**	0.03	0.15	−16.0
618	−0.13	−1.20	**−0.84**	**−14.9**	0.30	0.24	−22.8
617	−0.13	−0.87	**−0.82**	**−8.4**	0.08	−0.01	−6.1
616	−0.01	−0.11	**−0.78**	**−16.8**	0.22	0.00	−9.6
648	−0.14	−1.46	**−0.62**	**−11.2**	**0.33**	**−0.01**	−8.6
662	−0.04	−0.29	**−0.54**	**−10.5**	0.15	0.01	5.7
747	−0.10	−0.79	**−0.60**	**−9.0**	0.06	0.01	2.9
632	−0.24	−1.89	**−0.77**	**−6.6**	−0.20	0.00	−14.0
636	0.02	0.16	**−0.68**	**−12.7**	0.25	0.00	−8.3
780	0.04	0.17	**−0.61**	**−10.2**	−0.19	0.03	−2.2
765	0.02	0.12	**−0.70**	**−10.1**	0.28	0.23	−7.8
807	−0.12	−0.65	**−0.72**	**−12.3**	0.25	0.00	−10.7
893	0.01	0.04	**−0.53**	**−11.7**	−0.12	0.00	2.9
813	−0.16	−0.63	**−0.70**	**−9.9**	0.10	0.00	−10.2
778	−0.01	−0.05	**−0.72**	**−10.0**	**0.36**	**0.00**	−11.7
678	−0.22	−0.96	**−0.63**	**−12.0**	0.14	0.00	−3.9
817	**−0.33**	**−1.38**	**−0.75**	**−4.5**	−0.06	0.00	−5.7
822	−0.16	−0.66	**−0.38**	**−3.5**	0.09	0.00	8.0
827	−0.22	−1.23	**−0.52**	**−6.5**	−0.28	0.00	−6.5
837	0.08	0.39	**−0.60**	**−7.2**	0.14	0.00	−5.7

1989 and 1990–2005). Correlations showed that winter temperature had a significant effect on the flowering date of the apricots. The relationship between temperature and timing of flowering in spring is well documented (e.g. Walther et al. 2002, Root et al. 2003, Gordo & Sanz 2005, Menzel et al. 2006).

The principal finding of this study indicates that phenological events have been gradually changing in recent decades, in response to increasing temperature. In Japan, winter climate changed abruptly between 1989 and 1990. This abrupt climate change may have an effect on phenological timing of the apricot, evident in the significant correlation between phenological timing and winter temperature. Since abrupt climate change is predicted in the future, we should expect corresponding changes in the phenology of plants.

The difference between mean flowering dates in 1953–1989 and 1990–2005 is strongly correlated with the correlation coefficient between flowering date and temperature. The regimes of flowering date may be strongly affected by *in situ* air-temperature changes. On the other hand, the latitude and mean air temperature of the stations did not directly affect the changes related to flowering date. Thus, the regimes of flowering date shifted in correspondence with the regional air-temperature regime.

Almost all phenological studies have reported an advance in spring phenology, a delay in autumn phenology, and lengthening of the growing season (e.g. Walther et al. 2002, Parmesan & Yohe 2003, Root et al. 2003, Gordo & Sanz 2005, Menzel et al. 2006). Our results indicate that timing of flowering has occurred earlier in winter during the past 5 decades. Reproductive success of winter flowering plants is strongly affected by pollinators, because climate (and temperature in particular) is unlikely to be the primary selective factor for such an unusual reproductive behavior (Aizen 2003, Alonso 2004). Thus, the changes in winter temperature may decouple the timings of flowering and appearance of pollinators (Gordo & Sanz 2005).

Kozlov & Berlina (2002) reported that the significant increase (44%) in snow precipitation in their study area might have caused the significant delay observed in the thawing of the first patches. Thus, winter flowering events could change due to a reduction in snow cover. In this study, however, snowfall was not significantly correlated with the flowering date at most sites. Thus, the snow cover effect on phenological events may vary widely along with the temperature and snow precipitation.

To summarize, the present findings indicate that winter phenological timing has advanced as a result of recent climate changes. Two distinct regimes of phenological timing are observed over the 50 yr dataset, corresponding to similar patterns in air temperature regimes. The results from the present study underline the need to fully estimate the reactions of plants to climate change in all seasons.

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