Chapter 3
Spatial Pattern of Plant Phenology

Abstract Plant phenological observations show that occurrence dates of plant growth and reproduction stages are different at different locations, which is mainly a macroscopic and integrative reflection of climatic spatial heterogeneity. Early studies on spatial differences of plant phenology focused on geographical dependence of phenological spatial differences. Typical geographical models of plant phenology were shown as multiple linear regression equations between multi-year mean phenological occurrence dates at individual sites and geo-location parameters (latitude, longitude, and elevation). More recent studies attempt to reveal the relationship between phenological and climatic spatial patterns. Because air temperature is the most important factor influencing spatial variation of plant phenology, multi-year mean monthly temperatures at individual sites (replacing geo-location parameters) have be used as the independent variable for fitting spatial patterns of plant phenological occurrence dates.

Keywords Phenological spatial difference · Bioclimatic law · Multiple linear regression equation · Geo-location parameters · Climatic attribution · Multi-year mean monthly temperature

3.1 Geographical Dependence of Phenological Spatial Differences

Based on early 20th century investigations in the eastern US, Hopkins proposed a "Bioclimatic Law" to estimate the offset in onset of spring as a function of latitude, longitude, and elevation. He wrote:

> Other things being equal, this variation is at the rate of four days for each degree of latitude, five degrees of longitude and 400 ft of altitude. Therefore, from any given place, as related to extensive regions, an entire country, or a continent, the variation in a given periodical event is (at the rate stated) later northward, eastward and upward in the spring and early summer and the reverse in the late summer and during autumn (Hopkins 1919).

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There is no doubt that this "Bioclimatic Law" was an important milestone in revealing geographical attribution of phenological spatial differences. Nevertheless, the geographical pattern and spatial changing rate of plant phenology is diverse and highly dependent on specific regions, years, and phenological phenomena. Subsequently, Nakahara (1948) derived a multiple linear regression equation between multi-year mean flowering date (y) of *Prunus yedoensis* at individual sites and geo-location parameters, such as latitude (ϕ), longitude (λ) and elevation (h). Park-Ono et al. (1993) modified this model (using 37 years of phenological data, 1953–1989) as follows:

$$y = 92.56 + 4.77(\phi - 35^\circ) - 0.59(\lambda - 135^\circ) + 1.28h \quad (3.1)$$

The equation shows that the multi-year mean flowering date of *P. yedoensis* was delayed at a rate of 4.77 days per latitudinal degree northward, 0.59 days per longitudinal degree westward and 1.28 days per 100 m upward. Based on this kind of regression equation, average flowering date isophanes of *P. yedoensis* could be drawn (Momose 1974).

Following the above study, such multiple linear regression equations were also constructed in other regions of the world. The general model for China was described as follows (Gong and Jian 1983):

$$y = a + b(\phi - 30^\circ) + c(\lambda - 110^\circ) + dh \quad (3.2)$$

Table 3.1 indicates that from spring to summer the representative phenophases tended to be delayed by 0.49–5.61 days per latitudinal degree northward, 0.07–1.10 days per longitudinal degree eastward, and 0.32–1.54 days per 100 m upward. In autumn, however, the last three phenophases tended to advance by 2.39–3.81 days per latitudinal degree northward, 0.02 to 0.36 days per longitudinal degree eastward, and 0.06–0.77 days per 100 m upward.

On the basis of multiple linear regression equations between plant phenological occurrence dates in multi-year mean and extreme years, and geo-location parameters, phenological maps of Europe were drawn showing spatial patterns of beginning date, end date and length of the growing season during 1961–1998 and in the warm year 1990 (Rötzer and Chmielewski 2001).

3.2 Climatic Attribution of Phenological Spatial Differences

Overall, the above geographical models of plant phenology have two major disadvantages: (1) geo-location parameters are not climatic factors, so that they neither explain the essential environmental causes nor detect the climatic differences driving plant phenology spatial variations; and (2) since geo-location parameters are constant at a given site, multiple linear regression equation cannot represent the

Table 3.1 Spatial changing rates of plant phenological occurrence dates in China (Gong and Jian 1983)

Species	Phenophase	b (day/degree)	c (day/degree)	d (day/100 m)
Prunus persica	bud swelling	+5.61	+0.92	+1.25
Ulmus pumila	bud swelling	+4.16	+0.53	+0.59
Salix babylonica	budburst	+3.88	+0.78	+0.97
Ulmus pumila	first flowering	+3.55	+0.37	+0.90
Prunus davidiana	first flowering	+3.28	+0.55	+0.81
Thuja orientalis	first flowering	+4.73	+0.87	+0.36
Prunus armeniaca	first flowering	+3.74	+0.78	+1.54
Prunus persica	first flowering	+3.98	+0.71	+1.36
Salix babylonica	first flowering	+3.62	+0.71	+0.38
Morus alba	first flowering	+3.09	+0.36	+0.72
Juglans regia	first flowering	+2.53	+0.73	+1.37
Wisteria sinensis	first flowering	+2.40	+1.10	+0.73
Castanea mollissima	first flowering	+2.02	+0.90	+1.00
Albizzia julibrissin	first flowering	+2.53	+0.07	+0.60
Firmiana simplex	first flowering	+1.06	+0.36	−0.33
Sophora japonica	first flowering	+0.72	+0.19	+0.32
Lagerstroemia indica	first flowering	+0.49	+0.25	+0.53
Osmanthus fragrans	first flowering	−2.39	−0.02	−0.06
Chrysanthemum indicum	first flowering	−3.81	−0.08	−0.69
Ulmus pumila	the end of defoliation	−3.62	−0.36	−0.77

+: The occurrence date delays from south to north, from west to east, from low elevation to high elevation

−: The occurrence date advances from south to north, from west to east, from low elevation to high elevation

interannual variation of plant phenologcal spatial pattern related to climate change. Because air temperature is the most important factor influencing spatial and temporal variations of plant phenology (Chen 1994; Chmielewski and Rötzer 2001; Schwartz and Chen 2002; Menzel 2003; Gordo and Sanz 2010; Chen and Xu 2012), the spatial series of multi-year mean monthly temperature at individual sites (replacing geo-locations) were used for fitting the spatial pattern of growing season beginning date (BGS) and end date (EGS) derived from surface phenological data and remote sensing data (Chen et al. 2005). The results show that spatial series of multi-year mean BGS date correlates negatively ($P < 0.001$) with spatial series of multi-year mean temperature from March to May across temperate eastern China. The multinomial fitting (Fig. 3.1) shows that the dependence of BGS date on multi-year mean temperature is much stronger at sites with March-May temperature above 0 °C (linear correlation coefficient $r = -0.8276$, $n = 51$, $P < 0.001$) than at sites with March-May temperature below 0 °C (linear correlation coefficient

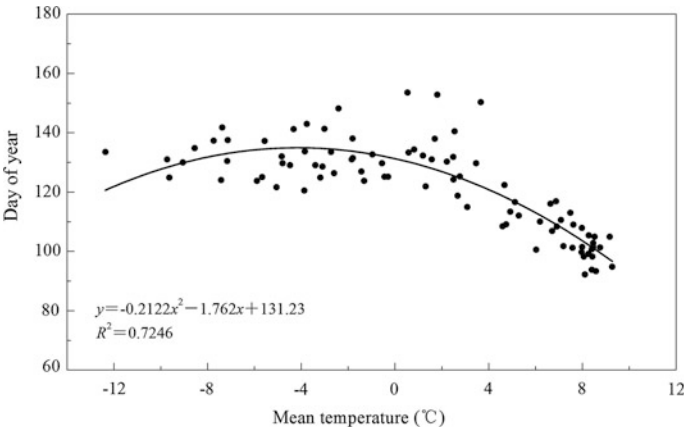

Fig. 3.1 Spatial relationships between March–May mean temperatures and average growing season beginning dates from 1982 to 1993 [Reprinted from Chen et al. (2005), with permission from John Wiley and Sons]

r = −0.0454, n = 36, $P > 0.1$). The negative correlation indicates that the higher the multi-year mean temperature during March and May at a site, the earlier the average growing season beginning time. In contrast, spatial series of multi-year mean EGS date correlates positively ($P < 0.001$) with spatial series of multi-year mean temperature from August to October across temperate eastern China. The positive correlation indicates that the higher the multi-year mean temperature during August and October at a site, the later the average growing season end time (Fig. 3.2).

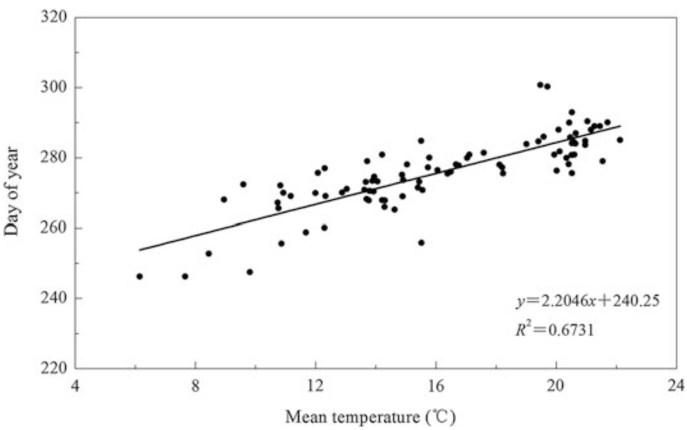

Fig. 3.2 Spatial relationships between August-October mean temperatures and average growing season end dates from 1982 to 1993 [Reprinted from Chen et al. (2005), with permission from John Wiley and Sons]

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