## NOTES AND CORRESPONDENCE

# Phenology of Mongolian Grasslands and Moisture Conditions

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## Abstract

Unique long-term agro-meteorological measurements of Mongolian grasslands enabled us to investigate the relationship between the phenology of *Stipa* spp., one of the dominant perennial species (such as emergence, heading, flowering, maturity, and senescence), and moisture conditions for three stations representative of the major vegetation zones, during 1993 to 2002.

The results showed that the emergence date relates neither to a specific temperature nor to an effective accumulative temperature, but to the presence of precipitation that occurs within five days prior to the emergence in most cases. For a northern-most wettest forest steppe region (Bulgan), the precipitation amount, and period of days from emergence to heading are significantly correlated ($r = 0.93$), while a southward typical steppe region (Arvaikheer) also exhibited a positive correlation (but not exceeding the 5% significance level). The positive correlation occurred at Bulgan most likely, because for drought years, *Stipa* spp. tended to switch a phenological stage from the vegetative growth (that is, a biomass increase), to reproductive phase (that is, seed production) earlier than for a normal year. One possible trigger for the switching is a decreased soil moisture, associated with a break of the rainy season.

## 1. Introduction

Recently, droughts have become widespread in the Northern Hemisphere continent, including Mongolia (Dai et al. 1998; Lotch et al. 2005; among others). In Mongolia, this topic has increasingly been concerned relevant to

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the ongoing, and projected future global warming (e.g., Natsgadorj 2003). These global changes are most likely to have a substantial influence not only on the quantitative aspect of the Eurasian grasslands (such as biomass), but also on their qualitative aspect (such as phenology and composition of species).

Previous studies investigated the relationship between the ground-measured pasture biomass, and meteorological/soil moisture conditions (Erdenetsetseg et al. 2004; Zhang et al. 2005; among others), but little attention has been paid to the phenology that varies substantially from-year-to-year, with the exception for a few studies such as Kondoh et al. (2005). On the interannual basis, the emergence timing differs in the range exceeding 60 days, while the period of a growing season from emergence to senescence differs at the maximum of 75 days (Kondoh et al. 2005). In addition, the phenology changes not only from-year-to-year, but also from-species-to-species and from-region-to-region. They related the emergence timing, to observed soil moisture conditions in the spring. However, detailed analysis of how meteorological factors (such as thermal versus moisture conditions), control the seasonal timings and lengths of period of each phenological stage, from emergence through senescence has not yet been conducted. This approach should be based on ground observations of phenology. This is because subtle, but physiologically significant changes of emergence and qualitative changes of heading, flowering, and the followings cannot be detected by satellite observations. Those with an optical sensor only observe drastic and quantitative changes of greening. Moreover, the ground observations have an advantage in identifying different species with different phenologies. With this background in mind, this study aims to elucidate meteorological factors controlling the phenology of *Stipa* spp., one of the dominant species representing not only the Mongolian grasslands, but also the Eurasian steppe.

## 2. Data

We used plant height and phenology data of *Stipa* spp. for 1993–2002, in each fenced area of three stations as explained below. The genus is chosen because this is one of the dominant species representing the Mongolian steppe. These in-fenced observations have no influence of grazing, thus being useful for research of the relationship between the natural-state vegetation and its atmospheric environments. Note that in Mongolia, the remote-sensed vegetation usually undergoes grazing. In this analysis, used is the data for the timing when more than half of samples of *Stipa* spp. shows a phenological phenomenon such as emergence (hereafter referred to as Em), heading (Hd), flowering (Fl), maturity (Mt), and senescence (Ss). The plant height and phenology measurements have been conducted on a 10-day interval and on alternative days (every even-numbered day), respectively, by the Institute of Meteorology and Hydrology (IMH) of Mongolia. Since more missing observations were seen in the phenological data for flowering and its later stages compared with that for the earlier stages of emergence and heading, these two phenological timings were mainly analyzed in this study. In the operation at the IMH, the phenomenon of heading for *Stipa* spp. is referred to as the Mongolian term that is translated into 'tillering'. In this, the common term of heading was used to indicate the phenomenon for worldwide readers. Detailed information of agro-meteorological observations in Mongolia is found in Shinoda and Morinaga (2005), and Kondoh et al. (2005). As for the name of *Stipa* species, *S. krylovii* is seen in the areas of Bulgan and Arvaikheer, while *S. gobica* is found in Mandalgovi. All the precipitation and temperature data used here is also derived from the IMH.

Also used is model-estimated soil moisture data (Shinoda et al. 2004). The advantages of using such a model estimate, instead of observed data are as follows; (1) the model estimate is useful for eliminating questionable observed data, and (2) it has a daily time resolution instead of 10-day, for the observations. For the practical purpose of the present study, a modification of the one-layer water balance model, namely, the bucket model (Yamaguchi and Shinoda 2002) was employed with an additional consideration of soil freezing and snowmelt water. The original model was used for a climate change study in the African Sahel (Shinoda and Yamaguchi 2003). The model used here calculates absolute soil moisture amounts, using only daily precipitation

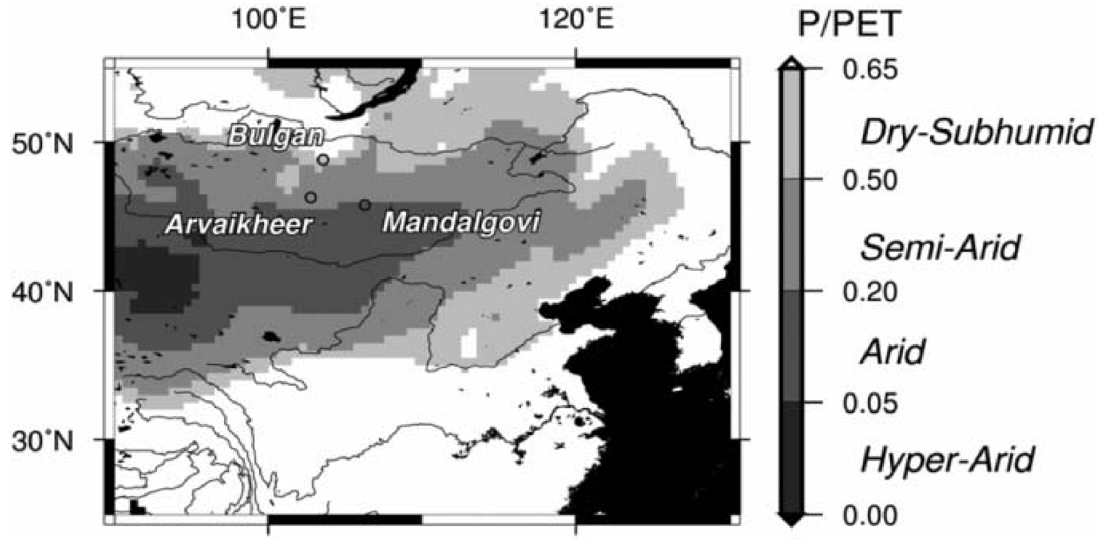


Fig. 1. Locations of three study sites in Mongolia. The shading denotes the arid region that is defined by the aridity index of annual mean precipitation, divided by the annual mean potential evapotranspiration (P/PET) (UNEP 1992). The index was calculated using the precipitation and temperature data averaged over the 30-year period of 1961–1990.

and temperature data with a limited number of measured (or estimated) soil parameters. This model performance was validated with the soil moisture observations on a 10-day interval from April to October during 1993–2002 in a fenced pasture (Shinoda et al. 2004). The data are volumetric plant-available soil moisture values—that is, the total soil moisture minus the wilting level—taken by means of direct gravimetric measurements. Based on the model validation, the daily-based plant-available soil moisture values (mm) of the top 20-cm-deep for Mandalgovi, the 50-cm-deep layer for both Bulgan and Arvaikheer were estimated with the above-mentioned model. These layers represent the major root zones of perennial grasses (such as *Stipa* spp.), dominating at each site. The layer is shallowest at the southern-most driest site, Mandalgovi.

The three sites are located in the wide area of Mongolia, including major vegetation zones from the forest steppe (Bulgan, BL), southward to typical (Arvaikheer, AV), and desert (Mandalgovi, MG) steppes. All the three stations are located on the highlands, exceeding an elevation of 1200 m in the similar latitudinal range, between 45°N to 49°N. As indicated by the aridity index, namely, the ratio of annual precipitation, to annual potential evapotranspiration (Fig. 1), precipitation decreases and temperature (that is, evapotranspiration) increases southward, resulting in more arid conditions southward. This climatic pattern with latitude corresponds to that of vegetation. Figure 2 displays the interannual variations of precipitation during the growing season. Note the recent occurrence of severe droughts as evident in 2002, along with a decreasing trend during the analyzed decade.

## 3. Climatological relationships between phenology and meteorological conditions

The five phenological events were observed during the period of 1993–2002, although there were some gaps of the measurements in a series of the phenological events. The gaps tended to occur, due to severe drought conditions and resultant missing phenological events. These are found in the years of 2001 and 2002 for Arvaikheer. All the missing data was excluded from the ensuing analysis. On the climatological basis, all the events are later southward (Fig. 3). On the other hand, interestingly, the lengths of two periods from emergence to heading, and from emergence to maturity, coincide

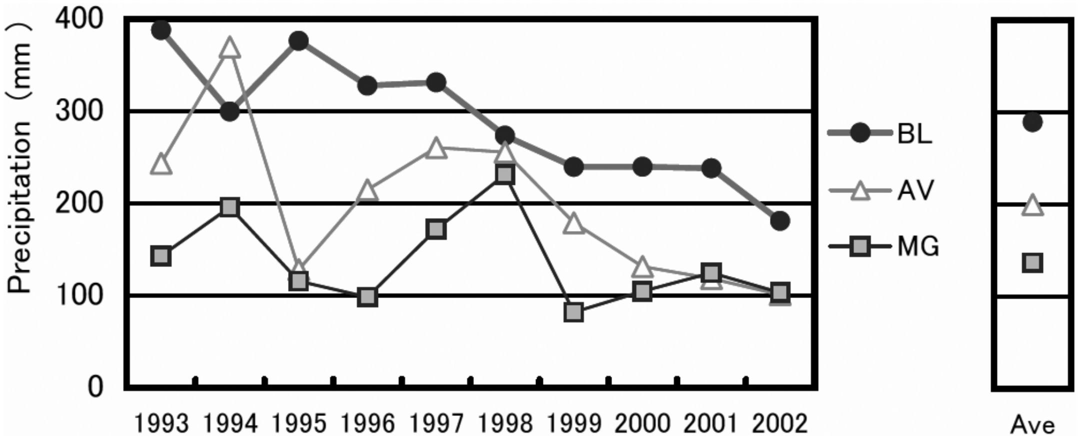


Fig. 2. Interannual changes of precipitation during the growing season of April–August for the three sites. Ave denotes values averaged over 1993–2002.

roughly with each other. The periods are approximately 61 and 108 days. This may be a common physiological, and phenological feature of the same genus.

The climatological temperature at the emergence timing varies from-region-to-region, with the highest temperature at the southern-most driest site, Mandalgovi (Fig. 3). This large regional difference in the thermal conditions for the same phenological event, implies that temperature may not be a determinant factor controlling the phenology. On the climatological basis, soil moisture tends to exhibit a slight increase during early April, in conjunction with increased temperature (Fig. 3), when the daily-maximum exceeds 0°C (not shown). This is because the spring-time snowmelt water adds to the root-zone soil, as simulated in the soil moisture model. Then, the soil moisture continues to decrease at the emergence timing until the onset of the rainy season. These facts imply that temperature at the snowmelt timing is too low (near 0°C), to cause the emergence and the generated snowmelt water is evaporated quickly, not affecting the emergence directly.

It is noteworthy that heading occurs near the first peak of soil moisture at all the sites, accompanied by decreased soil moisture resulting from the break of the rainy season (Fig. 3). The break, climatologically phase-locked around mid-July over Mongolia, is associated with a barotropic ridge embedded in the stationary Rossby wave of the westerlies (Iwasaki and Nii 2006). It is possible that *Stipa* spp. has a nature adaptive to such a rainy season's pattern by completing the vegetative growth in the first half of the rainy season prior to its break around mid-July, and shifting to the reproductive phase. Furthermore, flowering tends to occur near the second peak of the soil moisture. From these facts, it is inferred that the characteristic rainy season pattern may determine the phenological timings.

## 4. Interannual variations of phenology, and meteorological conditions

First, this section examined the emergence/heading timings, and moisture conditions on the interannual basis. It is seen that in five days prior to emergence, daily precipitation event tends to occur in most cases; that is, nine of the analyzed ten years for Bulgan, eight years for Arvaikheer, and six years for Mandalgovi. In general, this result coincides with the previous analysis of soil moisture data for Arvaikheer and Mandalgovi (Kondoh et al. 2005). No precipitation occurred prior to 10 days, only for four cases among 30 cases (3 sites by 10 years); 1996 for Bulgan, 1993 and 1994 for Arvaikheer, and 1993 for Mandalgovi. One possible explanation for these exceptional cases is that dew, formed in the diurnal temperature range sandwiching 0°C, might be added to the near-surface soil, enough to cause the emergence. Out of the three stations, this possibility is higher at Bulgan, having higher humidity

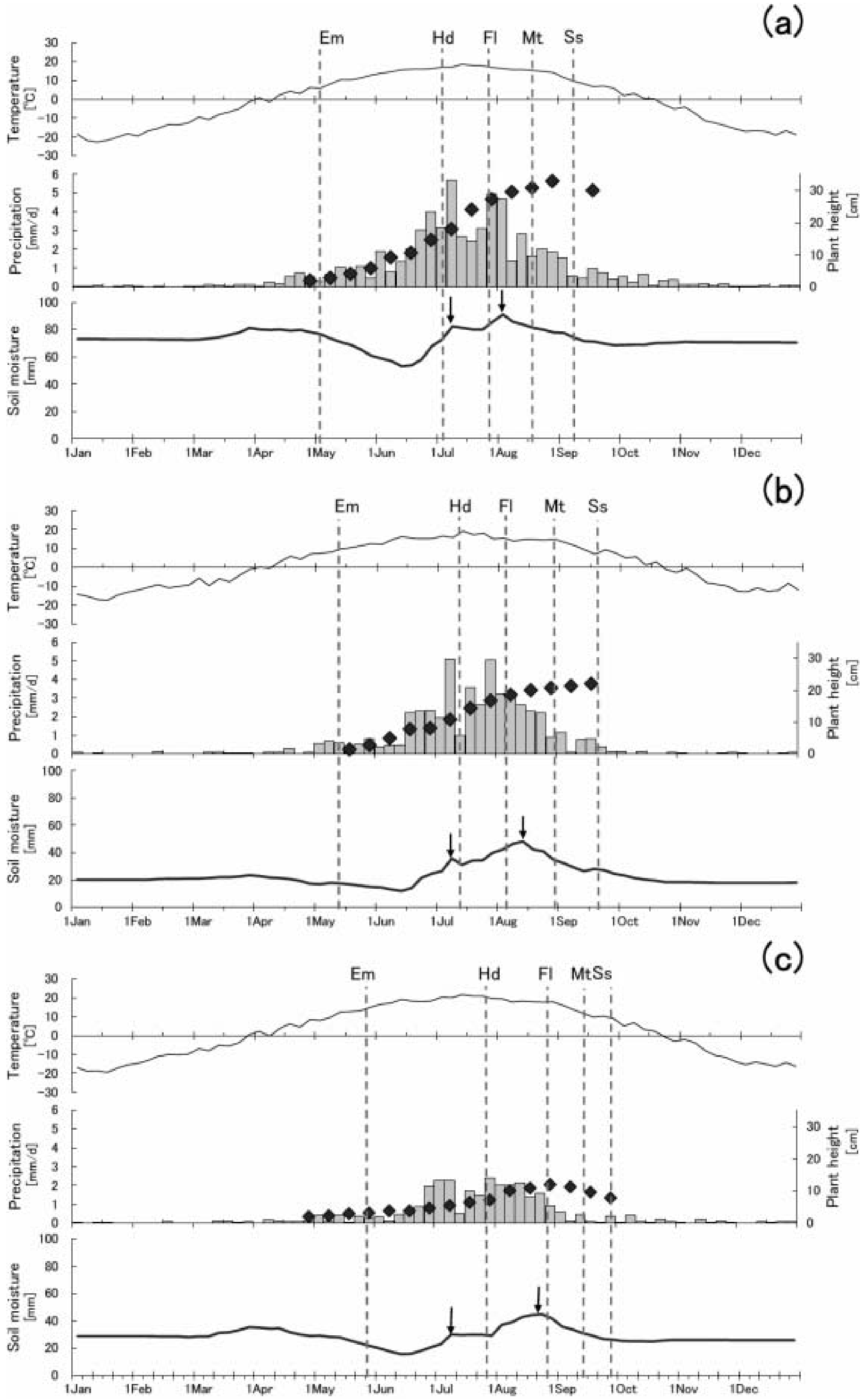


Fig. 3. Climatological seasonal changes of five-day-based temperature (°C), precipitation (bar, mm/d), modeled soil moisture (mm), plant height (diamond, cm), and phenological phenomena (vertical dashed lines, Em to Ss) for Bulgan (a), Arvaikheer (b), and Mandalgovi (c). The climatological values, and phenological dates were averaged over the available years. The thicknesses of the top soil layer for Bulgan, Arvaikheer, and Mandalgovi used for the soil moisture modeling are 50 cm, 50 cm, and 20 cm, respectively. The arrows denote the double peaks of soil moisture.

and lower temperature. The effective accumulative temperature, until the emergence, differs substantially from-year-to-year and from-region-to-region (not shown). This year-to-year difference is also manifested in the effective accumulative temperature, from the emergence to heading (not shown). It is reasonable to state that the effective accumulative temperature value should be the same for a given plant species regardless of year and geographical location, if it holds specific significance for the phenology. These facts strongly suggest that temperature does not play a crucial role in the emergence and heading.

The extremely dry conditions in 2001 and 2002 at Arvaikheer (see Fig. 2) exerted a substantial influence on the failure of heading. The failure in a series of the normal phenology (like drying as an extreme case), is the largest impact of meteorological drought (decreased rainfall) on the plant. With the exception of the extremely dry years, the length of the period from emergence to heading is correlated with the total amount of the precipitation that occurred during the phenological period. The correlation was found to be positive at all the sites, and the most significant (at the 1% level, $R = 0.93$) for Bulgan (Fig. 4). This relationship is interpreted as the casual mechanism that drought conditions lead to an earlier heading, that is, a drought-avoiding strategy of the plant to shift from the vegetative to reproductive stage for leaving offspring under the limited soil moisture conditions.

Development of a plant is its progress from seed germination or budding, through floral bud differentiation to flowering, and eventually to fruit maturity, while growth is the accumulation of dry matter or material of the photosynthetic process. The process of development is often independent of the growth process. An additional analysis revealed a positive correlation significant at the 5% level, between the emergence-heading precipitation, and plant height at the heading for Bulgan. This suggests that development tends to influence growth, and thus biomass through growth duration, which determines the amount of solar radiation that the plant can intercept. Namely, higher (lower) precipitation results in longer (shorter) growth duration and thus larger (smaller) net primary production. In brief, precipitation relates

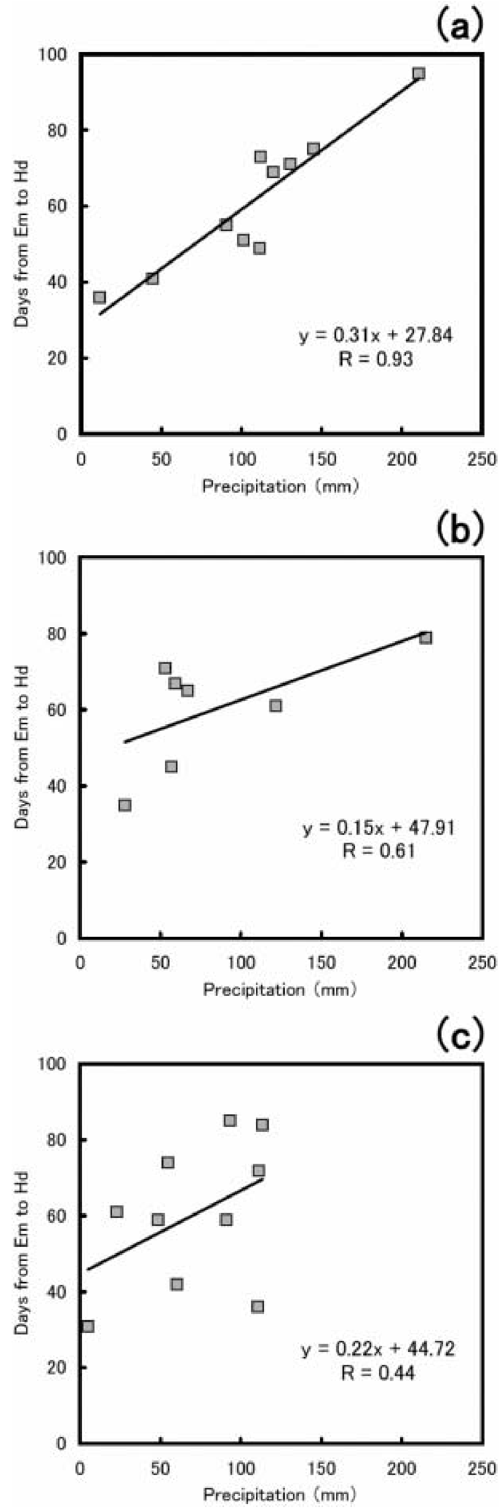


Fig. 4. Scatter diagrams between the length of period (days) from Em to Hd and total precipitation (mm) for Bulgan (a), Arvaikheer (b), and Mandalgovi (c).

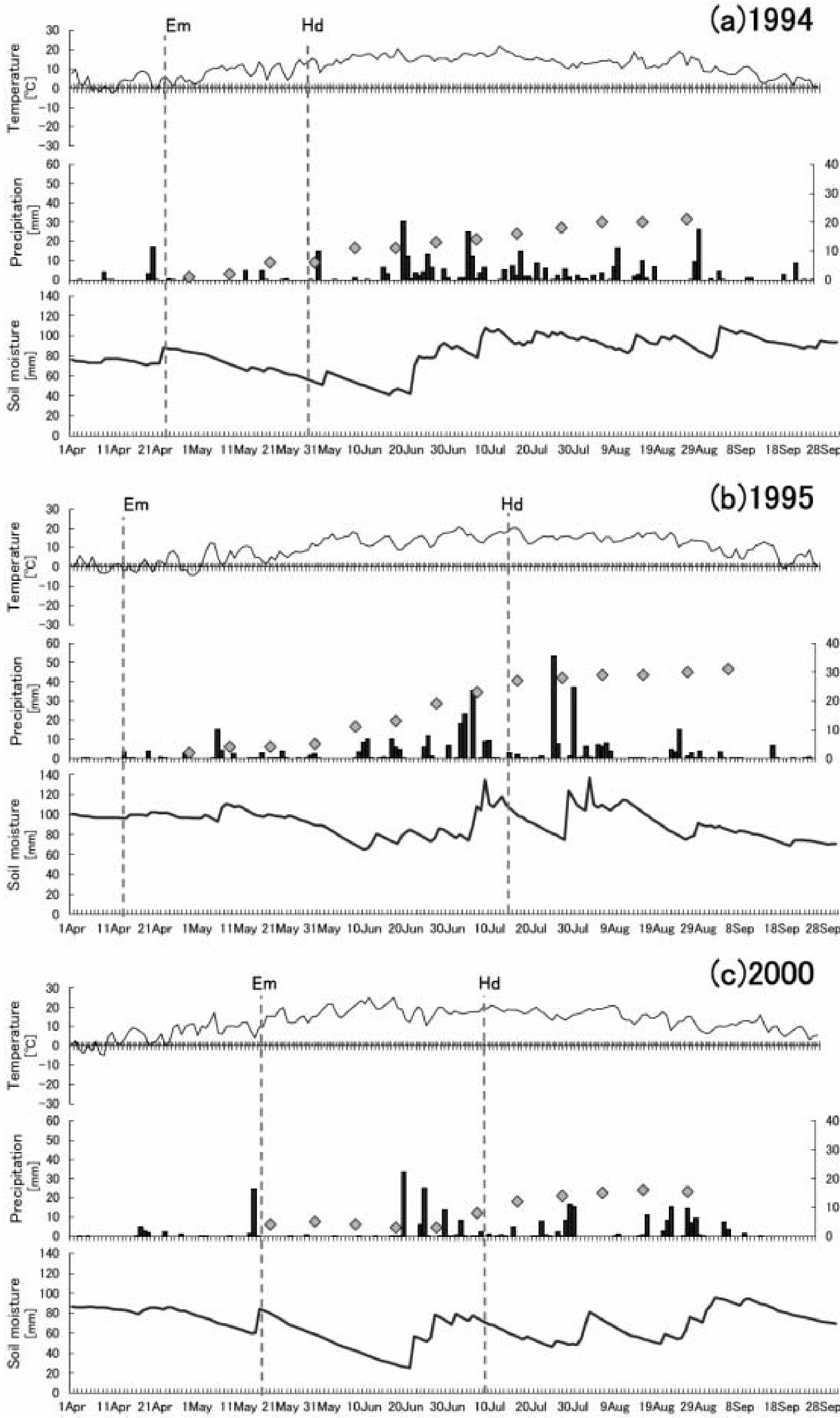


Fig. 5. Five-day-based time series of daily-mean temperature (°C), precipitation (bar, mm/d), modeled soil moisture (mm), plant height (diamond, cm), and Em/Hd timings of *Stipa* spp. (vertical lines) at Bulgan for 1994 (a), 1995 (b), and 2000 (c).

strongly to biomass, not only through growth itself, but also through development. This relationship coincides with the relationship between the ground-based precipitation and yearly-maximum biomass (Erdenetsetseg et al. 2004). Miyazaki et al. (2005) indicated the importance of rainfall for the early growth season through July for the satellite-inferred yearly-maximum leaf area index. In a future study, this point should be considered in the phenological context as demonstrated in this investigation.

Figure 5 illustrates a comparison between the years having the shortest (36 days for 1994), and longest (95 days for 1995) periods, from emergence to heading at Bulgan. For the two periods, the total precipitation recorded 11.7 mm and 210.6 mm, respectively. For 1995, a large amount of rainfall produced a large growth of plant height to 30 cm at the heading timing, in comparison with less than 10 cm for 1994. Interestingly, in 1995, the heading occurred at the intermediate dry period existing in the rainy season. Also, a similar phenomenon was observed for a near-normal year 2000. During 1994 and 2000, plant growth, as seen in plant height, was suppressed just prior to, or at the heading due to water stress. Judging from these results, the break of the rainy season is likely a trigger to cause the heading. Additional analysis revealed a significant correlation (at the 1% level), between the precipitation amount, and intensity (total precipitation divided by the length of the period between emergence-heading). This means that the lower precipitation total during the entire emergence-heading period for the drought years resulted not only from the shorter period, but also from the lower precipitation intensity for a day. This focused on the total precipitation (but not its intensity) for the vegetative growth phase, because the accumulated precipitation reflects soil moisture conditions that the plant senses at the heading timing. In fact, as for Bulgan, the modeled soil moisture, prior to heading, revealed a significant correlation with the emergence-heading period. Further analysis remains to be done on the question why the two southward stations did not exhibit a strong relationship between the precipitation and phenology, as seen in Bulgan.

In addition to the water control of the interannual change in the phenology, that of the interregional difference is manifested in Fig. 3; namely, the earlier emergence at Bulgan is caused by the similarly earlier onset of spring precipitation in spite of lower temperature. The earlier heading is attributed to the earlier start of the break of the rainy season. Thus, all the phenological phenomena take place earlier at Bulgan than at the other sites, most likely due to the earlier seasonal march of the rainy season.

## 5. Conclusions

The present ground-based phenological study of the Mongolian grasslands have demonstrated that since temperature requirements are satisfied during the warm season in the arid environment, soil water is one of the most crucial factors controlling the region-to-region and year-to-year variations of phenological timings in the early growth stage. As for the emergence, its date relates neither to a specific temperature, nor to an effective accumulative temperature, but to the presence of precipitation that occurs within five days prior to the emergence in most cases. Interestingly, drought during the early growth tends to hasten maturity, as manifested at Bulgan, or the plants may even die before they reach maturity under very severe drought conditions, as seen at Arvaikheer in 2002. In addition, drought was found to result in shorter growth duration and thus smaller net primary production, suggesting that precipitation relates closely to biomass through the two-way processes; growth and development. A question, however, remains unsolved: how the plant sensed and responded to the drought conditions unfavorable for its growth and development. Future study should, therefore, highlight the physiological response of the plant to decreased atmospheric and soil moisture at the exact timing of heading, requiring a comprehensive measurement of water movement in the atmosphere-plant-soil continuum.

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