Driving Forces of Intra-Annual Variation in Plant Spectral Beta Diversity in Inner Mongolia Grassland

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Abstract. The variation trend of plant spectral beta diversity index of different types of grasslands in Inner Mongolia and its key climate drivers were explored by analyzing the changes of monthly and annual climate variables and spectral index of plant diversity during the period from 1982 to 2017. All the study areas are located in nature reserves that provide protection for fragile ecosystems and biodiversity, so grazing and human disturbance can be ignored. The results show that the variation trends in plant spectral diversity of different types of grassland in Inner Mongolia were different. The plant diversity in Anxi nature reserve reached the highest in October, while that in West Ordos, Xilingol and Tumuji nature reserve reached the highest in April. Temperature is a key driving factor for the variation of beta diversity of all types of grassland plants, and is negatively correlated with the plant diversity. Compared with the inter-annual scale, the climatic factors on the inter-monthly scale have a greater impact on the grassland plant diversity. Understanding monthly climate variables help us monitor the dynamic change of grassland plant diversity in a timely and effective manner.

Keywords. Plant diversity; nature reserves; grasslands; climate variables; remote sensing.

1. Introduction
As an important part of ecosystem component, plant diversity is of great significance for maintaining the stability of ecosystem. Existing studies have shown that plant diversity contributes to maintaining ecosystem multifunctionality provided by grasslands and is critical to productivity and stability of ecosystem [1-2]. The distribution pattern of species diversity and its formation mechanism are one of the hotspots of biodiversity research [3]. In natural grassland ecosystems, plant diversity is affected by environmental factors such as geographical topography, soil, grazing and climate change [4]. Among them, climate factor has been believed the main mechanism to explain the change in species diversity [5].

Some hypotheses suggest that historical climate and contemporary changes in water and energy resources have affected the distribution and spatial pattern of species diversity [6-7], especially that regions with high water and energy efficiency can accommodate more species [8]. In addition, the physiological tolerance hypothesis [9] holds that many species cannot survive in extreme environments. Therefore, the more suitable the temperature and water conditions are, the higher the species richness [8]. It is worth noting that the impact of climate on plant diversity shows spatial and temporal heterogeneity with different vegetation types and ecosystems [10]. Studies have found that changes in average temperature directly reduce species richness, while changes in total precipitation directly undermine community stability [11].

The driving factors of plant diversity in different types of grassland are different. The study on
species diversity of shrub community in Jilin province found that species richness was negatively correlated with precipitation, but not significantly correlated with low temperature in winter [5]. In Kruger national park in South Africa and in the tall grass grasslands of northeast Kansas in the United States, the decrease of annual rainfall has resulted in the loss of species richness [12]. Under the influence of latitude, longitude, altitude, water and heat conditions, the Inner Mongolia grassland is obviously zonal. The study on the change of plant diversity in the grassland community along gradients of precipitation and elevation in the Xilin River Basin found that species diversity was positively correlated with annual precipitation, but negatively correlated with annual average temperature [13]. In the desert steppe area of Inner Mongolia, species diversity has the highest correlation with hydrothermal factors [14]. Mu et al found that there was a strong correlation between desert vegetation in Inner Mongolia and precipitation in the inter-annual and inter-monthly scales [15].

In conclusion, the research on the relationship between plant species diversity and climate factors mainly focuses on the inter-annual scale or regional scale, but the response of the whole Inner Mongolia grassland plant beta diversity to monthly climate change is seldom explored. Beta diversity is an indispensable part of biodiversity, which is of great significance to reveal the mechanism of plant diversity maintenance. In this study, we extracted the plant spectral beta diversity index from the satellite data set from 1982 to 2017, combined with the monthly and annual climate data, analyzed the response of beta diversity of four different types of grasslands in Inner Mongolia to monthly and annual climate changes, and determined key climate variables affecting the diversity of grassland plants. This study provides references for revealing the relationship between grassland plant diversity and climate change, the mechanism of plant diversity maintenance, and the sustainable utilization of grassland plant diversity in Inner Mongolia.

2. Methods

2.1. Study Site

We chose four nature reserve in northern China to represent a range of environment and vegetation conditions across four different types of temperate grasslands. Anxi Extra-arid Desert National Nature Reserve (94°45′~97°00′E, 39°52′~41°53′N) (hereafter Anxi) located in the western end of Hexi corridor in Gansu Province. It is the only multi-functional and comprehensive nature reserve in China which is mainly devoted to the protection of the extremely arid desert ecosystem and its biodiversity. The total topographic features of the study areas are high in the south and low in the north, and the elevation is above 1300 meters. The climate of the reserve belongs to the temperate continental arid climate. The vegetation types include Gravel desert vegetation, Sandy desert vegetation, Halophytic meadow vegetation of low wetland, Swamp vegetation, Solonchak vegetation and so on.

West Ordos National Nature Reserve (106°40′~107°44′E, 39°13′~40°11′N) (hereafter West Ordos) located in the Inner Mongolia Autonomous Region. It is a comprehensive nature reserve with the main objects of protecting ancient relic and endangered plants, vegetation belt and diverse ecosystem from grassland to desert. The reserve is a typical warm temperate continental climate with harsh natural conditions. The landscape is dominated by steppe, desert and desert steppe. There are 335 species of wild plants in the reserve, among which 7 species are rare and endangered at the national level.

Xilingol Grassland National Nature Reserve (115°32′~117°12′E, 43°26′~44°33′N) (hereafter Xilingol) located in the eastern part of Inner Mongolia plateau, bordering the lower hills and hills on the western side of the greater Hinggan mountains. It mainly protects the typical grassland ecosystem and meadow grassland ecosystem, and carries out special protection for endangered species. The nature reserve is a semi-arid, arid continental monsoon climate in the temperate zone.

Tumuji National Nature Reserve (122°44′13″~123°10′24″E, 46°04′12″~46°25′47″N) (hereafter Tumuji) located in Jalaid Banner of Inner Mongolia autonomous region, is an important wetland with rich biodiversity. The reserve belongs to the temperate continental monsoon climate, and the habitat types are very rich, forming a diverse ecosystem of grassland, wetland and shrub.
2.2. Plant Diversity Indices
Optical diversity [16] refers to spectral reflectance changes detected by optical remote sensing, and many remote sensing indicators are used to estimate plant diversity. Wang et al. [17-18] found that the coefficient of variation (CV) derived from spectral reflectance in space can be an ideal indicator of species diversity. Remote sensing images data used in this study were Landsat products from 1982 to 2017, and remote sensing data were downloaded from the Geospatial Data Cloud (http://www.gscloud.cn/). Remote sensing images in April, July and October of each year were selected, and images with more than 10% of cloud cover were discarded. The remote sensing image needs a series of pretreatment including geometric correction, radiation correction and terrain impact removal. Then, the sum of the coefficient of variation of 1-7 bands of remote sensing images were calculated, which was used as an indicator of spectral diversity [18-19]:

\[ CV_{sum} = \sum_{\lambda=1}^{12} \left( \frac{\sigma(\rho_\lambda)}{\mu(\rho_\lambda)} \right) \]  

where \( \sigma(\rho_\lambda) \) and \( \mu(\rho_\lambda) \) denote the standard deviation and mean value of each band. Calculate in ERDAS IMAGINE 2015 and ArcGIS10.4 software.

2.3. Climate Data
Climatological data are derived from grid temperature and precipitation data obtained by interpolation of more than 2,400 meteorological stations in China, and the time span is completely consistent with the Landsat remote sensing images data. Obtained by China meteorological data service center. Meteorological data are mainly used to study the influence of climate on the variation trend of plant diversity in the research area during the observation period.

In this study, 7 climatic variables were set: annual maximum temperature (ATmax), annual minimum temperature (ATmin), mean monthly temperature (MMT), monthly minimum temperature (MTmin), monthly maximum temperature (MTmax), annual precipitation (AP) and precipitation seasonality (see table 1 for alternative climatic factors).

2.4. Statistical Analysis
The relationship between climate variables and plant diversity were analyzed using the Stepwise Linear Regression (SLR) method. These climate variables may be correlated, rather than independent, and it is not known which variables will be introduced into the regression equation before screening. The basic process is that only those that have been tested for significance can be introduced, otherwise they are removed. Moreover, SLR can eliminate multicollinearity among variables, and climatic variables with weak explanatory power were removed. In this study, the climate variables introduced into the optimal regression model are more closely and directly related to the beta diversity of grassland plants. SLR analysis were conducted in the SPSS Statistics 23.

3. Results

3.1. Variation of Beta Diversity of Grassland Plants in Inner Mongolia
The results show that (figure 1) in Anxi, plant diversity was highest in October, followed by July and finally April. In West Ordos, overall plant diversity in July was slightly lower than that in April and October. In Xilingol and Tumuji, the annual variation of plant diversity fluctuated greatly, but the variation trend was generally consistent, with the highest plant diversity in April, followed by October, and the lowest plant diversity in July.

3.2. Driving Factors of Plant Beta Diversity Change in Anxi
Stepwise regression analysis show that in Anxi, the climate variables introduced into the plant diversity regression equation in April are the ATmin of present year (X4) and the MTmin one year ago
in July (X26). The climate variable introduced into the diversity regression equation in July is the MTMin one year ago in October (X32). In October, the MMT one year ago in January (X35), the MTMax one year ago in March (X49), the MMT in July of present year (X23), the MTMin one year ago in October (X44), ATMin of present year (X4), the MTMin in March of present year (X40), and the MTMin one year ago in September (X34) are introduced (Table 2).

Table 1. Alternative climate factors and their implications.

| Factor | Implication |
|--------|-------------|
| X1     | ATMax one year ago (°C) |
| X2     | ATMax of present year (°C) |
| X3     | ATMin one year ago (°C) |
| X4     | ATMin of present year (°C) |
| X5     | MMT in Jan one year ago (°C) |
| X6     | MMT in Feb one year ago (°C) |
| X7     | MMT in Mar one year ago (°C) |
| X8     | MMT in Apr one year ago (°C) |
| X9     | MMT in May one year ago (°C) |
| X10    | MMT in June one year ago (°C) |
|     | MMT          | MTmax in Jan of one year ago (℃) | MTmax in Mar of one year ago (℃) | MTmax in May of one year ago (℃) |
|-----|--------------|----------------------------------|----------------------------------|----------------------------------|
| X11 | MMT in Jul one year ago (℃) | MTmax in Aug one year ago (℃) | MTmax in Apr of present year (℃) | MTmax in Nov one year ago (℃) |
| X12 | MMT in Aug one year ago (℃) | MTmax in Sep one year ago (℃) | MTmax in May of present year (℃) | MTmax in Dec one year ago (℃) |
| X13 | MMT in Sep one year ago (℃) | MTmax in Oct one year ago (℃) | MTmax in Jun of present year (℃) | MTmax in Jan of present year (℃) |
| X14 | MMT in Oct one year ago (℃) | MTmax in Nov one year ago (℃) | MTmin in Feb of one year ago (℃) | MTmax in Feb of present year (℃) |
| X15 | MMT in Nov one year ago (℃) | MTmax in Dec one year ago (℃) | MTmin in Feb of one year ago (℃) | MTmax in Mar of present year (℃) |
| X16 | MMT in Dec one year ago (℃) | MTmax in Jan of present year (℃) | MTmin in Mar of one year ago (℃) | MTmax in Apr of present year (℃) |
| X17 | MMT in Jan of present year (℃) | MTmax in Feb of present year (℃) | MTmin in May of one year ago (℃) | MTmax in May of present year (℃) |
| X18 | MMT in Feb of present year (℃) | MTmax in Mar of present year (℃) | MTmin in Jun of one year ago (℃) | MTmax in Jun of present year (℃) |
| X19 | MMT in Mar of present year (℃) | MTmin in one year ago (℃) | MTmin in Jun of one year ago (℃) | MTmax in Dec one year ago (℃) |
| X20 | MMT in Jun one year ago (℃) | MTmin in Jul one year ago (℃) | MTmin in Jul one year ago (℃) | MTmax in Dec one year ago (℃) |
| X21 | MMT in Jul one year ago (℃) | MTmin in Aug one year ago (℃) | MTmin in Aug one year ago (℃) | MTmax in May one year ago (℃) |
| X22 | MMT in Aug one year ago (℃) | MTmin in Sep one year ago (℃) | MTmin in Sep one year ago (℃) | MTmax in May one year ago (℃) |

Winter seasonal precipitation of spring seasonal precipitation of summer seasonal precipitation of
| MTmin in Apr one year ago (℃) | ATmax in Oct one year ago (℃) | MTmin in Nov one year ago (℃) | ATmax of present year (℃) | MTmin in Sep one year ago (℃) | MTmax in May of present year (℃) |
|-----------------------------|-------------------------------|--------------------------------|-------------------------|-------------------------------|---------------------------------|
| X23                         | X32                           | X1                             | X2                      | X3                            | X63                             |
| MTmin in May one year ago (℃) | ATmax of present X33 year (℃) | MTmin in Dec one year ago (℃) | ATmin in Jan of present (℃) | MTmin in Nov one year ago (℃) | MTmin in Aug one year ago (℃) |
| X24                         |                               | X3                             |                          |                               |                                 |
| MTmin in Jun one year ago (℃) | ATmin of present X34 year (℃) | MMT in Jan one year ago (℃)    |                          | MMT in Jul one year (℃)       |                                 |
| X25                         |                               | X5                             |                          | X5                            |                                 |
| MTmin in Jul one year ago (℃) | X35                           | MMT in Feb one year ago (℃)    |                          | MMT in Aug one year (℃)       |                                 |
| X26                         |                               | X6                             |                          | X6                            |                                 |
| MTmin in Aug one year ago (℃) | X36                           | MMT in Mar one year ago (℃)    |                          | MMT in Sep one year (℃)       |                                 |
| X27                         |                               | X7                             |                          | X7                            |                                 |
| MTmin in Sep one year ago (℃) | X38                           | MMT in Apr one year ago (℃)    |                          | MMT in Jul one year (℃)       |                                 |
| X28                         |                               | X8                             |                          | X8                            |                                 |
| MTmin in Oct one year ago (℃) | X39                           | MMT in May of present year (℃) |                          | MMT in Aug one year (℃)       |                                 |
| X29                         |                               | X9                             |                          | X9                            |                                 |
| MTmin in Nov one year ago (℃) | X40                           | MMT in Jun of present year (℃) |                          | MMT in Sep one year (℃)       |                                 |
| X30                         |                               |                                |                          |                               |                                 |
| MTmin in Dec one year ago (℃) |                                |                                 |                          |                               |                                 |
| X31                         |                               |                                |                          |                               |                                 |

Figure 1. Intra-annual variation of beta diversity of grassland plants in Inner Mongolia.
The three regression equations all introduce the climatic factors of the MTmin one year ago, in which April is the MTmin one year ago in July, and both July and October are the MTmin one year ago in October. These climate variables were negatively correlated with plant diversity, that is, the higher the MTmin one year ago was, the lower the plant diversity was. In addition, the ATmin of present year were introduced in April and July, which were also negatively correlated with plant diversity. It can be seen that plant diversity in different seasons in Anxi is mainly affected by climate variables related to temperature.

Table 2. Regression equation of beta diversity of grassland plants and climate factors in Anxi reserve.

| Month | Optimal regression equation | Adjusted R² | P-Value |
|-------|-----------------------------|-------------|---------|
| 4     | Y=−0.179−0.004*X4−0.006*X26 | 0.030       | 0.000   |
| 7     | Y=−0.433−0.012*X32           | 0.017       | 0.000   |
| 10    | Y=−0.871−0.005*X5−0.003*X49−0.003*X23−0.001*X35−0.001*X40+0.001*X34 | 0.755       | 0.000   |

Note: Y represents the diversity of grassland plant species.

3.3. Driving Factors of Plant Beta Diversity Change in West Ordos

In West Ordos, the climatic factors introduced into the regression equation of plant diversity in April are the MTmax in December (X46), the MTmin in June (X25), the MTmax in February (X36) and the MTmin in April (X23) one year ago. The climate variable introduced into the diversity regression equation in July are the MTmax in March (X '43), the MTmax in January (X '41) and the MTmax in February (X' 42) one year ago, and the MTmax in February of the present year (X' 54). In October, the MTmax in January (X "47) and the MTmax in March (X" 49) one year ago are introduced (table 3).

All three equations introduce the MTmax one year ago. In the regression equations of July and October, the MTmax in January and the MTmax in March one year ago are introduced. All of them are negatively correlated with plant diversity, the higher the temperature, the lower the diversity. Both April and July introduced the MTmax in February one year ago, but the difference was that the MTmax in February one year ago was positively correlated with the plant diversity in April, on the contrary, negatively correlated with that in July. It can be seen that the plant diversity in different seasons in West Ordos is mainly affected by climate variables related to temperature.

Table 3. Regression equation of beta diversity of grassland plants and climate factors grassland in West Ordos reserve.

| Month | Optimal regression equation | Adjusted R² | P-Value |
|-------|-----------------------------|-------------|---------|
| 4     | Y=−0.338+0.001*X46+0.002*X25+0.001*X36−0.001*X23 | 0.868       | 0.000   |
| 7     | Y=1.503−0.007*X'43+0.003*X'54+0.003*X'41−0.003*X'42 | 0.986       | 0.000   |
| 10    | Y=0.418−0.001*X"47−0.001*X"49 | 0.931       | 0.000   |

3.4. Driving Factors of Plant Beta Diversity Change in Xilingol

In Xilingol, the climate factor introduced into the regression equation of plant diversity in April is the MTmin in August one year ago (X27). The ATmax of present year (X '2) is introduced in July. In October, the MMT in August one year ago (X"12), the MTmax in June of the present year (X" 64) and the MTmax in November one year ago (X "57) are introduced (table 4).

It can be seen that plant diversity in Xilingol is mainly affected by temperature. Plant diversity in April was affected by the MTmin in August one year ago. The higher the temperature, the lower the diversity. The plant diversity in July was negatively correlated with the ATmax of present year. In October, plant diversity was negatively correlated with the MMT in August one year ago, while positively correlated with the MTmax in November one year ago. However, it is worth noting that the
Adjusted $R^2 < 0.02$, which means that only considering temperature and precipitation variables cannot well explain the change in plant diversity in this region. This indicates that there are other variables not taken into account in the model that can further explain the variation in diversity.

Table 4. Regression equation of beta diversity of grassland plants and climate factors grassland in Xilingol reserve.

| Month | Optimal regression equation | Adjusted $R^2$ | $P$-Value |
|-------|-----------------------------|----------------|-----------|
| 4     | $Y=2.026-0.03*X^2$          | 0.010          | 0.000     |
| 7     | $Y=0.878-0.002*X^2$         | 0.017          | 0.000     |
| 10    | $Y=10.481-0.025*X^12-0.019*X^64+0.002*X^57$ | 0.018 | 0.000     |

3.5. Driving Factors of Plant Diversity Change in Tumuji

In Tumuji, the climate factor introduced into the regression equation of plant diversity in April is the $AT_{max}$ of present year ($X^2$) and the $MT_{min}$ in October one year ago ($X^{29}$). In July, the $MT_{max}$ in April of the present year ($X^{'56}$) is introduced. In October, the $MT_{max}$ in May of the present year ($X^{''63}$) is introduced (table 5).

Plant diversity in July and October is related to the $MT_{max}$ of the present year. The difference was that plant diversity in July was positively correlated with the $MT_{max}$ in April of the present year, while October was negatively correlated with the $MT_{max}$ in May of the present year. It can be seen that plant diversity in different seasons in Tumuji is mainly affected by climate variables related to temperature.

Table 5. Regression equation of beta diversity of grassland plants and climate factors grassland in Tumuji reserve.

| Month | Optimal regression equation | Adjusted $R^2$ | $P$-Value |
|-------|-----------------------------|----------------|-----------|
| 4     | $Y=7.256-0.016*X^2+0.013*X^2$ | 0.049          | 0.000     |
| 7     | $Y=-0.261+0.001*X^{'56}$    | 0.083          | 0.000     |
| 10    | $Y=7.953-0.021*X^{''63}$    | 0.052          | 0.000     |

4. Discussion

4.1. Variation of Beta Diversity of Different Types of Grassland Plants in Inner Mongolia

The annual variation of plant diversity in different types of grassland was significantly different, indicating that the variation of species diversity in each research area was also different due to different community types. There are differences in plant biological characteristics and responses to climatic factors such as water and heat at different growth and development stages. Therefore, the spectral diversity of the same vegetation cover varies with the phenological cycle characteristic of each plant. In this study, the annual variation trend of plant diversity in Xilingol and Tumuji is basically consistent: April > October > July. In Anxi: October > July > April. In West Ordos, the diversity in April and October was close, and slightly higher than in July. Preliminary results show that in typical grasslands, meadow grasslands, grassland desertification and desert grasslands, some non-dominant species are restricted by environmental factor such as temperature and precipitation, have poor ecological adaptability and are sensitive to monthly scale climate change [20-21], thus affecting the diversity of grassland plants. Studies have shown that annuals, biennial and mesophytes in typical grasslands are relatively sensitive to air temperature and surface temperature changes [20].

In desert areas, imbalanced precipitation also causes randomness in plant growth and development. It was found that the decline in species diversity in the desert steppe in October revealed the dominance of cold-resistant species [22]. In addition, the response of plant phenology to climate change will also affect grassland plant diversity. It was found that the typical grassland and meadow
grassland in Inner Mongolia had the largest tendency of plants to return to green earlier and to yellow and withered later, extending growing season. In desert steppe, however, the growing season extension trend is less pronounced [23].

4.2. Driving Factors of Beta Diversity of Different Types of Grassland Plants in Inner Mongolia

The climatic driving factors for the change of plant diversity in different types of grasslands are different. Interestingly, climate factors on the monthly scale have a greater impact on the diversity of grassland plants than on the annual scale. Among the 7 climate variables introduced, precipitation variables (including annual precipitation and seasonal precipitation) are not introduced in the four nature reserves. Temperature variables are the main drivers of plant diversity in each month.

The results showed that in Anxi, for nearly 35 years, MTmin in July and October are significantly negatively correlated with plant diversity. As MTmin in July and October increases, plant diversity decreases gradually (figure 2). Marcilio-Silva et al. [24] also stressed the importance of temperature to woody plant diversity in the Atlantic forest of Brazil, and found that the diversity is negatively correlated with the lowest temperature in the coldest month. The plant diversity in West Ordos is mainly affected by the monthly maximum temperature. Plant diversity in October is negatively correlated with the MTmax in January and March. In the context of global warming, plant diversity will gradually decrease as the monthly maximum temperature increases (figure 3).

Figure 2. Monthly minimum temperature (MTmin) change in Anxi from 1982 to 2017. The dotted lines represent the temperature trend.

Figure 3. Monthly maximum temperature (MTmax) change in West Ordos from 1982 to 2017. The dotted lines represent the temperature trend.
In Xilingol and Tumuji, plant diversity in July was significantly lower than that in April and October. In Xilingol, plant diversity in July is affected by the ATmax of the present year. The higher the annual temperature, the lower the plant diversity. However, plant diversity in July in Tumuji is affected by the MTmax in April. The higher the temperature, the lower the plant diversity (figure 4). This is in line with the trend of biodiversity decline caused by climate warming.

![Figure 4](image)

**Figure 4.** Annual maximum temperature change in Xilingol and monthly maximum temperature in April change in Tumuji from 1982-2017. The dotted lines represent the temperature trend.

5. Conclusion

The variation trend of plant beta diversity in the different types of grasslands in Inner Mongolia is different. Plant diversity was highest in Anxi in October, followed by July and April. The variation trend of plant diversity in West Ordos, Xilingol and Tumuji is consistent, reaching the highest in April, followed by October and July. Temperature is the key driving force for the plant beta diversity in Inner Mongolia grassland, with negative correlation. Grassland plant diversity is not only affected by climatic factors, but also by many factors such as topography, soil and spatial heterogeneity.

This study gives priority to the impact of climate on the diversity of grassland plants. The soil physical and chemical properties and soil types of the same research site are generally stable, so their influence is relatively small. Moreover, the study areas are all located in the nature reserve, which protect the fragile ecosystem of the grassland and its endangered animals and plants, therefore, overgrazing and human interference are prohibited.

The study complements the effect of climate on plant diversity under vegetation conditions from desert to meadow steppe. Precipitation has little effect on the variation of grassland plant diversity, while temperature is the most important climatic factor. Climate factors related to temperature had negative effects on plant diversity in each research area. As the temperature increases, the diversity gradually decreases. In addition, the monthly temperature changes were statistically significant. Most previous studies started from the annual climate scale to explore the response of plant diversity to climate change. However, due to the uneven spatial and temporal distribution of water-heat conditions, the relationship between the diversity of grassland plants and climate change under different growing conditions can be more accurately understood by using monthly climate variables [25-26].

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