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Stability of alpine meadow ecosystem on the Qinghai-Tibetan Plateau

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Abstract The meadow ecosystem on the Qinghai-Tibetan Plateau is considered to be sensitive to climate change. An understanding of the alpine meadow ecosystem is therefore important for predicting the response of ecosystems to climate change. In this study, we use the coefficients of variation (*Cv*) and stability (*E*) obtained from the Haibei Alpine Meadow Ecosystem Research Station to characterize the ecosystem stability. The results suggest that the net primary production of the alpine meadow ecosystem was more stable (Cv = 13.18%) than annual precipitation (Cv = 16.55%) and annual mean air temperature (Cv = 28.82%). The net primary production was insensitive to either the precipitation (E = 0.0782) or air temperature (E = 0.1113). In summary, the alpine meadow ecosystem on the Qinghai-Tibetan Plateau is much stable. Comparison of alpine meadow ecosystem stability with other five natural grassland ecosystems in Israel and southern African indicates that the alpine meadow ecosystem on the Qinghai-Tibetan Plateau is the most stable ecosystem. The alpine meadow ecosystem with relatively simple structure has high stability, which indicates that community stability is not only correlated with biodiversity and community complicity but also with environmental stability. An average oscillation cycles of 3－4 years existed in annual precipitation, annual mean air temperature, net primary production and the population size of consumers at the Haibei natural ecosystem. The high stability of the alpine meadow ecosystem may be resulting also from the adaptation of the ecosystem to the alpine environment.

Keywords: alpine meadow, stability, coefficient of variance, ecosystem diversity, net primary production, precipitation, temperature.

The Qinghai-Tibetan Plateau plays an important role in the atmospheric circulation and regional monsoon climate, which has great influence on the regional and global climate. Thus, the change of the Qinghai-Tibetan Plateau ecosystem is expected to affect the regional or global climate. Many studies[1－3] suggested that the responses of plateau ecosystems to global climate change was very sensitive. Its behavior can serve as an early warning on global change. An understanding of the behavior of the plateau ecosystem is therefore of great significance.

The behavior of ecosystems can be well defined by two distinct properties: stability and resilience[4]. The stability of the ecosystem is the system capacity returning to equilibrium status after the temporarily disturbance according to the definition of Holling[5]. The higher returning speed and the less fluctuation, the more stable it is. The disturbances on ecosystem include not only random event of large probability (such as random climate change), but also those caused by the human activity. In the past years, many studies[6－8] discussed the response of dynamical system to disturbances with mathematical models. However, the ecosystems in randomly disturbed environment is also an evolutional process[9]. In recent years, with the expanding exploitation of natural resource, human activities have being changed many ecosystems from the equilibrium state to a developing state. Therefore, the deterministic concept of resting equilibrium state does not always accord with the real ecosystem. Because of the complexity of ecosystem stability and the shortage of efficient methods, many researches[6,7,10] that use the concept mentioned above have been performed under a series of simplified assumptions. The results can be used to interpret the behavior of simple ecosystems under stable statues, such as neutral stable cycle, stable equilibrium, gravitation zone, stable point and so on.

Connel and Sousa[11] reviewed the studies of ecosystem stability of the past 49 years, but could not find the typical case of single stable equilibrium and multi-stable equilibrium in natural ecosystem. Holling[5] discussed the ecosystem stability using the “equilibrium state”, which is defined by the classical stability of math and physics to some extent. He considered that ecosystem is a nonliner system. Because of the difficulty in the behavior analysis of non-liner system, researchers always assume that the system state is around the equilibrium point using mathematical stability analysis. In fact, the instantaneous state of the ecosystem is not likely to be close to the equilibrium state, i.e. the Holling's definition of ecosystem stability can not reflect ecosystem reality. We therefore define the stability as follows: stability is the capacity of a system to remain in a particular status with variable external conditions. The less fluctuation, the more stable the system is. The stability indicates the ecosystem dynamic property as well as the one side of its self-regulation capacity of an ecosystem. On the other hand, the resilience is often used to describe the self-regulation capacity of ecosystem.

The stability of grassland ecosystem is one of the most important topics in modern ecology[12]. Tilman and his group examined the species diversity and ecosystem functions with many controlled experiments of grassland communities, and concluded that the stability of ecosystems was correlated with not only community components, but also climatic conditions, environment disturbance, nutrient availability and others[13−17]. Bai *et al.*[18], Wang *et al.*[19], Guo[20], and Wu *et al.*[21] analyzed and discussed the correlation between the ecosystem stability and climate factors, species diversity and functional group diversity as well in natural *Leymus chinensis* grassland and *Stipa grandis* grassland in Inner Mongolia. However, little relevant information is available for the alpine meadow on the Qinghai-Tibetan Plateau. In this work, we examined the ecosystem stability and its sensitivity to environment variations in an alpine meadow using the quantitative methods. Because of the influence of the Qinghai-Tibetan Plateau on global climate and the alpine meadow ecosystem is the most extensive grassland ecosystem on the plateau[22,23]. This study may provide significant insight into our understanding of the local climate change and the mechanism of ecosystem stability. The study may also provide basic information for knowing the plateau environment.

1 Methods

1.1 Study site

The study was conducted at the Haibei Alpine Meadow Ecosystem Research Station (37°29′ — 37°45′N, 101°12′—101°23′E; 3200 m asl.), the Chinese Academy of Sciences. The Haibei Station is located on the east side of Lenlongling, the northern branch of the Qilian Mountains, on the northeastern edge of the Qinghai-Tibet Plateau[22]. It has a continental monsoon type climate, with severe long winters and short cool summers. The yearly difference of temperature is low, while the day/night temperature difference is great with strong sun radiation at the Haibei Station[24]. The soil types are characterized by alpine meadow soil and alpine shrub meadow soil. The soil layer with high organic matter content is very thin. The major vegetations are alpine meadow, alpine shrub and alpine swamp meadow, dominated by *Kobresia humilis* meadow, *Potentilla fruticosa* shrub meadow and *K. tibetica* swamp meadow, respectively. Some palatable herbage can be found in the *K. humilis* meadow such as *K. humilis*, *K. pygmaea, Scirpus distigmaticus*, *Elymus nutans, Poa* spp, *Stipa aliena*, *Lagotis brachystachya*, *Leontopodium nanum*, *Ajania tenuifolia*, *Lancea tibetica*, *Saussurea superba*, *Halerpestes tricuspis*, etc.[23].

In this study, the air temperature and precipitation were measured by regular meteorological methods. The above-ground net primary production was measured by the harvest method. The annual variations of precipitation and mean air temperature from 1957 to 2000, and the above-ground net primary production of the *K. humilis* meadow from 1980 to 2000 are shown in Figs. 1 and 2, respectively. Here, the meteorological data before 1980 was estimated with the method of Li *et al.*[24] using the data measured in Haibei Prefecture because the meteorological observation at the Haibei Station began from 1980. The above-ground net primary production was measured at the fixed site of *K. humilis* meadow on the 1st ten days of September[22,23] every year.

1.2 Ecosystem stability

Many ecologists thought that the stability is correlated with ecosystem diversity and complexity and tried to find the quantitative correlation among them. Based on the energy distribution of ecosystem, MacArthur[25] developed an index to determine the ecosystem stability according to the selection of energy path. Mulholland[26] introduced an index relating to stability, diversity and complexity of ecosystem by the method of information theory. Holling[5] suggested that the modeling methods should be constructed to analyze the behavior of ecosystem in the phase space. However, May[6] continued to determine stability of the disturbed ecosystem by the classical mathematical method. Yue and Ma[7] introduced the thermodynamics theory into ecosystem studies to discuss the stability of K type increasing population in the general background. As mentioned above,

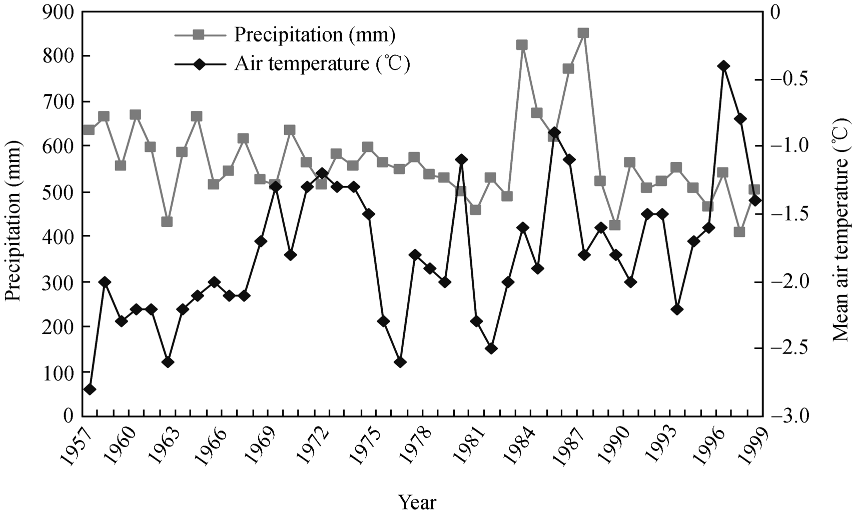

Fig. 1. The annual variation of air temperature and precipitation of Haibei Station from 1957 to 2000.

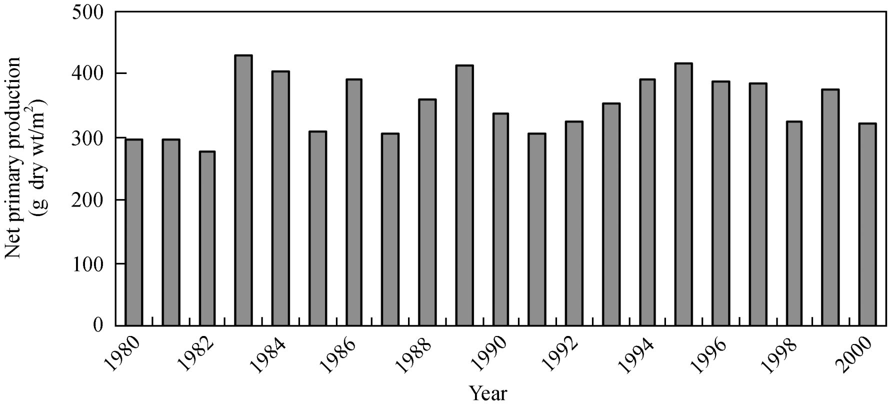

Fig. 2. The annual variation of above-ground net primary production of Haibei alpine meadow from 1980 to 2000.

math models should be constructed to describe ecosystem stability for all methods, so we defined them as model methods. However, this method cannot be used widely in the ecosystem stability study, since the long-term study and data are always necessary, which makes it difficult to construct the math model.

Another method of determining ecosystem stability is the direct analyzing method of using the measured data. Ecosystem stability was described by mathematical statistics with the data measured in natural or experimental ecosystems according to the definition of ecosystem stability. Noy-Meir and Walker[27] discussed the stability of some grassland ecosystems in Israel and South Africa by this method, and analyzed the annual change in the same ecosystem stability.

According to the definition of stability in this paper, the changing degree of the main variables at the different time can be looked upon as the simple measurement of ecosystem stability. The less the variation it is, the more stable it will be, while the less stable usually is accompanied by the greater variation. It is well known that the coefficient of variance is a statistical index describing the changing degree of variable to its relative mean value.

$$Cv = \frac{s}{\overline{y}}, \tag{1}$$

where Cv is the coefficient of variance of variable y; s, the standard deviation, and $\overline{y}$, the mean value of y (temporal sequence y_i, i = 1, 2, ⋯, n). To avoid the influence exerted by the symbol, let

$$Cv = |Cv| = \left|\frac{s}{\overline{y}}\right|, \tag{2}$$

i.e. we can measure the changing degree of variable y with Cv.

The most important biological variables should be chosen as the measuring value of studying ecosystem stability. The changing degree of biological variables is also influenced by the change in non-biological variables. The *Cv* value of biological variable only represents its changing degree within a period, the changing extent of the factors influencing *Cv* was not considered. So it is not enough to judge the ecosystem stability only by the *Cv* value of biological variables[19,20]. We should consider the changing extent of main abiotic variables affecting the biological variable in the measurement of the ecosystem stability.

If x is the main abiotic variable influencing the biological variable (y), then the $\frac{\Delta y}{\Delta x}$ is the changing extent of y when x changes one unit. To avoid the influence of dimension on $\frac{\Delta y}{\Delta x}$, the relative changing values $\left(\frac{\Delta x}{\bar{x}}, \frac{\Delta y}{\bar{y}}\right)$ are introduced in this study, then the $\frac{\Delta y}{\Delta x}$ can be converted into $\left(\frac{\Delta y}{\bar{y}} \Big/ \frac{\Delta x}{\bar{x}}\right)$. Let

$$E = \left|\left(\frac{\Delta y}{\bar{y}}\right) \Big/ \left(\frac{\Delta x}{\bar{x}}\right)\right| = \left|\left(\frac{\Delta y}{\Delta x}\right) \Big/ \left(\frac{\bar{y}}{\bar{x}}\right)\right|, \qquad (3)$$

where E is the elasticity of the system. In fact, E is the sensitivity of y to x under the background of relative mean value. From eq. (3), the greater the elasticity, the less stable the system.

If there is a liner function between variables x and y: $y = a+bx$ (a, b are constant), eq. (3) becomes

$$E = \left|\left(\frac{\Delta y}{\Delta x}\right) \Big/ \left(\frac{\bar{y}}{\bar{x}}\right)\right| = \left|b \Big/ \left(\frac{\bar{y}}{\bar{x}}\right)\right|. \qquad (4)$$

When the E does not change with x or time (t) in a given period, E is constant. The constant E means the measurement of system stability of abiotic factor. Furthermore, it is easy to compare them because the parameters are dimensionless.

If there is no a liner relationship between x and y, i.e. $\frac{\Delta y}{\Delta x}$ or $\frac{dy}{dx}$ changes with the variation of t and x, then the liner regressive coefficient of y to x should be taken as the mean value of $\frac{\Delta y}{\Delta x}$ during the observed period in this study:

$$B = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}. \qquad (5)$$

Because eq. (5) is an insignificant liner function between y and x here, the precision of E from eq. (4) will decrease.

2 Results

The stability of alpine meadow ecosystem was evaluated using the above data and models. The net primary production (NPP) is the most important variable for the ecosystem because it is the food source for all living beings. We regarded it as the critical variable of ecosystem stability in this study. Precipitation and air temperature are the two most important abiotic factors in alpine meadow ecosystem[23]. The annual variation in precipitation and its seasonal distribution are one the key factors influencing the annual variation of NPP. And, air temperature is the main factor limiting the NPP in alpine meadow ecosystem[24]; it affects NPP through plant growing days and light utilization efficiency. Therefore, the annual precipitation and mean air temperature were chosen as the major abiotic factors to assess the annual variation of NPP in this study.

The *Cv* of the annual NPP, the annual precipitation and mean air temperature were obtained from eq. (2). As NPP was available only from 1980 to 2000, and precipitation and temperature had been observed for more than 40 years, the data of precipitation and temperature were also examined only for the same period from 1980 to 2000 to obtain the elasticity (E). Firstly, we calculated the regression coefficients B of the NPP to the annual precipitation and mean air temperature by eq. (5), performed the significant test, and then calculated E by eq. (4). The results are shown in Table 1.

The coefficients of variation of the annual precipitation and mean air temperature are 16.55% and 28.82% for 44 years, respectively. We consider that variation of the annual precipitation and mean air temperature is stable for the ecosystem. The coefficient of variance of the NPP is 13.18%, which indicates that NPP is more stable than those of precipitation and temperature. The variation of the NPP is insensitive to that of annual mean air temperature (E = 0.1113) while it is more insensitive to that of the annual precipitation (E = 0.0782). When the elasticity is considered as the variation of NPP in measured period, the elasticity of the NPP to the

Table 1 The stability of alpine meadow

Observing interval	Variable	Cv (%)[a)]	B[b)]	E[c)]
1957—2000	annual precipitation	16.55	0.05 (n.s.)[d)]	0.0782
1957—2000	annual air temperature	28.82	–24.45 (n.s.)[d)]	0.1113
1980—2000	net primary production	13.18		

a) *Cv*, The absolute value of coefficient of variance; b) the slope coefficient for linear regression of the NPP on the precipitation and mean air temperature; c) the elasticity of the NPP to the precipitation and mean air temperature; d) n.s., not significant.

precipitation (E = 0.0782) indicates that the fluctuating extent of the NPP to its mean value is 0.0782 when the relative fluctuating extent of precipitation is 1. From this viewpoint, the variation of NPP is still very slender after the precipitation is involved in its measurement. Similarly, the elasticity of the NPP to annual mean air temperature (E = 0.1113) indicates that the stability of the alpine meadow ecosystem is great after the air temperature is involved in its measurement, too. The fluctuating extent of the main abiotic factors (the annual precipitation and temperature) of the alpine meadow ecosystem is low and the main variable of biological community (the NPP) is insensitive to these fluctuations. All the results indicated that the stability of natural alpine meadow ecosystem is great. In this study, the mean $\frac{\Delta y}{\Delta x}$ was replaced by regressive coefficient B during the observed period. The replacement will result in an error because the liner correlation of the NPP to the precipitation and air temperature is not significant. So, the sensitivity or elasticity E is not very exact. We can regard E as a relative simple evaluation to ecosystem stability.

3 Discussion

To evaluate the ecosystem stability, we compared the alpine meadow with 5 other natural grassland ecosystems reported by Noy-Meir and Walker[27] in Israel and South Africa (Table 2). Among these ecosystems Midga is a semi-arid grassland with 250 mm annual precipitation in Israel, Kare-Deshe is an inland mixed grassland with 600 mm annual precipitation in Israel. Matopos is a sub-wet savanna with 605 mm annual precipitation in South Africa, Tuli is a semi-arid savanna with 425 mm annual precipitation in South Africa, and Towoomba is a sub-wet savanna with 614 mm annual precipitation in South Africa. The fluctuating extent of the annual precipitation (Cv = 16.55%) of Haibei alpine meadow ecosystem is the smallest among all the sites, i.e. the annual precipitation of Haibei Station is the most stable environmental factor. The fluctuating extent of the NPP (Cv = 13.18%) of Haibei alpine meadow ecosystem is less than that of other grasslands. The Cv of the alpine ecosystem is slightly less than that of Kare-Deshe although the annual precipitation is similar. The stability of NPP in the alpine meadow ecosystem is greater than that of the other 5 grassland ecosystems if Cv value can be used to evaluate the ecosystem stability. The elasticity of the NPP to the precipitation (E = 0.0782) is less than the other 5 grassland ecosystems but close to that of Kare-Deshe. The stability of alpine meadow ecosystem of the NPP is greater than other 5 grassland ecosystems if E value can be used to evaluate the ecosystem stability. It is the natural grassland ecosystem with relative great stability.

Table 2 shows that the semi-arid grasslands (Midga and Tuli) are very sensitive to precipitation because their E is approximately 1. The changing proportions of primary production and precipitation are similar for the lack of precipitation, resulting in the low stability of these grasslands. The stability of Midga and Tuli grassland ecosystem is similar to that of Keerqing sandy vegetation and Xilingguole typical grassland in Inner Mongolia. The fluctuation of precipitation influenced the species composition and primary production significantly[18,28]. The stability of three sub-wet grasslands, Kare-Deshe, Matopos and Towoomba, is high, medium and low, respectively, suggesting that the stability of wetter grassland is not very high. The annual precipitation of Haibei alpine meadow ecosystem is 567.10 mm (Fig. 1). The warm season climate is close to that of sub-wet because more than 80% precipitation falls in this season. And, the cold season climate is relatively arid at Haibei Station[24]. The stability of Haibei alpine meadow ecosystem is higher than that of Kare-Deshe mixed grassland.

The experimental and theoretical researches by MacArthur[25], Mulholland[26] and Tilman *et al.*[15] indicated that an increase in biodiversity can result in an increase in the ecosystem stability, i.e. the more complicated structure an ecosystem has, the more stable the ecosystem will be. Using math model, May[6] suggested

Table 2 Stability comparison of different grassland ecosystems

Sites	Observing interval	Variable	Cv (%)[a)]	B[b)]	E[c)]
Haibei	1957－2000	annual precipitation	16.55	0.05 (n.s.)[d)]	0.0782
	1980－2000	net primary production	13.18		
Midga	1963－1980	annual precipitation	37	8.3	0.96
	1963－1980	net primary production	40		
Kare-Deshe	1969－1977	annual precipitation	24	1.1 (n.s.)[d)]	0.20
	1969－1972	net primary production	14		
Tuli	1964－1977	annual precipitation	47	1.4	0.98
	1964－1977	net primary production	59		
Matopos	1963－1977	annual precipitation	38	0.96	0.46
	1963－1977	net primary production	27		
Towoomba	1949－1979	annual precipitation	27	2.36	0.98
	1949－1979	net primary production	59		

a) *Cv*, The absolute value of coefficient of variance; b) the slope coefficient for linear regression of the NPP on the precipitation and mean air temperature; c) the elasticity of the NPP to the precipitation and mean air temperature; d) n.s., not significant.

that the more complicated an ecosystem is, the less stable it will be to the complicated ecosystem combined randomly by many populations. Lawlor[29] pointed out that a natural biological community is unlikely to combine randomly by different populations because of their restriction and interaction. May's random ecosystem is different from the practice ecosystem, so his conclusion may be unsuitable for practice ecosystem. The correlation between diversity and stability of biological community has not been elucidated as yet[12,30].

The structure of Haibei alpine meadow ecosystem is relatively simple with about 20 dominant species and main companion species. There are about 4 levels of food chain with several dominant consumers per level. It is difficult to find consumers above 3rd level in the alpine meadow[23,31]. However, this ecosystem has higher stability although its food chain and food web is simple, and biodiversity is low. We have not found their quantitative correlation, though ecosystem stability is correlated with its diversity and complexity. Ecosystem stability may be correlated with other factors such as species composition and various environmental disturbances, which has been reported for many alpine meadow ecosystems including Haibei1), Maqu in Gansu[34], the source of Yangze River and Yellow River2). In Haibei alpine meadow, the experiments with fertilizing[32], fencing2), grazing2), simulating greenhouse effect[2,33], rainfall control[32], UV-B increase[1,20], plowing[1,20] and scarification[1,20] suggested that different disturbance influenced the species, diversity pattern and functions of the ecosystem. The productivity and stability of this ecosystem is influenced by the resource conversion and functional compensation of biological components. The vegetation surveys on different alpine meadows suggested that the productivity and stability were influenced not only by species diversity, species density and evenness of different plant functional groups and other species characters but also by environmental factors[34,35]. These studies also indicate that ecosystem stability is a complicated issue that is correlated with the components, ecological function and all disturbance of ecosystem.

A random cycle of 3－4 years is actually present in the annual precipitation and mean air temperature in the alpine meadow ecosystem in recent years. The varying behavior is stable with statistics pattern, though random climate fluctuation of the Haibei alpine meadow ecosystem has the drying and warming trends[24]. Under the climatic conditions, the NPP is randomly fluctuated by 3.60 years per period (major frequency: 0.2778 period per year) which is the same as the fluctuation of annual precipitation and consumer populations[1]. The periodical and random fluctuating behavior of alpine meadow ecosystem implies one highly stable mode analogous to neutrally stable cycles. The behavior track is not very regular due to the randomness. The fluctu-

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ating behavior of the alpine ecosystem may result from the random fluctuation of main climate factors and the evolution of the biological community adapting environment.

Li *et al.*[24] reported the changing pattern of air temperature and precipitation of Haibei Station for 40 years. He found that there is an air temperature rise of 0.16℃ per 10 years while the precipitation is declined by 18.6 mm per 10 years at Haibei Station. From the long-term observation of Haibei Station, it seems that the climate change had no significant influence on the community structure and primary productivity of alpine meadow. The Haibei alpine meadow has no significant degrading trend until today1). However, other alpine meadow ecosystems, which are widely distributed in the source region of the Yangtze River and Yellow River in southern Qinghai2), are found to be heavily degraded and their stability should also be decreasing. Many studies suggested that over-grazing and other anthropogenic factors were the major causes that resulted in the degradation of the alpine meadow ecosystems[23]. Some other studies suggested that the degradation of alpine meadow resulted from temperature elevation and drought2). Therefore, alpine meadow can tolerate disturbance and climatic fluctuation to some extent. However, if the disturbance and climatic change approach some thresholds, the ecosystem would be unstable.

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1) see footnote 1) on p325.

2) see footnote 2) on p325.