Ecohydrological Optimality in Northeast China Transect

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Abstract. Northeast China Transect (NECT) is one of International Geosphere-Biosphere Program (IGBP) terrestrial transects. In this transect area, there is a significant precipitation gradient from east to west, as well as a vegetation transition of forest-grasslands-dessert. In this paper, we use vegetation cover as an index to describe the properties of vegetation distribution and dynamics in NECT. Normalized Difference Vegetation Index (NDVI) is used to derive the actual vegetation cover M, while

10   Eagleson's ecohydrological optimality theory is applied to calculate the optimal canopy cover M^* along NECT. The result indicates that the theoretical M^* fits the actual M well (for forest, $M^* = 0.822$ while $M = 0.826$; for grassland, $M^* = 0.353$ while $M = 0.352$; the correlation coefficient between M and M^* is 0.81). Water balance are also calculated using Eagleson's theory. The result is compared to the field measured data and shows a relative good match, which further demonstrates the reliability of the ecohydrological optimality theory in this area. M^* increases with the decrease of LAI, stem fraction,

15   temperature, and the increase of leaf angle and precipitation amount. The ecohydrological optimality method offers a quantitative way to analyse the impacts of climate change to canopy cover quantitatively, thus providing advices for eco-restoration projects.

Key Words: NECT; canopy cover; optimality; ecohydrology, climate change

1 Introduction

20   Transect study plays an important role in ecohydrological studies (Ni and Wang, 2004), because the change of climate or landscape properties in these areas have great effects on the establishment and development of terrestrial ecosystems. The Global Change and Terrestrial Ecosystems (GCTE) project of International Geosphere-Biosphere Program (IGBP) has chosen fifteen transects along with environmental or land-use gradients, aiming at understanding how these factors influence terrestrial ecosystem and the interaction between biosphere and atmosphere (Koch et al, 1995; Canadell et al, 2002; Austin and Sala,

25   2002). Northeast China Transect (NECT) is one of the IGBP transects. It was established by Zhang in 1993, with precipitation/moisture as the main driving climate factor (Ni and Zhang, 2000; Zhang and Zhou, 2011). Along with the moisture gradient, the vegetation types vary gradually from forests in the east, to the cropland in the middle, and grassland and bare soil in the west.

Vegetation plays an important role in terrestrial ecosystem. It strongly influences the exchange of energy, substances and

30   moisture between land and atmosphere through photosynthesis, respiration and transpiration (Graetz, 1991; Mcpherson, 2007).

At the same time, the vegetation growth condition is largely effected by climate factors, such as precipitation, temperature and greenhouse gases (Füssler and Gassmann, 2000; Lotsch et al, 2003; Liu and Notaro, 2005). Vegetation is considered as the indicator of climate, therefore, the study of vegetation growth and distribution is of great importance to cognize the ecosystem construction and functions.

5   The most common index to describe vegetation performance include Normalized Difference Vegetation Index (NDVI) and vegetation canopy cover. NDVI is a linear combination of remotely-sensed near-infrared reflectance and red reflectance. It is an index reflecting the greenness of vegetation canopy and photosynthetic activity (Dorman et al, 2013; Fontana et al, 2008; Hmimina et al, 2013). Vegetation canopy cover is defined as the fraction of total ground surface covered by vegetation. Semi-empirical relationships between NDVI and canopy cover were used to derive the possible arithmetic expression of canopy

10   cover (Baret et al, 1995; Carlson and Ripley, 1997; Gutman and Ignatov, 1998; Jiang et al, 2006). With the rising attention of the climate change issue, researches about the relationship between vegetation cover and climate factors have been conducted in different regions of the world (Zhou et al, 2001; Schultz and Halpert, 1993; Piao et al, 2011; Park and Sohn, 2010; Li et al, 2002; Wang et al, 2003). Nie et al (2011) used correlation analysis to check the relationship between NDVI and climate factors in NECT area, with regression equations given for different time scales. Other studies suggest both precipitation and

15   temperature have significant effects on the vegetation along NECT (Piao et al, 2006; Duan et al, 2011; Mao et al, 2012; Peng et al, 2012; Yuan et al, 2015).

Although the statistical models have been established to describe the response of vegetation to climate factors, they cannot express the underlying mechanism of the response quantitatively. Vegetation models were developed to detect how vegetation react to climate change based on the biophysical and physiological processes, including plant life cycle, carbon and nitrogen

20   cycles, but too much data were required (Myoung et al, 2011). In practice, people care about not only the response of vegetation to climate change, but also the upper limit of vegetation density in a resource-limited region. Even if the problems mentioned above could be solved, we still cannot get the upper limit of vegetation density. In this study, Eagleson's ecohydrological optimality theory is applied to calculate the optimal canopy cover. Under the framework, a statistical-dynamic model of equilibrium water balance is used to describe the interactions among atmosphere, soil and vegetation (Eagleson 1978a, b, c, d,

25   e, f, g, 1982; Eagleson and Tellers, 1982). Despite the Eagleson's work is regarded as the basis for ecohydrology and of great importance (Hotton et al, 1997; Kerkhoff et al, 2004), limited researches have been conducted using the theory in the practical (Shao et al, 2011; Mo et al, 2015).

The objective of this study is to calculate the optimal canopy cover along NECT and analyse the quantitative relationship between the optimal canopy cover and climate factors, thus offering information to eco-restoration engineering, as well as a

30   new method to explore the quantitative relation between vegetation and climate factors.

2 Study area and data

2.1 Study area

The Northeast China Transect (NECT) is one of the mid-latitude IGBP terrestrial transects. It ranges from 42 ° to 46 °N and from 106 ° to 134 °E. The major global change gradient is precipitation, which decreases gradually from the eastern

5   mountainous region to the middle farmland and western steppes (Fig. 1). In the east, there is abundant rainfall over 600mm/year; however, in the west, the precipitation is under 200mm, which means the western steppes are under severe drought. The land cover types show a significant zonal distribution from east to west: temperate evergreen conifer-deciduous broad leaf mixed forests, deciduous broad leaf forests and woodlands in the east, shrublands and crop in the middle, grassland and bare soil in the west (Fig. 2).

10 ### 2.2 Remote sensing data

Monthly NDVI (MOD13A3), yearly Land Cover Types (MCD12Q1) and 8-day LAI (MCD15A2) datasets derived from Moderate-resolution Imaging Spectroradiometer (MODIS) aboard the Aqua and Terra satellite are applied. These satellite data are available on NASA website (http://reverb.echo.nasa.gov/).

The spatial resolution of NDVI, Land Cover Types and LAI dataset are 1km, 500m and 1km, respectively. Considering the

15 wide longitudinal and latitudinal extends of NECT, these remote-sensed data are resampled to be 10km x 10km. The MODIS Reprojection Tool (MRT) is applied to define coordinate systems for the images. MRT was also used to generate NDVI and LAI data for growing season of each year.

Canopy cover is defined as the fraction of total ground surface covered by vegetation (Eagleson, 2002). Scientists used a linear transformation of remote-sensed NDVI to calculate actual canopy cover (M) (Gutman and Ignatov, 1998; Jiang et al, 2006):

20 $$M = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \qquad (1)$$

in which $NDVI_{min}$ is the NDVI of barren soil, and $NDVI_{max}$ is the NDVI of forests. Though the land cover types did not change much from 2000—2013, it was hard to define the real barren soil or the forest areas, as the satellite data is not accurate in some respects. We considered the area sensed as barren soil for every year is the barren soil area, and the $NDVI_{min}$ is the spatial average of barren area NDVI. The same procedure was adapted to obtain $NDVI_{max}$ value. In this study, $NDVI_{min}$ and $NDVI_{max}$

25 are 0.05 and 0.63 respectively, which means the canopy cover can be regarded as 1 if the NDVI is above 0.63 and as 0 if the NDVI is below 0.05.

2.3 Meteorological data

The meteorological data used in this study from 2000—2013 is provided by China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). The spatial distribution of the 45 meteorological stations is shown in Fig. 1. Atmospheric

30 pressure (P_a), wind speed (W_{nd}), average temperature (T_a), sunshine hours (S_h), relative humidity (R_h), minimum temperature (T_n), and maximum temperature (T_m) are required to calculate the potential evapotranspiration by Penman Monteith Equation

(Ni and Zhang, 2000; Eagleson, 2002). Kriging interpolation method is applied to generate the spatial distribution of the meteorological factors and potential evapotranspiration. The spatial resolution is 10 km to be consistent with that of remote sensing data.

3 Methodology

5 Eagleson proposed three hypotheses in his optimality theory. He considered the climate and vegetation can influence and adapt to each other on different time scales. It says that when climate and soil changes in short time period, the canopy cover will adjust its value to maximize the soil moisture. As the time scales get longer, the species whose potential transpiration efficiency make the soil moisture highest will be selected through natural selection. Finally, the soil properties will be altered to ensure the species get their maximum canopy cover (Eagleson, 2002; Hatton et al, 1997). These hypotheses mentioned two important

10 canopy state variables, i.e., the canopy cover (M) and canopy conductance (k_v). Canopy conductance is defined to reflect the effective transpiring leaf surface area per unit vegetated land surface. It is the ratio of canopy transpiration rate Ev and bare soil potential evaporation rate Eps (Eagleson, 1978d; Eagleson, 2002):

$$k_v = \frac{E_v}{E_{ps}} \qquad (2)$$

When the stomates fully open, the canopy transpiration rate will reach its maximum value – potential canopy transpiration E_{pv},

15 thus making k_v to be its maximum value as well, which is called the potential canopy conductance k_v^*:

$$k_v^* = \frac{E_{pv}}{E_{ps}} = \frac{1 + \Delta/\gamma_0}{1 + \Delta/\gamma_0 + (1-M)\left(\frac{r_c}{r_a}\right)_{M \to 0} + M\left(\frac{r_c}{r_a}\right)_{M=1}} \qquad (3)$$

where

    Δ the slope of the saturation vapor pressure vs. temperature curve;

    γ_o the surface psychrometric constant;

20   r_c the lumped resistance to flow through the canopy which does not vary with water supply;

    r_a the lumped atmospheric resistance over the 2m above the canopy top.

$(r_c/r_a)_{M \to 0}$ is the resistance ratio for open canopies, which is related to the exponent relating shear stress on foliage to horizontal wind velocity and horizontal leaf area index. $(r_c/r_a)_{M=1}$ is the resistance ratio for closed ($M=1$) canopies whose mainly influence factor is the ratio of stem height h_s and tree height h. According to the Eq. (3) and explanations above, the

25 resistance ratio can be fixed once the vegetation specie is given. The potential canopy conductance kv* is inversely proportion to the canopy cover M. The kv*-M curve is called water demand curve.

The relationship between k_v^* and M can be also described by water balance equation. In growing season, the average inflows and outflows of the soil column:

$$P_\tau - m_v E[E_r] - \Delta S = m_v E[R_{sj}] + E[E_{T\tau}] + m_\tau v - m_\tau w \qquad (4)$$

30 The inflows include growing season precipitation P_τ, storm surface retention $m_v E_r$, average carryover (from dormant season to growing season) soil moisture storage ΔS. The outflows consist of storm runoff $m_v R_{sj}$, evapotranspiration $E_{T\tau}$, percolation to

water table $m_\tau v$ and capillary rise from water table to surface year round $m_\tau w$. The m_v is the number of independent storm times, and m_τ is the growing season length. $E[\ ]$ means the expected value of $[\ ]$.

Assumptions are made to describe each item (Eagleson 1978a, b, c, d, e, f, g). Thus, the water balance of growing season can be expressed as:

$$Mk_v^* = \frac{V_e}{m_{tb}E_{ps}} \tag{5}$$

where

$$V_e = m_h - m_h e^{-G-2\sigma^{3/2}} - \overline{h_0} + \frac{\Delta S}{m_v} - \frac{m_\tau K(1)}{m_v} s_0^c \tag{6}$$

The details of Eq. (6) are addressed in the appendix at the end of this paper.

Equation (5) describes water supply in naturally selected canopy moisture state, while Eq. (3) describes water demand of fixed vegetation species. By drawing these two lines in a figure (Fig. 3), one can notice that the water demand grows with the increase of M, but as water is limited, water supply decreases under M enhancement. The intersection point of these two lines is the theoretical optimal vegetation cover and potential canopy conductance in the vegetation state-space. This method is applied in each grid (10km x 10km) of NECT area, and the input values are listed in Table 1.

4 Results and discussion

4.1 Canopy cover of NECT

The observed canopy cover M shows a significant gradient ranging from 1 in the east forests to 0 in the west desert (Fig. 4). The dark blue area is mainly the forests of Changbai Mountains, where the average canopy cover reaches up to 0.83. The light blue area is the Songnen Plain. Songnen Plain is one of the most famous commodity grain bases, rich in corn, sorghum, soybean, wheat and paddies (Zhou and Wang, 2003), with the average canopy cover of 0.55. Farther westward, there is Horqin Sandy Land, in which most of the vegetation is grass. Then there is a narrow northeast-southwest-oriented band with relatively higher value (blue color) at around 120°E, which is mainly caused by the elevation. The band is the location of Greater Khingan Mountains. The east slope of the Greater Khingan Range is very steep, thus the maritime monsoon can bring a lot of rainfall, causing the existence of forest ecosystem. However, most of the vegetation on the west slope is grass, mainly because of the gentle gradient and dry climate (Guo and Zhang, 2013). The grassland is Inner Mongolia steppe.

The Ecohydrological optimality theory is applied in this study to simulate theoretic optimal canopy cover (M^*) of NECT. As shown in Fig. 5, the modeled canopy cover has the same trend with the actual M but transits more smoothly, which is mainly caused by the interpolation of meteorological data. The blank grids in the simulation result are due to the missing data of LAI. There are three regions where the differences between M and M^* is relatively large. The corresponding areas are highlighted in the figure of spatial distribution of ΔM, defined as M^* minus M (Fig. 6). Region 1 is Yanbian Korean Autonomous Prefecture. The simulation result is relatively small mainly because of human activity. The Natural Forest Protection Project (NFPP) has been conducted in Northeastern China since 1998, aiming at protecting the natural forest resources (Wei et al., 2014). Yanbian

forest acreage has increased by 800 km^2 during the first stage of NFPP. The dark red area is Hunchun City. Hunchun is a representative nature reserve, and the forest acreage has increased by 9,009 ha during 1999 to 2012 (Li, 2014). Region 2 is the southern Xilin Gol Grassland. In the past decades, Xilin Gol Grassland is extremely dry and had been suffering from severe degradation (Tong et al, 2002). The Beijing-Tianjin Sand Source Control Project is undertaken to improve the vegetation

5 coverage of degraded grassland. Over 66,000 water source projects and 47,000 water saving irrigation projects increased the water supply of this area, thus contributing to the increase of vegetation activities (Yu et al, 2010).The irrigation part is not considered in the Eagleson's water balance system, which leads to the deviation of the modeled results. In the crop region (the blue frame in Fig. 6), some M^* are higher than M while some are lower. This is because of the close relationship between canopy coverage and crop growth stage. The growth process of various crops are different, and the timing of plantation and

10 harvesting are mainly effected by human intervention rather than natural processes (Liu et al, 2013; Kim and Wang, 2005). Meanwhile, the water supply for the crop is not only from natural hydrological cycle but also from agricultural irrigation, which is not considered in the theory.

The correlation coefficient R between M and M^* is 0.81, which indicates the Ecohydrological Optimality theory is applied well in NECT during long-term period. Previous researches suggest there are lagged relationship between NDVI and climate

15 factors, and the time lags are different at different region scales or different biomes (Braswell et al., 1997; Piao et al., 2003; Li et al., 2011; Hu et al., 2011; Bao et al., 2015). Fig. 7 shows a two-year-lag between M^* and M during 2002-2012. This can be explained by the vegetation adaptation strategy to climate changes. Eagleson's Theory describes how vegetation adapt to climate change in a relatively long term (Eagleson, 2002). Once climate changes, it takes years for vegetation to reach its optimum canopy cover.

20 **4.2 Water balance components**

As NECT area is spanning a wide range from west to east, and the vegetation and climate vary significantly, the NECT area is divided into three parts according to land cover types: forests, cropland and grassland (Ni and Zhang, 2000). The proportions of the water balance components are calculated for each part, as shown in Table 2. According to the researches conducted before, in grassland area, the interception was 20.86% and 7.88% for shrub and grass respectively (Peng et al, 2014), and the

25 runoff of Xilin Gol grassland occupies around 0.046%~1.8% (Wang, 2008; Miao, 2008). In forest area, the dominant tree species are Pinus koraiensis (Pk), Quercus mongolica (Qm), Populus davidiana (Pd) and B. platyphylla (Bp) (Chen, 2001; Zhang and Zhou, 2009). The interception consists 19.61% for Pk and 14.97% for Bp in Great Greater Khingan Mountains, and 10.20% for Pk in Changbai Mountains (Cai et al, 2006; Wang et al, 2006). The runoff coefficient of Suifen River and Secondary Songhua River are around 20%~30%, both of which are located in forest area (Huang, 1999; Song, 2010). The

30 simulated interception and runoff for both grassland and forest area are within the observed range, which demonstrates the reasonability of this theory. The negative value of ΔS in forest area means a recharge of soil moisture. As the temperature in the non-growing season is low, most of the precipitation is snow rather than rain, so the water is frozen in the soil and melts

in the next spring (Fan et al, 2006; Yang et al, 2006). Therefore, most of the water is stored in the dormant season for the vegetation grow in the next growing season.

The rationality of the calculated proportions of water balance components for each part demonstrates the applicability of the optimality theory. By adapting this method, it is much easier to figure out the allocation of precipitation if the vegetation and

5 soil conditions are known.

4.3 Sensitivity of $M*$ to vegetation properties

LAI, β and h_s/h control the physical and biological processes of plant canopies, such as interception and evaporation (Chen and Black, 1992; Asner, 1998; Huete et al. 2002). β and LAI are the dominant parameters for the interception calculation, thus leading to the variance of water supply for vegetation growth. β and h_s/h affect the plant evaporation through affecting the

10 resistance ratio, which influences the water demand curve (Eagleson, 2002). The thresholds of the three parameters are from the experiments conducted before (Du, 2004; Wang et al, 2008; Rauner, 1976; Eagleson, 2002). Fig. 8 shows the different reactions of optimal canopy cover to vegetation species change between grassland and forest area. $M*$ increases with the increase of leaf angle and decrease of stem fraction and LAI. Mo (2015) studied the relationship between vegetation properties and optimal canopy cover in Horqin Sands, China, and got the same conclusion. In grassland area, the water demand curve is

15 more sensitive to the variation of h_s/h compared to β. $M*$ decreases by 0.037 as h_s/h increases 0.10. The water supply curve changes a lot with the change of LAI, but slightly with β or h_s/h. In forest area, $M*$ is less sensitive to h_s/h than β or LAI. Because the average stem fraction of trees (0.4~0.5) is usually larger than grasslands or shrub (0.0~0.1), the water demand curve is much gentler (Eagleson, 2002), and changes little with h_s/h. The forest interception consists 14.24% of precipitation during growing season, which is larger than that of grassland. $M*$ increases by 0.108 and 0.094 with the 0.56 decrease of β

20 and 2.45 of LAI, respectively.

The sensitivity of $M*$ to vegetation properties can be used to offer advices about specie choice and plant density to eco-restoration projects. If the purpose is to increase canopy cover, different strategies should be conducted in different area. For grassland area, shrubby or herbaceous plants with low h_s/h value are more welcome. Nevertheless, in forest area, as h_s/h does not affect canopy cover that much, more considerations should be taken into choosing the species with relatively lower β and

25 LAI values. However, vegetation with a larger canopy cover always requires more water to maintain functions (Woodward and Mckee, 1991; Zhang and Zhou, 2011). If the plant species are determined, the optimum canopy cover can be calculated, and the upper limit for plant density can be provided.

4.4 Sensitivity of $M*$ to climate factors

Studies of relationship between climate factors and vegetation growth condition reveal that precipitation and temperature are

30 the two dominant factors that affect $M*$ (Ichii et al, 2002; Liu et al, 2015). Under this framework, the variation of precipitation (P_τ) affects the availability of water, thus changing water supply curve; temperature (t_a) affects not only water supply but also water demand, through changing resistance ratio and evaporation (Fig. 9). In grassland area, $M*$ exhibits a positive relationship

with precipitation but a negative relationship with temperature (Fig. 9(a)(b)), of which is consistent with studies conducted before (He et al, 2015; Peng et al, 2012). This can be explained by the limited water supply in arid and semi-arid regions, and that the increase of temperature enhances transpiration and evaporation intensity (Duan et al, 2011; Mao et al, 2012). The variation of grassland M^* during 2000-2013 (Fig. 7(a)) also shows the similar trend of M^* and precipitation, while the trend of temperature is different from that of precipitation in most years. In forest area, M^* increases with the increase of precipitation and decrease of temperature, but the variance of grassland M^* is less than that of forest with the same range of temperature, which indicates the forest plants are more sensitive to temperature than grassland. However, the result is different to previous studies. Most correlation analysis of NDVI with temperature and precipitation shows that in forest area, NDVI increases with the increase of temperature and decrease of precipitation, because temperature is the dominant factor in humid areas, and the light use efficiency increases under elevated temperatures (Peng et al, 2012; Wang et al, 2014; Liu et al, 2011). The difference may be caused by the deficient hypotheses of the theory. Under this framework, the surface runoff is assumed to be Hortonian, but in most humid areas, the runoff is saturation excess. The improper hypothetical runoff mechanism leads to the deviation of runoff in water-sufficient areas, thus causing the deviation of water supply curve.

During the past few years, a lot of studies were carried out to detect the relationship between climate and vegetation. Nie et al. (2012) applied the wavelet regression analyses in NECT, demonstrating that the most suitable time scales for evaluating the impact of climate factors was 160-day for most stations. Zhang and Zhou (2011) conducted correlation analyses to study the relationships between net primary productivity (NPP) and climate factors, suggesting that precipitation played more important role than temperature for unchanged biomes, but when the biomes changed, the rate of NPP change had more close relation to temperature. Despite variance methods were developed by hydrologists to explore the vegetation response to climate, overwhelming majority of them are statistical. To understand the mechanism of climate influence on vegetation, more and more models with vegetation biophysical and physiological processes are developed. Nevertheless, these vegetation models require too many inputs, and some of the data are hard to get (Myoung et al, 2011). Different from the models above, Eagleson's ecohydrological optimality theory can not only explore the mechanism of canopy cover distribution, mainly from water balance perspective, but also easy to conduct. The optimality theory provides a new way to explore the quantitative relation between vegetation and climate factors.

5 Conclusion

In this study, remote-sensed NDVI is used to generate actual canopy cover of NECT, while the ecohydrological optimality method has been applied to calculate the optimal canopy cover. The proportions of water balance components have been explored, as well as the influence of vegetation properties and climate factors to optimal canopy cover. The main conclusions are as follows:

(1) The observed canopy cover M shows a significant decreasing gradient from east forests to west. The modeled canopy cover M^* has the same trend with M but transits more smoothly, which is mainly caused by the interpolation of meteorological data.

The relatively lower M^* in Yanbian Korean Autonomous Prefecture and Xilin Gol Grassland is mainly because of human activity. The correlation coefficient R between M and M^* is 0.81, which indicates the Ecohydrological Optimality theory is applied well in NECT during long-term period. There is a two-year-lag between M^* and M during 2002-2012, due to the long-term adaptation strategy of vegetation to climate change.

5 (2) The proportions of the water balance components are calculated for three parts: forest, cropland and grassland. The simulated results are within the observed range, which demonstrates the reasonability of this theory. By adapting this method, it is much easier to figure out the allocation of precipitation with fixed vegetation and soil conditions.

(3) M^* has the positive relationship with β and negative relationship with h_s/h and LAI. Grassland plants are more sensitive to h_s/h and LAI compared to β, while forest plants are more sensitive to β and LAI than h_s/h. The sensitivity of M^* to vegetation

10 properties can be used to offer advices about specie choice and plant density to eco-restoration projects.

(4) Precipitation and temperature are the two dominant climate factors that affect M^*. M^* increases with the increase of precipitation and decrease of temperature. Eagleson's ecohydrological optimality theory offers an opportunity to explore the quantitative relation between vegetation and climate factors from the mechanism, but the runoff mechanism description in wet region still needs improvement.

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Appendix

Algorithm of optimal canopy cover

Eagleson made several assumptions for each item of Eq. (4). Poisson precipitation model was used to simulate the precipitation

20 process by random storm depth and duration (Eagleson, 1978b). The probability density functions of storm depth and storm duration are incomplete gamma and exponential distribution, respectively. The growing season precipitation can be expressed as:

$$P_\tau = m_v/m_h \tag{A.1}$$

where m_h is the mean storm depth.

25 Surface retention $m_v E_r$ is the water held on the surface during the rainstorm of duration. The total surface retention is proportioned by bare soil and vegetation canopy:

$$E[E_r] = (1 - M)E[E_{rs}] + ME[E_{rv}] \tag{A.2}$$

where E_{rs} and E_{rv} are the surface retention loss of bare soil and vegetation canopy, and can be further expressed as:

$$E[E_r] = (1 + M\eta_0\beta L_t)h_0 = \overline{h_0} \tag{A.3}$$

30 where η_o is the ratio of stomated leaf area to illuminated leaf area, β is the cosine of leaf angle, L_t is the foliage area index, h_o

is the surface retention depth. The interception depth retained on the horizontal projection of leaves is assumed to be 0.10 cm (Eagleson, 1978d).

Average carryover soil moisture storage ΔS is determined by the soil profile and seasonality (Eagleson, 2002):

$$\Delta S = -[P_d - (1-M)E_{psd}m_d - Y_d] \tag{A.4}$$

5 where P_d, E_{psd}, m_d, and Y_d are the precipitation, evaporation, days and runoff in the non-growing season, respectively.

Assume that there is no surface inflow from outside of the region, and the surface runoff is Hortonian (Eagleson, 1978e). When the storm intensity m_i and storm duration m_{tr} are independent random variables, the storm surface runoff $m_v R_{sj}$ is:

$$\mathrm{E}(R_{sj}) = m_h e^{-G-2\sigma^{3/2}} \tag{A.5}$$

where

10 $$G \equiv \omega K(1)\left(\frac{1+s_0^c}{2}\right) \tag{A.6}$$

$$\sigma \equiv \left[\frac{5n_e\lambda_0^2 K(1)\psi(1)(1-s_0)^2\phi_i(d,s_0)}{6\pi\delta m\kappa_0^2}\right] \tag{A.7}$$

where

s_o	space-time average soil moisture in the root zone, dimensionless;
ω	$=1/m_i$;
15 $K(1)$	effective saturated hydraulic conductivity of soil, cm day^{-1};
n_e	effective soil porosity, dimensionless;
λ_0	scale parameter of probability density function of storm depth, cm^{-1};
$\psi(1)$	saturated matrix potential of soil, cm;
ϕ_i	sorption diffusivity, dimensionless;
20 δ	$=1/m_{tr}$, day^{-1};
m	soil pore size distribution index, dimensionless;
κ_o	shape parameter or distribution index of storm depth, dimensionless.

Evapotranspiration consists of bare soil evaporation and vegetal transpiration:

$$\mathrm{E}[E_{T\tau}] = m_v m_{tb} E_{ps\tau}[(1-M)\beta_s + Mk_v^*\beta_v] \tag{A.8}$$

25 where m_{tb} is the mean time between storms, $E_{ps\tau}$ is the potential free water surface potential evaporation during growing season, β_s and β_v are the bare soil evaporation efficiency and canopy transpiration efficiency respectively (Eagleson, 1978d).

The percolation rate is mainly affected by s_o (Eagleson, 1978f):

$$\mathrm{v}(s_0) = K(1)s_0^c \tag{A.9}$$

The capillary rise is considered to be 0 due to the deep water table in NECT.

30 Using Eq. (A.1)~(A.9), Eq. (4) gives the water balance of growing season as:

$$1 - e^{-G-2\sigma^{3/2}} - \frac{\overline{h_0}}{m_h} + \frac{\Delta S}{m_v m_h} = \frac{m_{tb}E_{ps}}{m_h}[(1-M)\beta_s + Mk_v^*\beta_v] + \frac{m_\tau K(1)}{P_\tau}s_0^c \tag{A.10}$$

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Table 1: The terminology, interpretation, units and values of inputs

	Terminology	Interpretation and units	Value
Remote Sensing Data	f_c	Average vegetation cover of growing season	0.00 ~ 1.00
	M_d	Agerage vegetation cover of non-growing season	0.00 ~ 1.00
	l_t	Leaf Area Index (LAI) in growing season, dimensionless	0.00 ~ 4.70
	l_{td}	Leaf Area Index (LAI) in dormant season, dimensionless	0.00 ~ 1.70
	m_t	length of the growing season, days	153
	m_d	length of the non-growing season, days	212
Meteorological Data	E_{pst}	free water surface potential evaporation during growing season, mm/d	3.6 ~ 4.4
	E_{psd}	free water surface potential evaporation during dormant season, mm/d	0.7 ~ 1.0
	P_τ	precipitation in growing season, mm	149.7 ~ 624.3
	P_d	precipitation in dormant season, mm	26.2 ~ 226.3
	t_0	average temperature in growing season, ℃	16.12 ~ 21.24
	m_{tb}	mean time between storms, days	4.65 ~ 6.35
	m_{tr}	mean storm duration, days	0.37 ~ 0.64
Vegetation Data	γ_0	surface psychrometric constant, Pa/K	0.06
	mn	m=0.5, n=2 for the foliage elements of trees	1.00
	η_0	eta0 = stomated leaf area / illuminated leaf area, dimensionless	2.50
	h_0	surface retention depth, mm	1.00
	β	cosine of leaf angle, dimensionless	0.45
	h_s/h	nh = hs/h, hs = stem height, h = tree height, dimensionless	0.00 ~ 0.40
Soil Data	m	soil pore size distribution index, dimensionless	0.50
	ne	effective soil porosity, dimensionless	0.45
	d	diffusivity index of soil, dimensionless	4.30
	ψ	saturated matrix potential of soil, mm	900.0
	k	effective saturated hydraulic conductivity of soil, mm/d	29.4
	s_0	space-time average soil moisture concentration in the root zone, dimensionless	0.30 ~ 0.62

Table 2. Water balance components of different land cover types

		grassland		cropland		forests	
result	M	0.352		0.548		0.826	
	M*	0.353		0.557		0.822	
		mm	/P	mm	/P	mm	/P
	P	253	100.00%	414	100.00%	478	100.00%
Water balance component	I	29	11.61%	39	9.29%	68	14.24%
	R	1	0.19%	119	28.77%	119	24.92%
	ΔS	91	36.29%	14	3.34%	-74	-15.47%
	E	131	51.90%	243	58.60%	365	76.31%

5 **Table 3: The variance of inputs and their corresponding M***

inputs	variation range	Grassland M*	Forest M*
β	0.01~0.57	0.346~0.358	0.755~0.863
LAI	0.10~2.55	0.313~0.357	0.770~0.864
h_s/h	0.00~0.10 (grassland); 0.35~0.45(forest)	0.317~0.354	0.817~0.827
P_t	24.26~26.26 (grassland); 46.83~48.83(forest)	0.330~0.377	0.800~0.844
t_a	18.08~20.08(grassland); 17.09~19.09(forest)	0.333~0.371	0.783~0.841

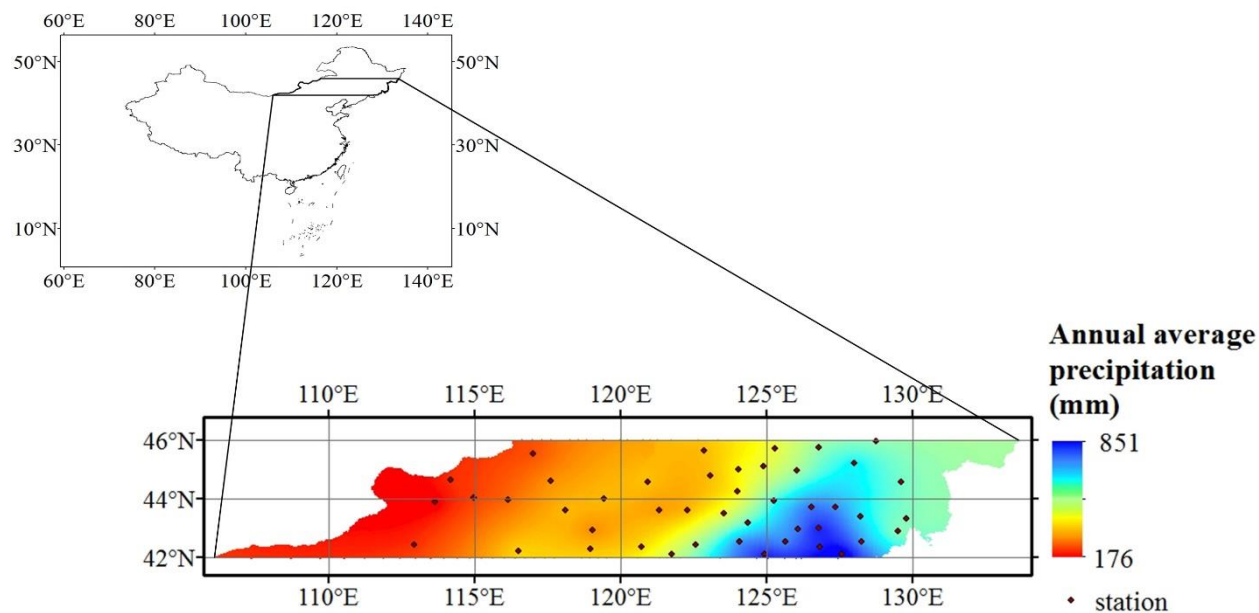



Figure 1: The geographic location, spatial distribution of precipitation and meteorological stations locations of NECT.

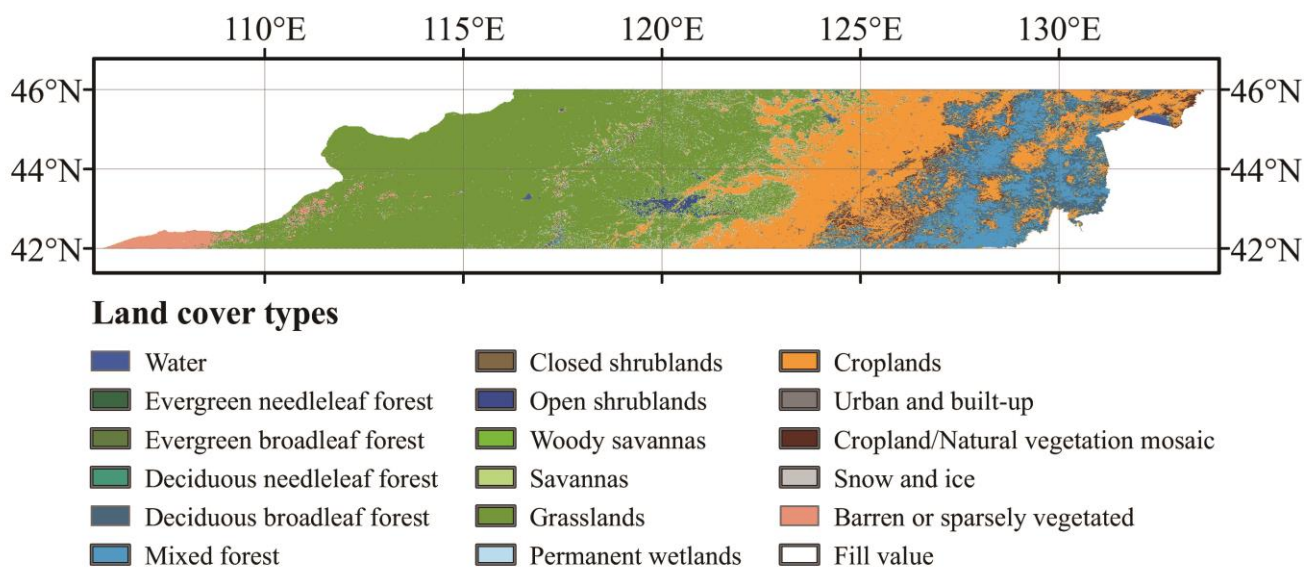



Figure 2: The land cover types of NECT.

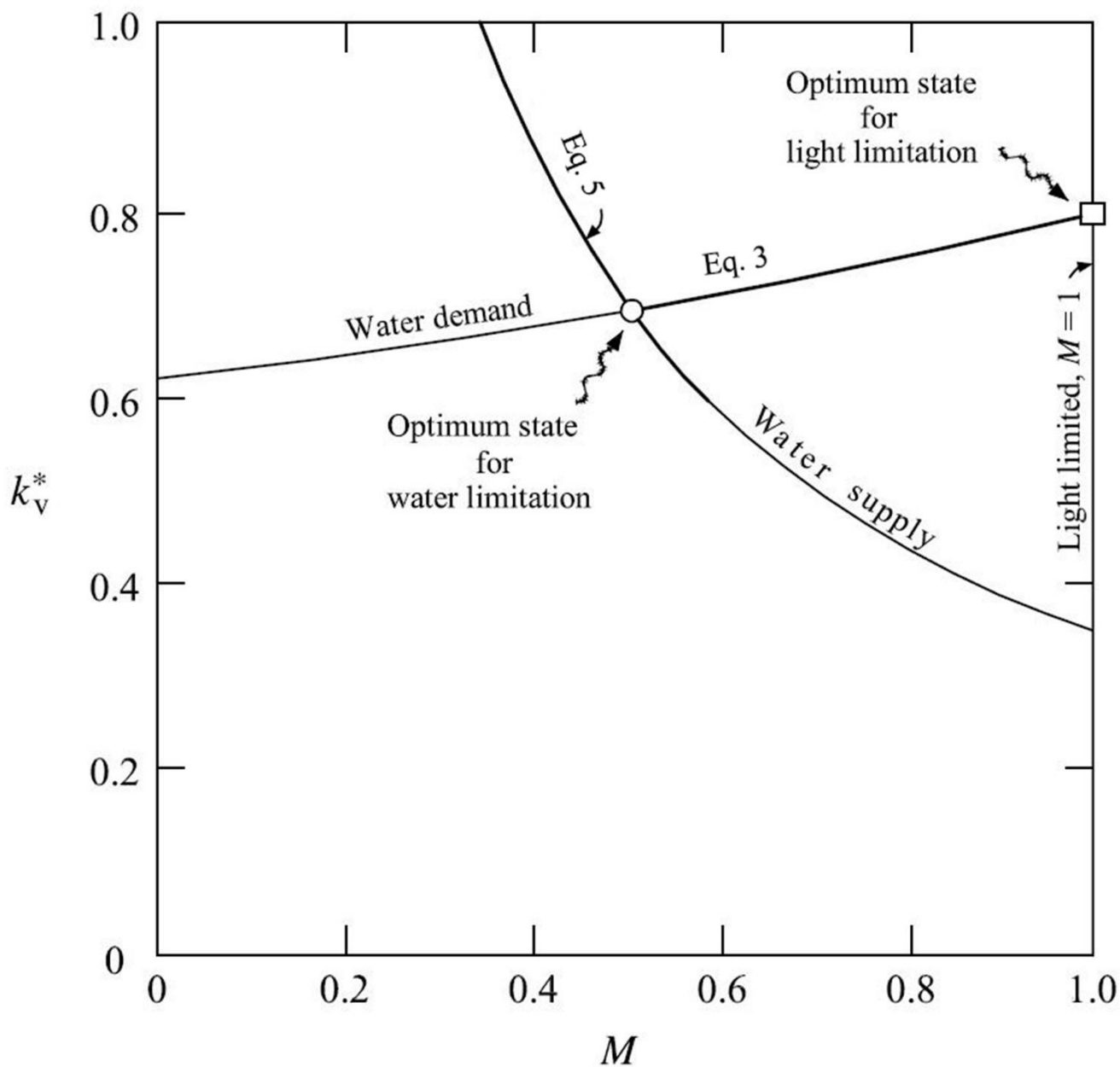



Figure 3: Optimum canopy state (from Eagleson, 2002).

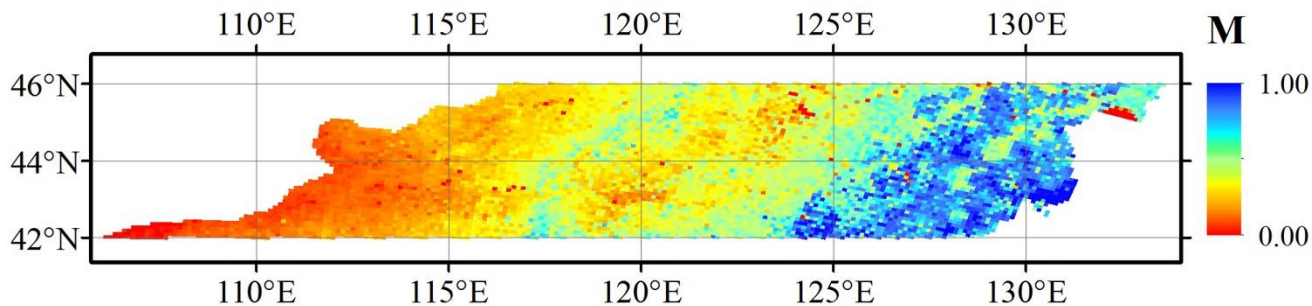



Figure 4: Spatial distribution of mean canopy cover of NECT from MODIS data.

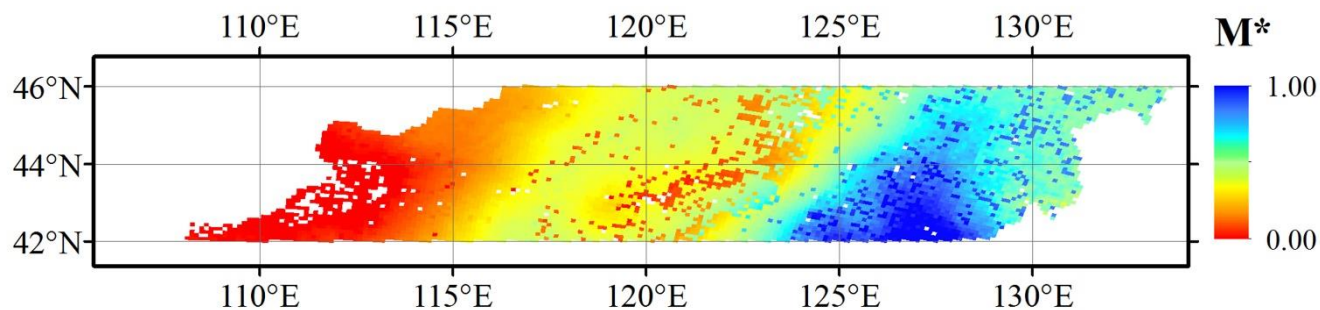
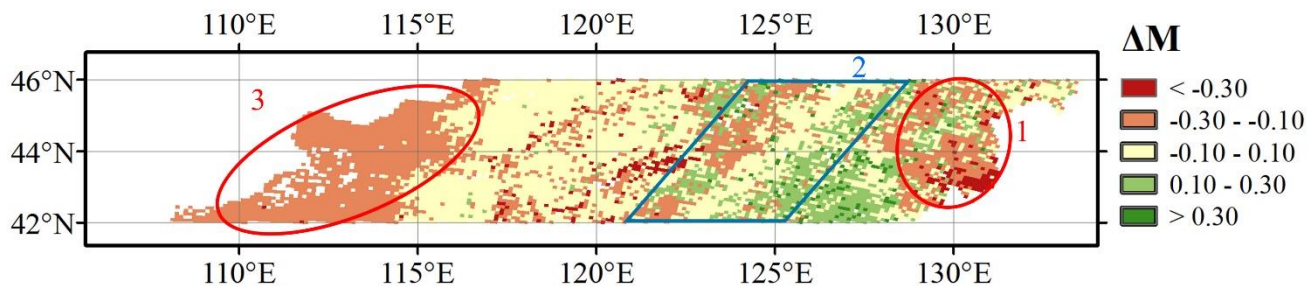



Figure 5: Spatial distribution of optimal canopy cover of NECT.

10   **Figure 6: Spatial distribution of *ΔM*.**

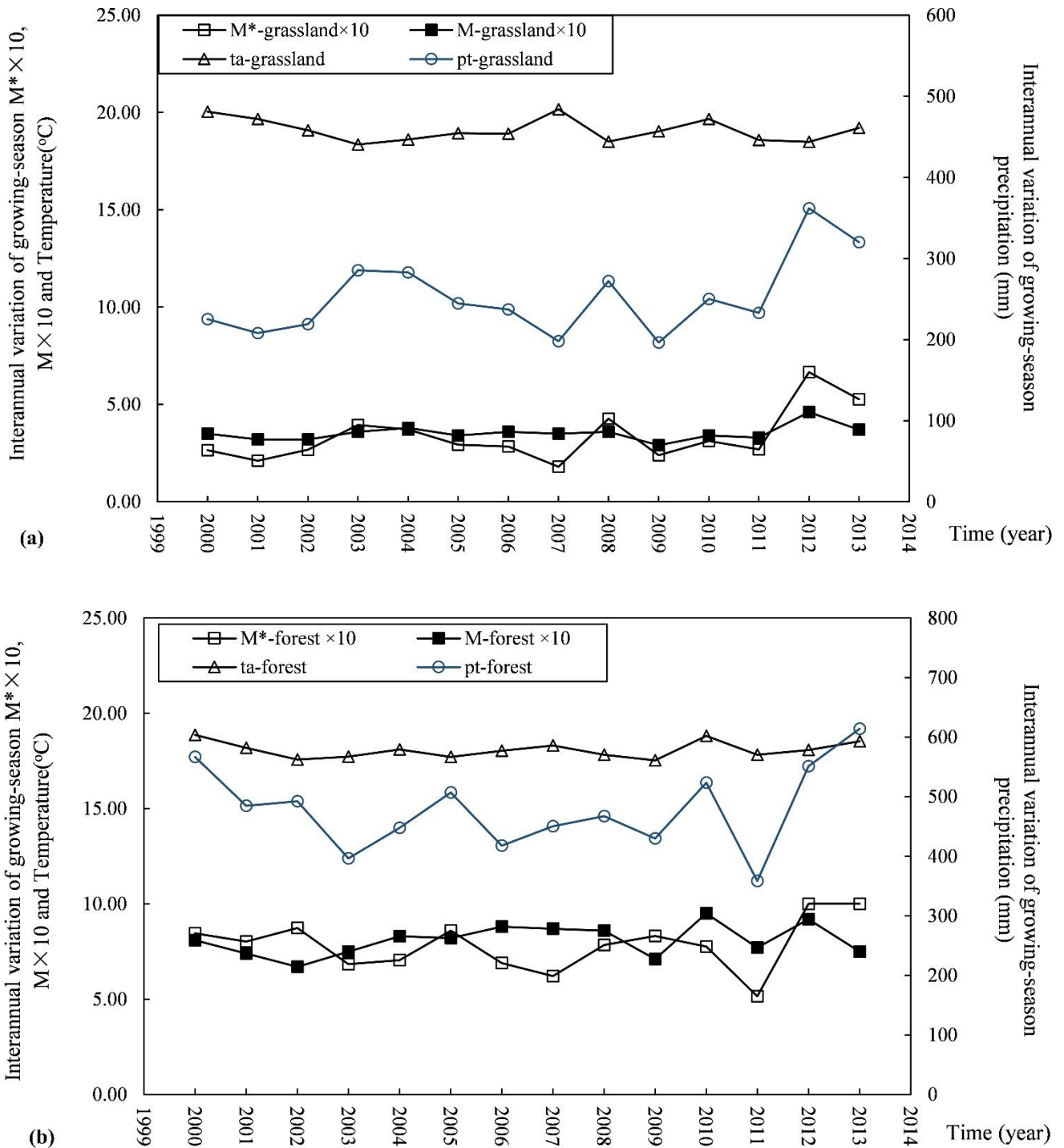



Figure 7: Variation of *M** and *M* during 2002-2012 ((a) grassland; (b) forest).

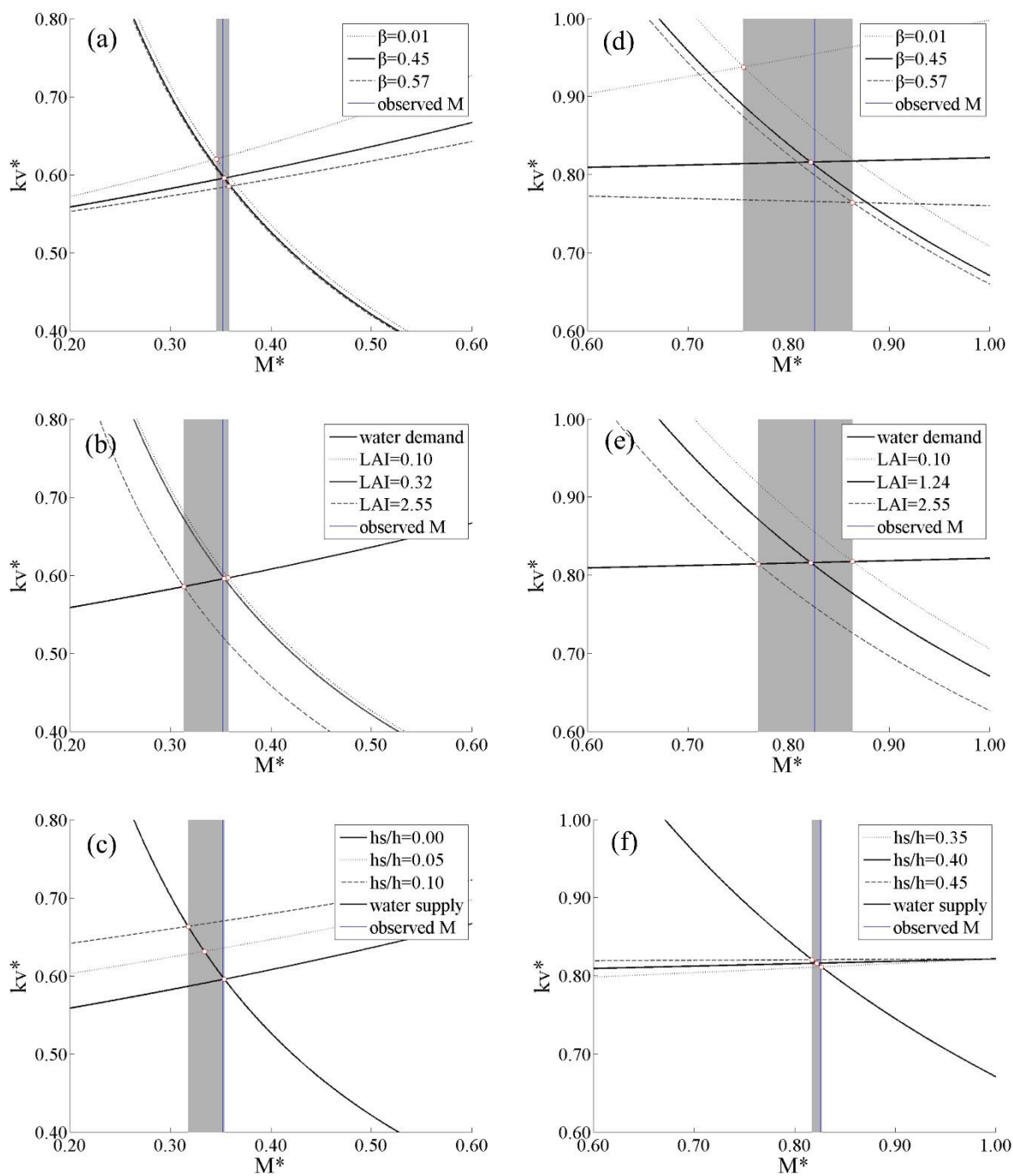



Figure 8: *M* changes with β, LAI and hₛ/h* ((a) ~ (c) grassland; (d) ~ (f) forest).

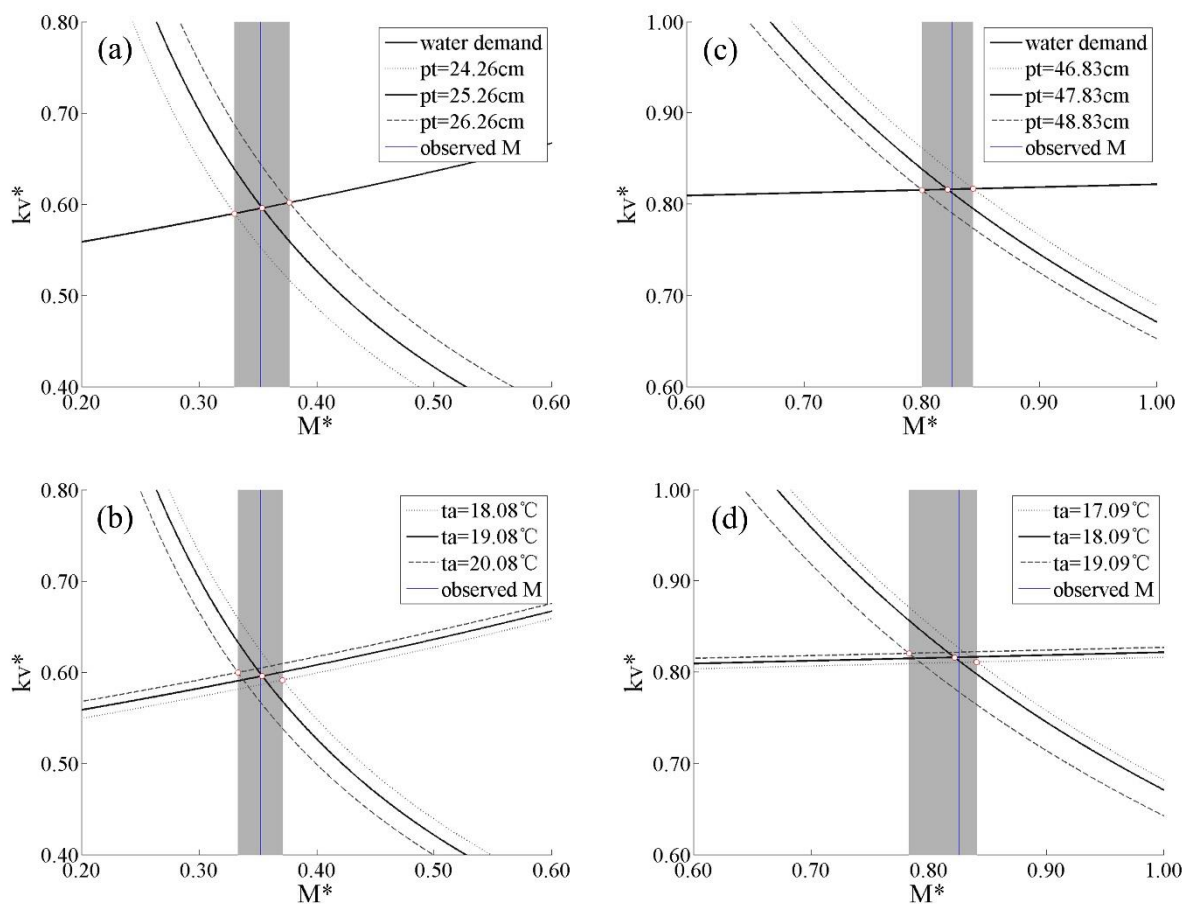



Figure 9: *M* changes with P_τ and t_a ((a) ~ (b) grassland; (c) ~ (d) forest).*