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Journal of Environmental Biology

ISSN: 0254-8704 (Print)
ISSN: 2394-0379 (Online)
CODEN: JEBIDP

Time scale influence on water and soil conservation effect of plot trees in Southern China

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Abstract

The vegetative effect on water and soil conservation is a key matter worldwide for water and soil loss research and management. However, few quantitative studies concerning these effects over multiple time scales have been conducted. In the present study, rainfall characteristics, vegetation fractional coverage (VFC), runoff and soil loss of five tree plots (*Pinus massoniana*) in Hetian Town, Changting County of Fujian Province, a typical water-eroded area in Southern China, resulting from each of the 144 natural erosive rainfall events that occurred from 2007 to 2010 were measured. VFC and water/soil conservation effect (RE/SE) quadratic polynomial regression models were established for various time scales, including each rainfall event, month, season and year. RE/SE was used to represent the runoff depth/soil loss ratio of tree plots to control plot. The models and their respective model determination coefficients (R^2) were analyzed in order to compare the effects of the water and soil conservation measures over different time scales. The results indicated that both RE and SE exhibited linearly descending (DS), descending-ascending (DA), ascending-descending (AD), and linearly ascending (AS) trends as vegetation fractional coverage increased. Four of the effect types exhibited similar trends over individual event and monthly time scale and gradually decreased over larger time scales. The AS trends diminished over seasonal scale, and DA trends were most prominent over the yearly scale. The runoff/soil loss weight coefficients (contributions) of DS and DA trends were higher, with sum ranging from 50% to 80%, and increased as time scales became larger. Most of the mean R^2 values of VFC-RE/SE models exceeded 0.6. As time scale increased, the mean R^2 values of VFC-RE models either descended linearly or initially ascended then descended. Maximum mean R^2 values of AD and DA trends occurred over seasonal scales. The mean R^2 values of VFC-SE models either ascended linearly or initially ascended then decreased as time scale increased. Maximum mean R^2 values of DS, DA, and AD trends also occurred over seasonal scale. Therefore, individual event and monthly time scales were optimal for observing various vegetative effects of water and soil conservation measures, while seasonal time scales were most suitable for evaluating the effect of water and soil conservation measures on tree plots. These results could be used as a reference for vegetative reconstruction research and management in water-eroded areas.

Key words

Runoff, Soil loss, Time scale, Vegetation fractional coverage, Water and soil conservation effect

Publication Info

Paper received:
14 October 2015

Revised received:
11 December 2015

Accepted:
26 December 2015

Introduction

Water and soil loss is a long-standing ecological problem. Numerous studies concerning these issues have been conducted worldwide (Phillips, 2010; Antonello *et al.*, 2015). Water and soil loss is affected by several factors, such as climate, topography, vegetation, soil, lithology and land-use (Kinnell, 2005; Xu *et al.*, 2008). These factors are heterogeneous with spatiotemporal distributions (Fekete *et al.,* 2001; Vrieling *et al.,* 2002; Cantón *et al.,* 2011) and significantly influence observed and predicted runoff and soil erosion amounts (Raclot and Albergel, 2006; Peng and Wang, 2012). Vegetation is a key factor in controlling water and soil loss (Braud *et al.,* 2001; Hany *et al.,* 2013). Thus quantitative studies on the effects of various amount of vegetation on water and soil loss over different spatiotemporal scales could contribute to better understanding of water and soil conservation mechanisms thereby, allowing improvement of vegetative restoration measures in water-eroded areas.

Studies regarding water and soil conservation methods have primarily been concentrated on individual spatial scales such as plot, patch, field, slope, watershed, catchment, regional and global scales (Bloschl, 1996; Keller *et al.,* 2002). At the plot, patch, field and slope scales, researchers have primarily focused on the effects of soil loss resulting from factors such as topography, soil properties, vegetative covering and human activities (Ludwig *et al.,* 2005; Wu *et al.,* 2014). The interactions among various hydrological processes such as gully erosion gravitational erosion and sedimentation, have been the main focus of studies conducted at the catchment scale (Govers, 1991; Fu, *et al.,* 2010; Zheng *et al.,* 2013). At regional, country-wide and global scales, the geographic information system (GIS) technique is usually used to monitor and estimate soil erosion and other sedimentary processes (Mellerowicz *et al.*, 1994; de Vente *et al.,* 2008; Bargiel *et al.,* 2013). However, increasing number of researchers have begun to observe the cross-scale effect of water and soil loss. These studies have found that large-scale runoff and soil erosion cannot necessarily be equated to the sum of corresponding small-scale runoff and soil erosion and that the conclusions derived from studies conducted at medium and small scales cannot be applied to studies conducted at larger scales (Wilcox *et al.,* 2003; Easton *et al.,* 2008).

Similarly, numerous studies concerning soil erosion over different time scales, including individual (rainfall) events, monthly, seasonal, yearly and larger scales have been documented (Andreu *et al.,* 2001; Hartanto *et al.,* 2003). Defersha and Melesse (2012) compared the runoff and sedimentary yield of bare soil, grassland and farmland of a river valley under natural rainfall events; the results indicated that farming activity significantly intensified land degradation in the river valley. Kothyari *et al.* (2004) established the relationship between precipitation and runoff depth, runoff depth and soil loss and nutrient loss and soil loss using monthly data obtained from 1998 to 2001 in the Bhetagad subwatershed of India. All these variables exhibited positive linear relationship with coefficients of determination (R^2) ranging from 0.49 to 0.90. According to seasonal data obtained from Sierra Calderona, Spain, Andreu *et al.* (2001) reported that less soil erosion occurred from winter to autumn, and that the north-facing soil exhibited lower level of degradation than the south-facing soil. Li *et al.* (2010) analyzed seasonal dynamics of the relationship between precipitation and sediment in black soil area of northeastern China. The results of the present study confirmed that two peaks occurred in the annual sedimentary yield at the end of spring and during summer. Wischmeier and Smith (1965) established the Universal Soil Loss Equation (USLE) based on the annual data of more than 10,000 plots; this equation has been used worldwide to estimate soil loss. Bulter (1994) monitored soil erosion that occurred in South Downs of England over 10 years and found that the annual soil loss varied greatly, with 71% of the total erosion occurring in one year. Based on 5-year interval of data obtained over 25 years from 58 plots with different levels of vegetation in Changting County of Fujian Province, China, Gao *et al.* (2011) reported that higher level of vegetation corresponded with 10-30% more coarse soil particles (>1 mm in diameter), 33-97% less soil erosion, 10-49% less runoff, higher level of total phosphorus and potassium soil nutrients, and higher level of both overstory and understory plant species richness. The effect of water and soil conservation measure over multiple time scales have also been reported in literature. Rudi (2005) used the Limburg Soil Erosion Model (LISEM) to predict runoff and soil erosion of a watershed in the Loess Plateau of China and found that the amount of erosion declined as time scale became greater. Zhao *et al.* (2007) established a simple calculation model for the monthly rainfall erosivity in the Loess hilly region in northern Shanxi, China based on the USLE. The results indicated that the time scale distinctively influenced the precision of the model in that the rainfall erosivity of the entire rainy season was less than that of one or several months.

Thus, numerous studies concerning water and soil conservation measures at various spatiotemporal scales have been conducted. However, lack of studies on vegetative effect of water and soil conservation measures over various time scales using quantitative vegetation indices has hindered our understanding of water and soil conservation. In the present study, the effect of various time scales on water and soil conservation measures were investigated based on the rainfall characteristics, vegetative parameters, and amount of water and soil loss of six experimental plots undergoing erosive rainfall events from 2007 to 2010. Quadratic polynomial regression models between vegetation fractional coverage and water/soil conservation effects (RE/SE) were established for individual (rainfall) event, monthly, seasonal and yearly scales. Curves and model determination coefficients (R^2) of the models at different time scales were then compared in order to evaluate the influence of time scales on water and soil conservation effects.

Materials and Methods

The experimental plots were located in Hetian Town of Changting County in Fujian Province, China (116°18'–116°31' E, 25°33'–25°48' N). This area is a basin valley surrounded by low hills, which slope gently from north to south. The area is characterized by a middle subtropical monsoon climate, with an annual mean temperature of 19.5° C and maximum and minimum recorded temperatures of 39.8°C and −4.9 °C, respectively. The annual mean precipitation is approximately 1,621 mm and rainy season generally occurs from March to August (Gu *et al.,* 2011). The mountain red soil of this region, which results from weathering of granite, is deep, sandy, loose and exhibits little resistance to erosion. Most of the mid-subtropical evergreen broadleaf forest in this region has been destroyed, causing it to be one of the most severely water-eroded areas in southern China (Jiang, 2005). Although vegetation reconstruction measures have been conducted since 1970 and the massive *Pinus massoniana* forest has been recovered, this area is still affected by severe water and soil loss due to shortage of shrubs and grass under the tree canopy and overall bareness of soil surface (Zhao, 2006).

In February 2007, five pure tree plots and one bare soil plot were established on a hill in Hetian Town at an elevation of approximately 200 m above sea level. Six plots were adjacent and had similar slopes of approximately 8°. The projected dimensions of each plot were 5 m × 20 m, and the boundaries consisted of cement sheets (50 cm × 50 cm × 10 cm) inserted into soil at depth up to 25 cm. The plots was of mountain red soil with distinctly high coarse particle contents, low bulk density (1.34±0.11 g cm^{-3}) and low pH (3.65±0.04), total nitrogen (0.24±0.05 g kg^{-1}), and total organic matter (4.40±0.68 g kg^{-1}). Soil erodibility (K) factor values of the plots were also similar, ranging from 1.06 ~ 1.47 Mg ha h 10^{-2} $[\text{ha MJ mm}]^{-1}$ (Gu *et al.,* 2013). Two 244 cm × 80 cm × 86 cm ponds were constructed in the downstream end of each plot for runoff and sediment collection. Vegetation in pure tree plots comprised of only *Pinus massoniana*, without herbs or shrubs under the canopy. The average age and height of trees were approximately fifteen years and seven meters, respectively. Prior to experiment, some of the trees were removed with their roots intact in order to make the gradient of vegetation fractional coverage (VFC), *i.e.*, percentage of trees covering the ground, ranged from 0.2 to 0.6 approximately. Plots were denoted as Plots 201, 301, 401, 501, and 601 in order of increasing level of VFC. The bare soil plot, which was used as control plot, was labeled as Plot 101, as shown in Fig. 1. The VFC gradients of

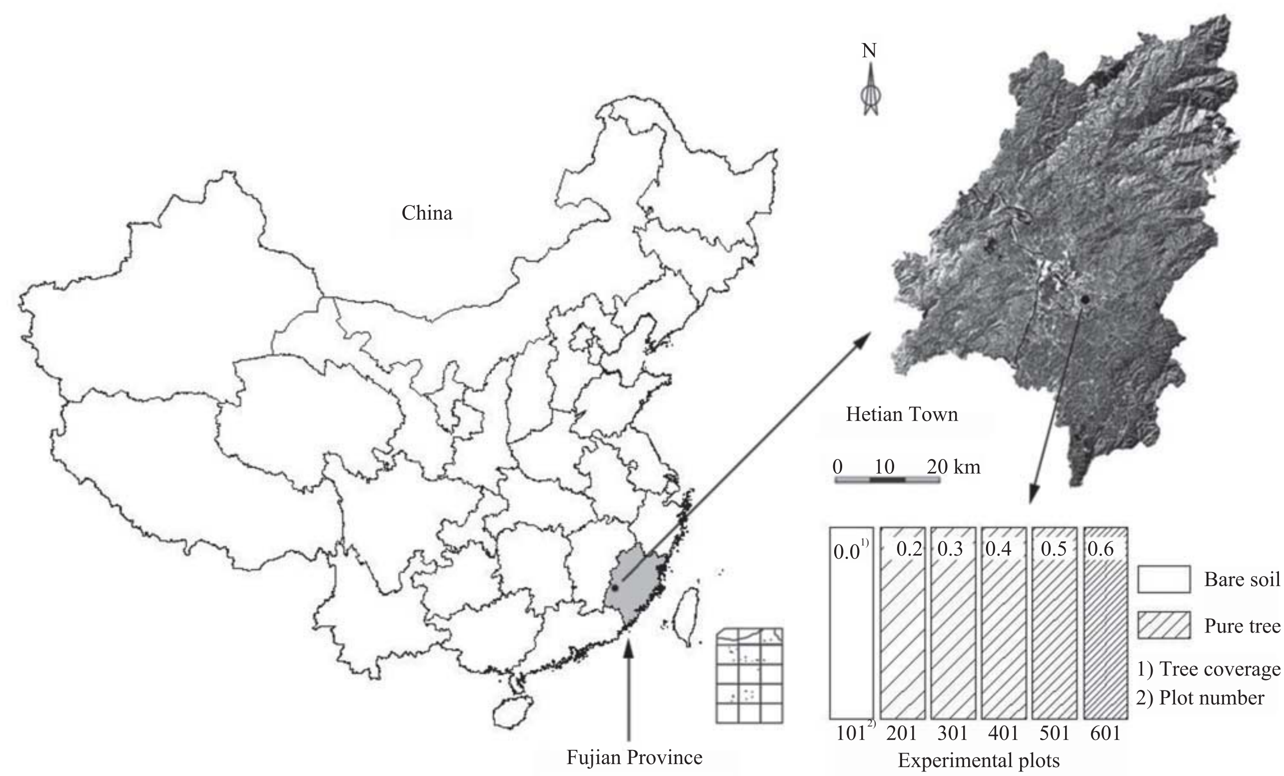

Fig. 1 : Location of study area and configuration of experimental plots in Hetian Town, Fujian Province, China. Five pure tree (*Pinus massoniana*) plots and one bare soil plot were established in the study area. Average tree coverage of the plots ranged from 0 to approximately 0.6. Based on their levels of ascending tree coverage, the plots were denoted as Plots 101, 201, 301, 401, 501, and 601. Plot 101 was assigned as control

the plots remained unchanged throughout the experimental period, but the VFC of each plot changed over time.

Observational data and **calculations :** From March 2007 to September 2010, the rainfall, VFC, runoff depth, and sedimentary deposit of each plot were measured or calculated following each rainfall event.

The rainfall curve of each plot was measured and continuously monitored from an automatic meteorological station near the plots. The amount of rainfall (P, mm), maximum 30-min intensity (I_{30}, mm h^{-1}) and rainfall duration (T, min) of each rainfall event were then calculated based on the rainfall curves.

VFC was measured using photograph methods described by Gu *et al.* (2010). Each plot was evenly divided into upper, middle and bottom subplots from upslope to downslope. VFC was measured weekly beginning March 2007 on sunny days with a digital camera mounted on a tripod. Photographs were captured on ground vertically upward for the tree canopy in each subplot, and VFC of each photo was calculated based on the difference in digital pixel values of the vegetative and non-vegetative pixels using decision tree tool in ENVI version 4.5 (Research Systems, Inc.). VFC of each plot was determined by averaging the VFCs of the three subplots. Since capturing photographs on rainy days is difficult, the VFCs' on these days were calculated by linearly interpolating the VFC measurements. Monthly, seasonal and annual VFCs were calculated by averaging the VFCs over the corresponding time scales.

The amounts of runoff and sediment were measured after each rainfall event for duration of the experimental period. Water depth of the pond in each plot was measured, and the amount of runoff was calculated and divided by the projected area of the plot (100 m^2) in order to obtain the runoff depth (RD, mm). The runoff collected in each pond was thoroughly mixed and dried in an oven at 105 °C in order to determine the constant sedimentary weight. Dry sediment weight was used to calculate soil loss (SL, t ha^{-1}). Monthly, seasonal, and annual RDs/SLs were calculated by summing the RDs/SLs over the corresponding time scales.

The RD/SL ratio of tree plots to control plot was used to monitor the water/soil conservation effects (RE/SE) over each time scale. Lower RE/SE values indicated better water/soil conservation effects. RE and SE are the ratios of water and soil loss of tree plots to water and soil loss of control plot, they do not describe the effects of other factors such as rain, terrain and soil. Therefore, RE and SE were selected as dependent variables to describe water and soil conservation effects of the trees.

Data analysis : The amount of water and soil loss (RD/SL) over different time scales was divided by total water and soil loss of the corresponding time scale in order to determine the practical contribution of each conservation effect. Hereafter, this value was referred to as runoff/soil loss weight coefficient.

The quadratic polynomial regression model, a simple model that represents the nonlinear characteristics of variables, was used to establish VFC-RE and VFC-SE models for each time scale according to the least square method, as shown in Eq. (1).

$$y = ax^2 + bx + c \qquad (1)$$

In this equation, y represents either RE or SE, x represents VFC of five tree plots at different time scales and a, b, and c are the model coefficients. Determination coefficient (R^2) of each model was calculated in order to determine its precision. All the analyses were conducted using SPSS 19.0 statistical analysis software (SPSS, Inc.).

Results and Discussion

Among the 268 natural rainfall events that occurred in the study plots from 2007 to 2010, 124 did not result in significant soil erosion and were excluded from the study. The remaining 144 rainfall events were considered erosive rainfall events and were used for the purpose of analysis. Thus, a total of 144 VFC-RE and VFC-SE quadratic polynomial models were established for individual event. Based on the curves, the water and soil conservation effects were grouped, contribution of each effect at different time scales was calculated and appropriate observation scales were determined.

At individual event scale, both RE and SE exhibited linearly descending (DS), descending-ascending (DA), ascending-descending (AD) and linearly ascending (AS) trends as VFC increased. The curves also exhibited corresponding descending, concave, convex and ascending trends. All the models were visually grouped into four types according to their curves. These four categories were used to describe the type of water and soil conservation effects, as shown in Fig. 2. The DS and AS trends were categorized as linear effects, and the DA and AD trends were categorized as transition effects. Among the four types of effects, DS trend, as well as linearly descending portions of AD/DA trends, indicated positive effect of vegetation. As the amount of vegetation increased, the amount of water and soil loss decreased. Similarly, the AS trend, as well as linearly ascending portions of AD/DA trends, exhibited negative effect of vegetation. As the amount of vegetation increased, the amount of water and soil loss increased.

Fig. 3 displays the occurrence of each effect type at different time scales. The occurrence frequency, or occurrence probability, of each effect type was calculated by dividing the number of occurrences by total number of events over the corresponding time scale (Fig.4). The number of effect types decreased as the time scale increased (Fig.3). At the individual event and monthly scale, all four effect types occurred. However, the AS trends disappeared at the seasonal scales, and only two of the effect types occurred at the yearly scale, of which the DA trends were predominant. According to Fig.4, the DA occurrence probabilities were always predominant, exceeding 30% of total occurrence at any scale for both water and soil conservation effects. The DA occurrence probabilities increased as the time scale became larger. The AS occurrence probabilities were lowest and less than 15% of the total occurrence at any scale. The AS occurrence probabilities decreased as time scale became larger. These results indicated that the effect of trees on water and soil conservation was diverse at smaller time scales, but became less diverse as the time scale became greater. The extreme rainfall events were concealed or transformed, making the dominant events more apparent (de Vente and Poesen, 2005). These results could be used to determine appropriate time scale for observing the effects of water and soil conservation measures.

The variation in type of effects at different scales were primarily due to the time heterogeneity of vegetation and rainfall. Over short periods of time, precipitation and rainfall intensity are altered by vegetative canopies, affecting runoff and sediment. Therefore, soil humidity significantly influences runoff during light rains, but slightly affects the peak runoff of heavy rainfall (Castillo *et al.,* 2003). Over long period of time, vegetation improves the properties of soil under vegetative canopies, distinguishing it from the existing vegetative gaps and, thereby significantly impacts runoff and sediment (Puigdefábregas *et al.*, 1999; Puigdefábregas, 2005). The recurrence interval of extreme rainfall events significantly influence the peak erosion occurrences (Cammeraat, 2004).

The weight coefficient shows the contribution of each conservation effect at corresponding time scale. Variation in the weight coefficient over different time scale is shown in Fig.5. The total runoff depth of 4a was equal to 5355.6 mm. In every case, the weight coefficient of two transitional effects, DA and AD, were higher than those of two linear effects, DS

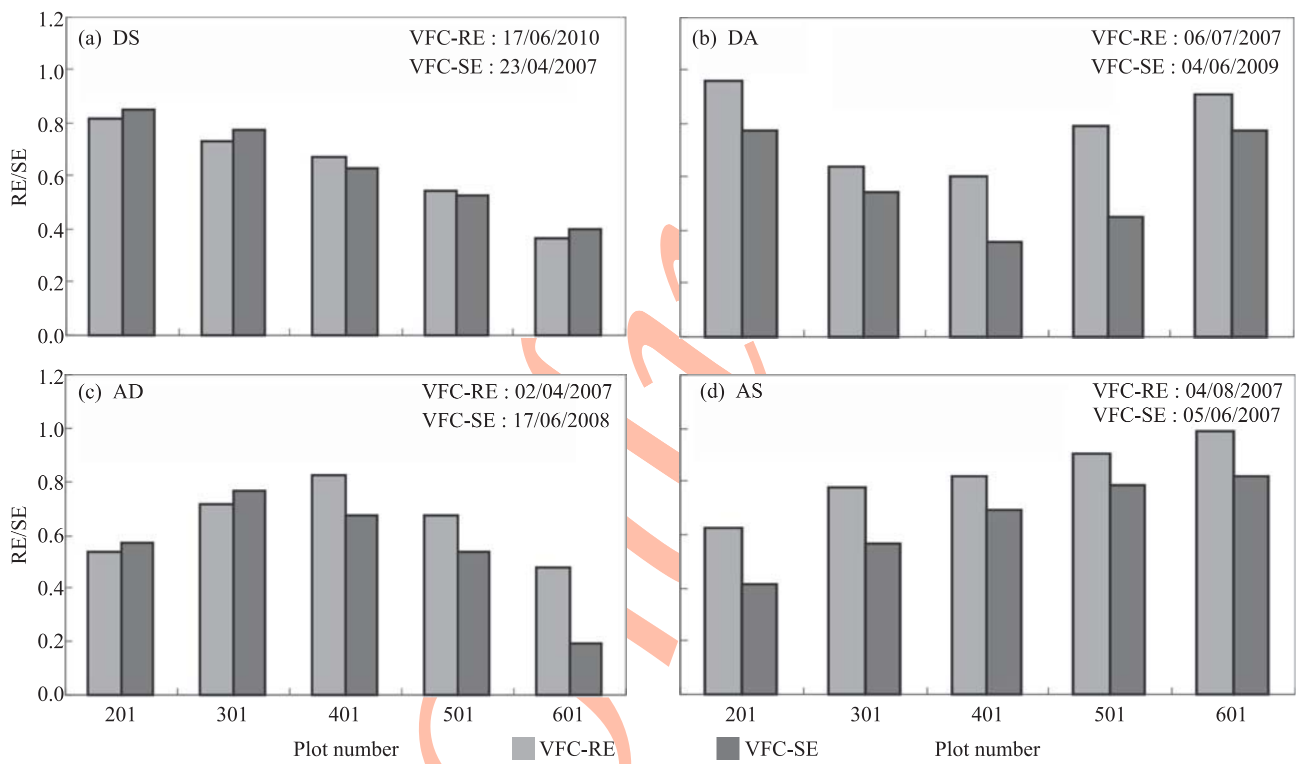

Fig. 2 : Effects on water and soil conservation during rainfall events. RE represents the runoff depth ratio of the tree plots to the control plot, and SE represents the soil loss ratio of the tree plots to the control plot. DS, DA, AD, and AS represent the effects of the increasing levels of Vegetation Fractional Coverage (VFC), in which the RE/SE ratio predominantly descended, initially descended then ascended, initially ascended then descended, or predominantly ascended, respectively

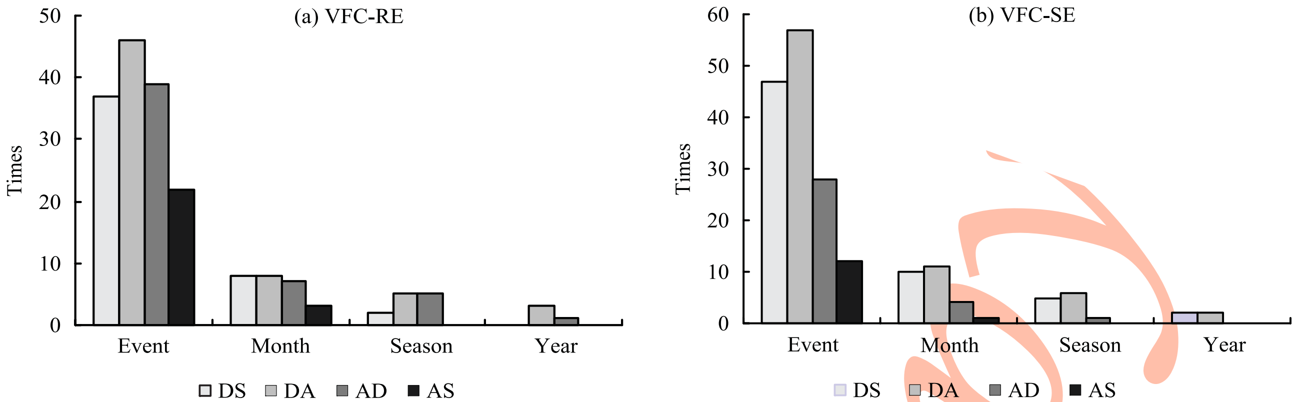

Fig. 3 : Influences of changes in the effects on water and soil conservation at different time scales. RE represents the runoff depth ratio of the tree plots to the control plot, and SE represents the soil loss ratio of the tree plots to the control plot. DS, DA, AD, and AS represent the effects of the increasing levels of Vegetative Fractional Coverage (VFC), in which the RE/SE ratio predominantly descended, initially descended then ascended, initially ascended then descended, or predominantly ascended, respectively

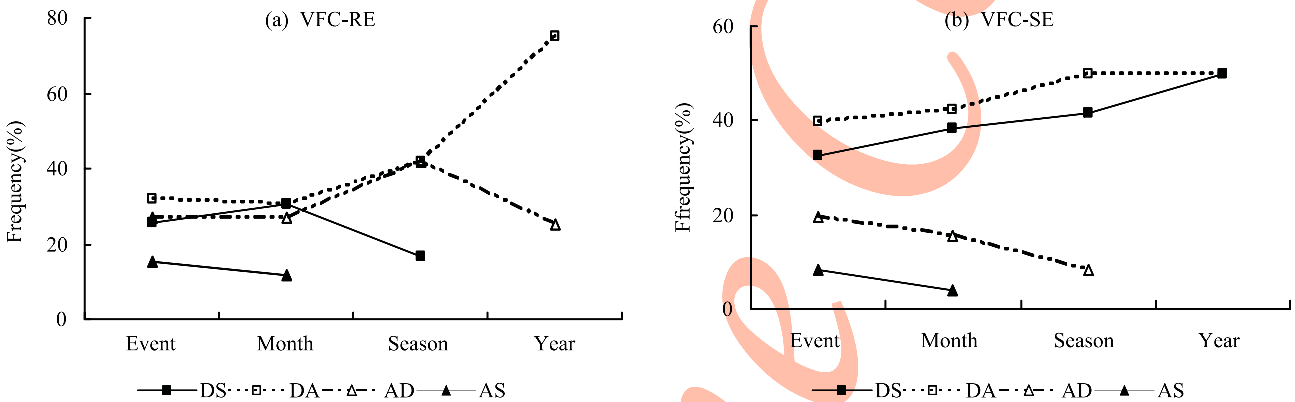

Fig. 4 : Influence of the frequency of the effects on water and soil conservation at different time scales. RE represents the runoff depth ratio of the tree plots to the control plot, and SE represents the soil loss ratio of the tree plots to the control plot. DS, DA, AD, AS represent the effects of the increasing levels of Vegetation Fractional Coverage (VFC), in which the RE/SE ratio predominantly descended, initially descended then ascended, initially ascended then descended, and predominantly ascended, respectively

and AS. DA exhibited highest weight coefficient (>35%) and AS exhibited lowest weight coefficient (<15%). The effect of DA ascended significantly as time scale became greater, while AD, DS and AS effect exhibited opposite trends. Total soil loss of 4a was equal to 191.6 $t\ ha^{-1}$. At each time scale, the weight coefficients of DS and DA were higher than those of AD and AS. DS was higher than DA at the individual event, monthly and yearly scales, and AS was lowest of all the scales (<5%). DS and DA fluctuated, but increased overall as time scale became greater, while AD and AS decreased linearly as the time scale became greater.

Overall, the sum of DS and DA runoff yield weight coefficients varied from 50% to 80% at every scale. However, the sum of DS and DA sediment yield weight coefficients exceeded 80%, even up to 100%. Both of these summations increased as time scale became greater. These effects indicated that RD/SL decreased or partially decreased as VFC increased, reflecting the positive effect of trees on water and soil conservation. As the runoff/sediment yield weight coefficient increased, the positive effects became more apparent. Numerous studies have affirmed the positive role of vegetation concerning water and soil conservation (Descroix *et a1.*, 2001; Gyssels *et al.*, 2005; Huang *et al.*, 2010). However, some studies have suggested that vegetation can exhibit negative effect on water and soil conservation in case of severe precipitation and rainfall intensity (Mosley, 1982; Morgan, 1982; Hartanto *et al.*, 2003). Xu (2005) suggested that coupling of vegetation and rainfall could degrade or aggravate water and soil loss. Without adequate vegetation, erosion resistance of soil was weak, and significant erosion could easily occur as a result of strong rainstorms. After reaching a certain threshold, vegetation could significantly improve erosion resistance

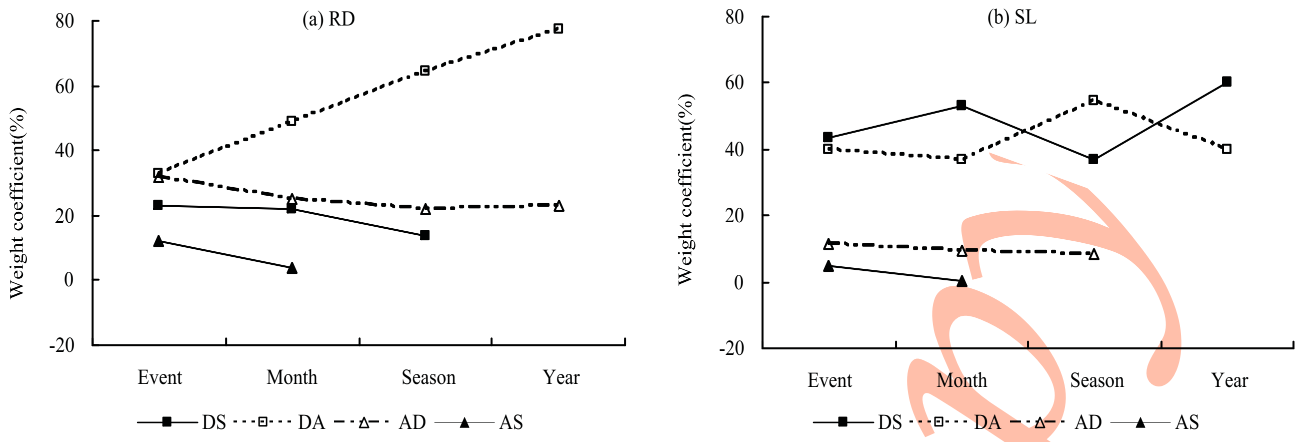

Fig. 5 : Water and soil erosion weight coefficients (contributions) of the effects on water and soil conservation at different time scales. RD represents the runoff depth, and SL represents the soil loss. DS, DA, AD, and AS represent the effects of the increasing levels of Vegetative Fractional Coverage (VFC), in which the RE/SE ratio predominantly descended, initially descended then ascended, initially ascended then descended, or predominantly ascended,

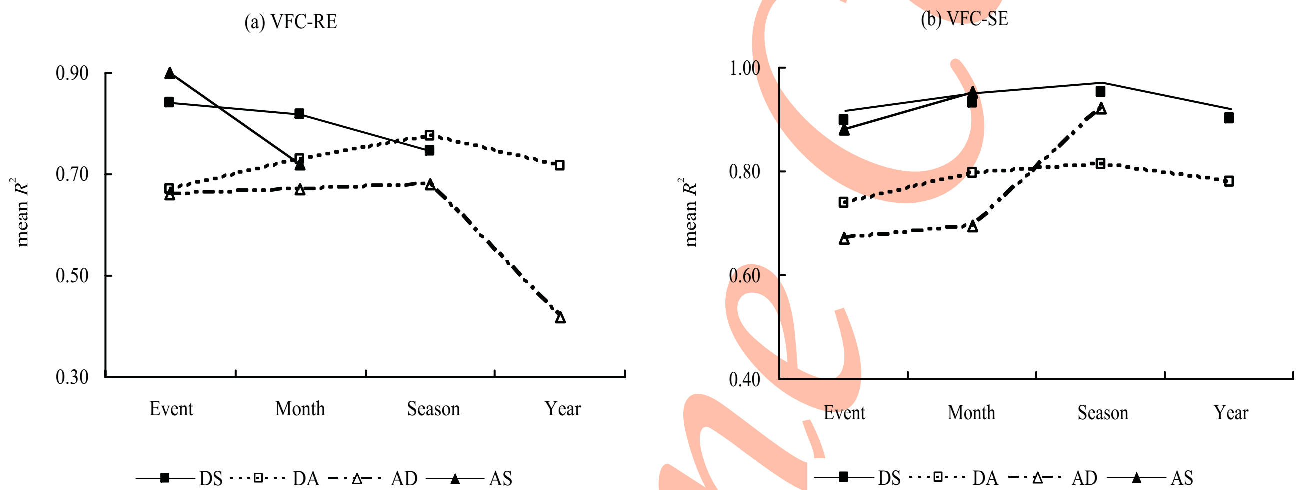

Fig. 6 : Mean R^2 values of the VFC-RE and VFC-SE of each of the effects on the water and soil conversation effects over different time scales. RE represents the runoff depth ratio of the tree plots to the control plot, and SE represents the soil loss ratio of the tree plots to the control plot. DS, DA, AD, and AS represent the effects of the increasing levels of Vegetative Fractional Coverage (VFC), in which the RE/SE ratio predominantly descended, initially

and prevent soil erosion.

According to Fig.6, in VFC-RE models, the mean R^2 values of two linear effects, DS and AS, were higher than those of the transitional effects, DA and AD. The linear effect decreased linearly as time scale became greater; their maximum value (0.90 and 0.84, respectively) occurred at individual event scale. The transitional effect initially increased, then decreased; their maximum values (0.78 and 0.68, respectively) occurred at seasonal scale. Similarly, in VFC-SE models, the mean R^2 values of two linear effects, DS and AS were also higher than those of transitional effects, DA and AD. As time scale became greater, the mean R^2 values of AS and AD effect increased continuously, while those of DS and DA effect initially increased, then decreased. The maximum mean R^2 values of DS, DA and AD effect (0.95, 0.81, and 0.92 respectively) occurred at seasonal scale. Thus, maximum mean R^2 values of all of the effects primarily occurred at the seasonal scale and all exceeded 0.65, the seasonal scale would be appropriate for evaluating the effects of trees on water and soil conservation. These results are consistent with the study of Zhang (2010). His study also indicated that the relationship models between VFC and runoff/soil loss performed better at seasonal scale than at monthly scale, indicating the potential of seasonal scale to evaluate the conservation effects of vegetation.

In this paper, the relationships between the vegetation fractional coverage (VFC) and water and soil conservation effects (RE or SE) over individual (rainfall) event, monthly, seasonal, and yearly time scales were analyzed based on the plot-level data of 144 erosive events that occurred from 2007 to 2010. Plot vegetation exhibited linear positive/negative and transition effects at rainfall event and monthly time scales, while the linear effects reduced at seasonal and/or yearly scales. The models more effectively described the seasonal (than other time scales) relationship between the VFC and water and soil conservation effects. This study suggested applicable time scales for vegetation effect observation (rainfall event and monthly scale) and evaluation (seasonal scale) in future investigation of soil and water conservation.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (No. 41571415/41071281/41271354), the Natural Science Foundation of Jiangsu Province (No. BK20131078/BK20130992), and the QingLan Project of the Jiangsu Provincial Department of Education. We are grateful for the comments and suggestions presented by anonymous reviewers, which were used to improve the quality of this paper.

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