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## Effect of forest vegetation on runoff and sediment production in sloping lands of Loess area

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**Abstract** According to fixed-position data for 1985–2003 from nine runoff plots of Caijiachuan watershed which lies in Jixian County of Shanxi Province in Loess area, this paper studied the relationship between vegetation and runoff and sediment production in sloping lands in detail, which helps to provide scientific basis for vegetation re-construction and studies on environmental transformation of water and sediment in watersheds of Loess area. Although, many study results testify that forest vegetation has an important function in soil and water conservation and cutting runoff, the effect of vegetation on runoff and sediment transmission is complicated, and this needs to be studied in depth. The results of the paper showed the following. Firstly, the natural secondary forest performs better function of soil and water conservation than artificial *Robinia pseudoacacia* forest, and runoff and sediment produced in the former in individual rainfall were 65%–82% and 23%–92% of those produced in the latter. At the same time, better correlative relationship between runoff and sediment production and rainfall and rainfall intensity were testified by multiple regression, but the correlation decreased gradually with the increase of canopy density of forest. Secondly, the difference of runoff and sediment production in several land use types was very distinct, and the amount of runoff and sediment produced from *Ostryopsis davidiana* forest and natural secondary forest were the least, and runoff and sediment produced from in artificial *Robinia pseudoacacia* forest and *Pinus tabulaeformis* forest were 5-fold as much as those from *O. davidiana* forest.

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Besides, runoff and sediment produced in mixed planting of apple trees and crops were 16.14-fold and 2.96-fold than those of *O. davidiana* forest, respectively, but the amount decreased obviously after high-standard soil preparation in the case of the former. Thirdly, based on gray cognate analyses of factors affecting runoff and sediment production in sloping land, the factors of stand canopy density and herb and litter biomass were the most significant ones, whose gray incidence degree exceeded 0.6. Therefore, mixed forest with multi-layer stand structure and shrub forest should be developed in vegetation re-construction of Loess area, which will help to increase coverage and litter thickness in order to cut down the runoff and sediment dramatically in sloping land.

**Keywords** vegetation, runoff and sediment production, gray cognate analyses, Loess area

### 1 Introduction

Reconstruction of vegetation in Loess area is an effective measure to decrease soil and water erosion and to improve the environment of the area; therefore, research about vegetation impacting runoff and transporting sediment is the key to understanding ecological environmental problems in the Loess area (Sun and Zhu, 1995; Cheng et al., 2002; Wang and Wang, 2002; Wang et al., 2004; Zhang et al., 2004). Vegetation includes natural forests and artificial forests, and a natural forest ecosystem that is not disturbed and has a higher capability of controlling the hydrologic cycle; different growing stages of artificial forest have different regulating effects on the hydrologic cycle and process. There are many studies on runoff and sediment production undertaken on different scales in China (Wang and Jiao, 1996a, 1996b; Chen, 1999; Huang et al., 1999; Fan et al., 2000; Ouyang, 2000; Liu and Cai, 2004;), and these experiments have verified the fact that vegetation growing on the Loess plateau performs the functions of conserving

water and soil, intercepting rain, reducing surface runoff, intercepting sediment and so on (Wu and Yang, 1998; Shen and Jiang, 1999; Chen et al., 2000; Yu and Qin, 2001; Wei, 2002; Xiao et al., 2002; Ding et al., 2004). Croke et al. (1999) stated that the question of the forest affecting the process of sediment transportation on slopes was a complex one, and lot of problems, which are related in some way to topographical characteristics and particle diameter of the soil, still need to be solved, at the same time, the question about transporting and depositing proceed of sediment in different slope also should be further researched. Breshears and Whicker (2003) believed that existing results about the construction of vegetation affecting sediment motion in slopes were not enough to explain natural vegetation affecting the regular kinetic movement of sediments.

This paper analyzed the fixed-site observational data for 1985–2003 in Caijiachuan watershed to study the relationships between forest vegetation and runoff and sediment production on the watershed scale, and to analyze the effect of natural forest, artificial forest and different land usages on runoff and sediment production, which would offer theoretical evidence for protecting the natural forest.

## 2 General situation of study area

We conducted our research at the test area of the Beijing Forestry University (BJFU), which is located in Caijiachuan nesting watershed of Jixian Country that belongs to Shanxi Province in China, the Southwest of Loss plateau. Its geographic coordinates is north latitude  $35^{\circ}53'–36^{\circ}21'$ , east longitude  $110^{\circ}27'–111^{\circ}07'$ . The yearly average precipitation is 579.5 mm and changes greatly over different years—the largest difference is 828.6 mm and the least difference is 227.2 mm, precipitation is concentrated in the period of July to September of every year. The area has warm temperature

and climate is semi-humid; the vegetation consists of semi-hygric deciduous board-leaved trees and this land belongs to the forestry-steppe zone. The kind of soil is drab soil, which is alkaline.

The total area of Jixian country is 1,777 km<sup>2</sup>, and the area of land having soil and water loss is 95,300 hm<sup>2</sup> which takes up 53.6% of the total area; the yearly erosion quantity is 21,000,000 t and erosion modulus is 11,818 t/(km<sup>2</sup>·year)

The vegetation on the upper watershed is mostly in the form of natural second-growth trees, which are composed of *Betula platyphylla*, *Populus davidiana*, *Syringa oblata*, *Ostryopsis davidiana* and so on. The middle watershed consists of artificial forest which includes *Robinia pseudoacacia*, *Pinus tabulaeformis*, *Platycladus orientalis* and natural grass vegetation cover. Besides, there still exists a large area of natural second-growth bush and grass vegetation cover comprising *Populus davidiana*, *Hippophae rhamnoides*, *Spiraea thunbergii*, *Rosa xanthina* and *heterophylla*.

## 3 Method

### 3.1 Precipitation

Eight tipping-bucket rain-gauges were installed in different parts of the watershed, which were charged to observe and record precipitation and the precipitation process across various years.

### 3.2 Runoff and sediment

The method of runoff plot was accepted. There were nine runoff plots of different land use surrounding the research area (Table 1), and their data used in this paper to study runoff and sediment were collected during the period of 1998–2003.

**Table 1** Condition of the runoff plots

| No.            | Area /m <sup>2</sup> | Method of soil preparation | Slope /( $^{\circ}$ ) | Aspect | Age /year | Mean height /m | Mean chest diameter /cm | Canopy density | Herb density /% | Density /(tree·hm <sup>-2</sup> ) | Bulk density /(g·cm <sup>-3</sup> ) | Porosity /% |
|----------------|----------------------|----------------------------|-----------------------|--------|-----------|----------------|-------------------------|----------------|-----------------|-----------------------------------|-------------------------------------|-------------|
| I <sub>1</sub> | 20×5                 | A                          | 25°                   | S      | 14        | 5.17           | 4.31                    | 0.74           | 85              | 2,204                             | 1.02                                | 48.5        |
| I <sub>2</sub> | 20×5                 |                            | 31°                   | E      | 14        | 7.91           | 7.69                    | 0.61           | 33              | 1,400                             | 1.17                                | 51.4        |
| I <sub>3</sub> | 20×5                 |                            | 28°                   | E      | 14        | 7.10           | 6.99                    | 0.60           | 56              | 2,000                             | 1.05                                | 48.3        |
| I <sub>4</sub> | 20×5                 |                            | 23°                   | NE20°  | 14        | 6.68           | 7.55                    | 0.60           | 73              | 1,200                             | 1.17                                | 48.6        |
| II             | 20×10                | –                          | 20°                   | W      | 12        | 3.50           | –                       | –              | –               | 600                               | –                                   | –           |
| III            | 20×10                | B                          | 25°                   | –      | 12        | 3.10           | –                       | –              | –               | 516                               | –                                   | –           |
| IV             | 20×5                 | A                          | 23°                   | WN38°  | –         | 2.10           | –                       | 0.95           | 60              | 3,700                             | –                                   | –           |
| V              | 20×5                 |                            | 25°                   | N      | 12        | 2.51           | 3.78                    | 0.70           | 20              | 1,800                             | 1.18                                | 53.7        |
| VI             | 20×5                 |                            | –                     | 23°    | NE32°     | –              | –                       | –              | 1.00            | 100                               | –                                   | 1.08        |

I : *Robinia pseudoacacia* forest; II : Mixed planting of apple trees and crops; III : Orchard; IV : *Ostryopsis davidiana* forest; V : *Pinus tabulaeformis* forest; VI : Natural secondary forest (*Populus davidiana*, *Pinus tabulaeformis*, *Ostryopsis davidiana*, *Spiraea thunbergii*, *Rosa xanthina*). A: Level bench, whose width is 1.5 m. B: Level band, whose width is 5 m, similar to level bench terrace. Before 2002, width of level band of orchard and crop is 2 m and the slope gradient of crop terrace of that is 25° and the mean slope length of that is 5 m. After high quality of soil preparation in 2003, width of level band of that is 3.5 m and the mean slope length of that is 3 m.

Spilt flow barrels were installed under the afflux canal of each runoff plot, and there was a discharge mouth at the bottom of the split flow barrel, which was connected to the measuring barrel. After rainfall, the quantity of runoff of each runoff plot was measured. Three bottles of runoff samples were taken and the column and weight of the samples were measured in the laboratory. The samples are then filtered to get sediments. The sediments were dried and then weighed to account for the average turbidity. The sediment yield was obtained by multiplying turbidity with the column of sample.

### 4 Results and discussion

#### 4.1 Natural and artificial vegetation reducing water quantity and sediment

The observing results of twenty-five individual precipitation events of four *Robinia pseudoacacia* forests and one natural secondary forest runoff plots during the period of 1985–2003 were shown in Figs. 1 and 2 (I was *Robinia pseudoacacia*

forest, VI was natural secondary forest).

According to Figs. 1 and 2, the quantities of runoff and sediment in runoff plots had better relationships with the amount of precipitation; meanwhile, runoff yield also had a better relationship with sediment yield. The quantities of runoff and sediment in natural secondary forest were bigger than those of artificial *Robinia pseudoacacia* forest. For example, August 8, 1997 was one instance (the ninth rainfall of Fig. 3), which received heavy rainfall during observation. The total amount of precipitation was 70.5 mm, rain intensity (I) of 10 min was  $I_{10}=1.02$  mm/min, rain intensity of 30 min was  $I_{30}=0.92$  mm/min, and average rain intensity was  $I_a=0.195$  mm/min. The quantities of runoff and sediment of natural secondary forest runoff plot produced was 65% and 23% lower than those of the forth *Robinia pseudoacacia* forest runoff plot. However, during the eighteenth rainfall on August 5, 2001, the total amount of precipitation was 50 mm, and average rain intensity was  $I_a=3.4$  mm/min. The quantities of runoff and sediment of natural secondary forest runoff plot produced was 70%–82% and 72%–92% lower than those of *Robinia pseudoacacia* forest runoff plot. Obviously, the functions of water conservation and prevention of soil

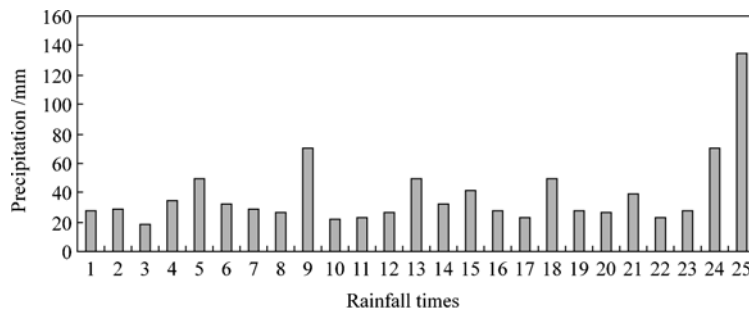


Fig. 1 Precipitation for 25 individual events from 1995 to 2003

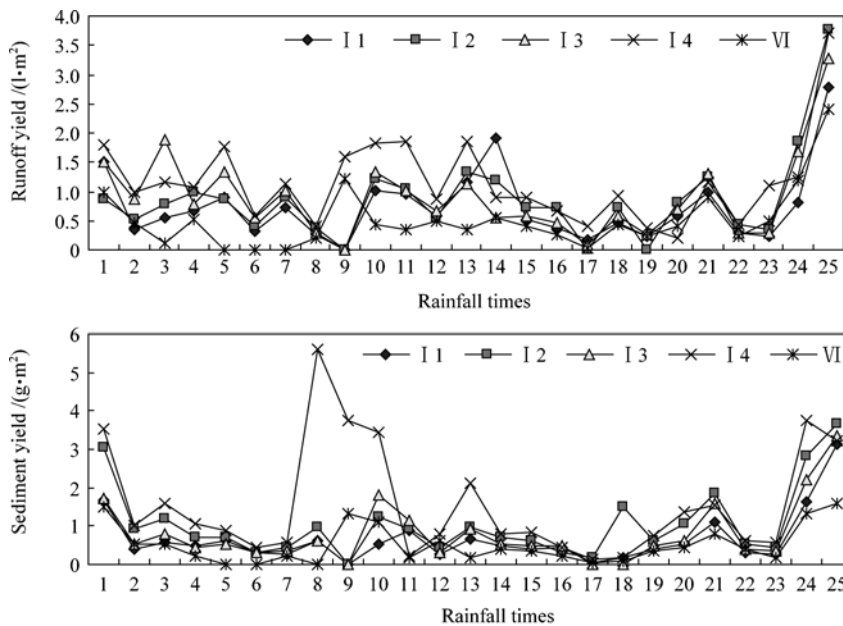


Fig. 2 Comparison of runoff yield and sediment yield among 5 runoff plots

erosion of natural forest were stronger than artificial *Robinia pseudoacacia* forest. Why? The main reason for this was that the closure degree and herbaceous coverage were much bigger than that in artificial forest (Table 1).

The quantities of runoff and sediment of four *Robinia pseudoacacia* forest runoff plots had significant differences. The stand density and closure degree of the first runoff plot of *Robinia pseudoacacia* forest were bigger than the remaining three, and the amount of runoff and sediment produced was much lower by comparison. But it was not correct to conclude that the more stand density, the better effect of stand (Li et al., 2003; Zhang and Yang, 2003). Especially, in order to maintain the balance of water in the forest land and to prevent soil and water erosion, the stand density of *Robinia pseudoacacia* should be less than 3,750 trees/hm<sup>2</sup> (Zhang et al., 2002).

Through the regression analysis between runoff yield ( $Q$ , L/m<sup>2</sup>), sediment yield ( $S$ , g/m<sup>2</sup>) and the total amount of rainfall ( $P$ , mm), rain intensity of 60 min ( $I_{60}$ , mm/min), regression equations for runoff yield and sediment yield affected by different stand coverage, the quantity of rainfall and rain intensity has been created (Table 2).

**Table 2** Regression analysis of runoff and sediment yield of runoff plots ( $n=25$ )

| No.            | Regression equation of runoff yield                      | Regression equation of sediment yield                    |
|----------------|--|--|
| I <sub>1</sub> | $Q = -0.564 + 0.018P + 0.068I_{60}$<br>( $R^2 = 0.964$ ) | $S = -0.730 + 0.020P + 0.085I_{60}$<br>( $R^2 = 0.96$ )  |
| I <sub>4</sub> | $Q = -0.594 + 0.027P + 0.073I_{60}$<br>( $R^2 = 0.958$ ) | $S = -1.702 + 0.046P + 0.191I_{60}$<br>( $R^2 = 0.939$ ) |
| VI             | $Q = -0.464 + 0.016P + 0.047I_{60}$<br>( $R^2 = 0.968$ ) | $S = -0.618 + 0.017P + 0.072I_{60}$<br>( $R^2 = 0.933$ ) |

According to Table 3, it is clear that runoff yield and sediment yield correlate well with the amount of precipitation and rain intensity, but with the increase of canopy density from 0.60 of I<sub>4</sub> to 1.00 of VI, the correlation coefficient of the regression equations decreased obviously. Therefore, the hydrographic process got more complicated with the increase in canopy density (Yu and Qin, 2001), which was in accordance with what Langbein and Schumn said. That is, with the change in the amount of rainfall, the critical phenomenon of the amount of sediment produced in the watershed

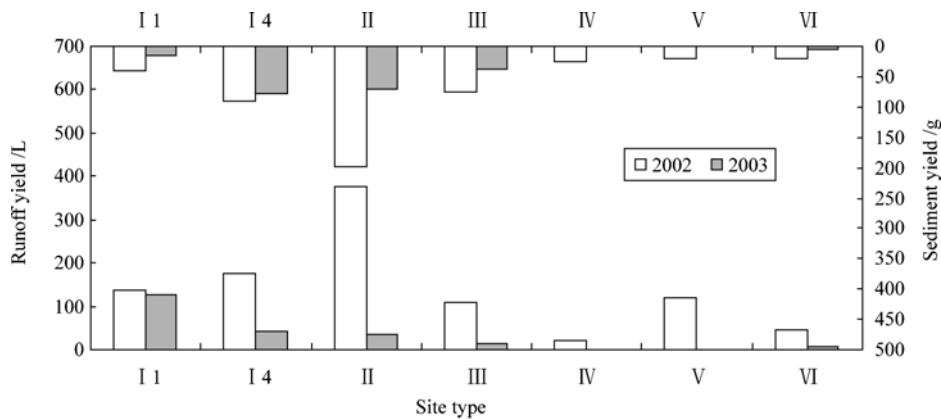
(catchment) area would result due to the effect of both the rainfall and vegetation (Langbein and Schumn, 1958; Schumn, 1977).

4.2 The quantities of runoff and sediment produced in runoff plots of different types of land

The average amount of runoff yield and sediment yield of runoff plots with different land usages during the period of July to September in the years 2002 and 2003 were taken into consideration for comparative analyses (Fig. 3).

From Fig. 3, the amount of runoff and sediment produced from the *Ostryopsis davidiana* bush and natural secondary forest was less than that of other stands. If the runoff and sediment produced in *O. davidiana* stand were both set as 1, then those of natural secondary forest was 1.34 and 0.57, *Robinia pseudoacacia* stand 4.54 and 2.05, *Pinus tabulaeformis* stand 5.98 and 4.49, mixed planting of apple trees and crops stand 17.14 and 3.96, respectively.

Obviously, the quantities of runoff and sediment produced had close relationships with stand coverage and thickness of litter. Take natural renewal-secondary forest as example, the canopy degree was 100%, the litter under tree was varied, which not only could intercept precipitation, but also could reduce the kinetic energy of raindrop when it reached the ground. Therefore, the quantities of runoff and sediment produced were less. To mixed planting of apple trees and crops stand, the band of fruit trees was terrace, but the terrain of crop band was sloping and eroded soil had been moved to lower, which would lead to the formation of continuous sloping surfaces. Besides, density of fruit tree was low, and there were no fallen leaves and herbaceous under trees. Therefore, when it was raining, especially during heavy rainfall, the infiltration capacity was little, and it was very easy to produce runoff. Orchard fared better in preventing the production of runoff and sediment than the former. This was because the method of soil preparation for orchard was a horizontal band with 5 m width, which was similar to horizontal terrace, and although there was runoff on slope between bands, rain mainly penetrated through the horizontal band and hardly produced runoff.



**Fig. 3** Comparison of runoff yield and sediment yield among 7 runoff plots with different land usages

By comparing the runoff and sediment produced in mixed planting of apple trees and crops stand between 2002 and 2003, it was seen that the quantities of those in 2003 decreased greatly than that in 2002. This was because quality of soil preparation was different (Table 1). Therefore, when land would be used for mixed planting of apple trees and crops stand, the band of fruit trees should be created with high-quality soil, which can not only increase farmers' incomes but also enhance the function of soil and water conservation.

In conclusion, in Loess gully area, in order to prevent soil and water erosion better, arbor-shrub-grass compound forest or *O. davidiana* bush should be developed in step slope where erosion was serious. On the contrary, it was not suitable to develop mixed planting of apple trees and crops stand in places where had deep slope degree, but it can be developed if where had the band of prepared soil with wider level band not level bench.

#### 4.3 The key factors affecting runoff and sediment produced in different stands in slope

By analyzing key factors affecting the runoff and sediment produced of different stands in the slope above, it can be found that, besides the factor of rain, terrain and stand structure are also important factors. These factors themselves affect each other. Now, not considering the effect of rainfall, we study the relationship between land usages of different stands and runoff yield and sediment yield by gray correlation analysis. Runoff yield and sediment yield of different stands were taken as mother series, and slope gradient, slope aspect, stand density, canopy density, herb coverage, herb biomass and litter biomass were set as daughter series, which was analyzed by gray correlation on the base of investigated data for 2002–2003 from different runoff plots with different land usages. The results are shown in Table 3.

The bigger the value of gray correlation, the bigger is the effect of comparative number sequence on referenced number sequence. To runoff yield, the values of gray correlation of the parameters were as follows: litter biomass (canopy density) > herbaceous coverage > stand density > slope aspect > herb biomass > slope degree. And to sediment yield, those were: grass biomass > litter biomass > herb coverage > canopy density > stand density > slope degree > slope aspect.

From aforementioned results, it could be seen that the affecting degrees of different factors were various. Litter biomass and canopy density had the most important effect on runoff yield, while grass biomass had the most important

effect on sediment yield. And slope aspect influenced the factors of stand structure through affecting moisture condition of forest. Therefore, it had a great impact on the runoff produced in slope. But in the case of slope degree, though gray correlation degree was smaller than those of other factors, it is wrong to take for granted that the slope degree has a low effect on the production of runoff yield and sediment. In the study, slope degrees of the runoff plots were almost equal and had no comparability, so the result of the paper agrees with the results of other similar studies (Zhen et al., 2003; Wang et al., 2004; Zhang et al., 2004). The gray correlations of stand density, herb coverage, litter biomass and grass were larger than 0.5, which showed that these affecting factors had a great effect on the function of soil and water conservation. Irregular mixed forest has more bush and herb coverage and grass and litter biomass; therefore, it performs a stronger function of soil and water conservation. This is in concurrence with many other such experiments (Chen et al., 2000; Zhang et al., 2003).

## 5 Conclusions

There was a better correlative relationship between runoff and sediment in sloping runoff plots. Moreover, the natural secondary forest performs better function of soil and water conservation than artificial *Robinia pseudoacacia* forest, and runoff and sediment produced in the former in individual rainfall were 65%–82% and 23%–92% of those produced in the latter. At the same time, better correlative relationship between runoff and sediment production and rainfall and rain intensity were testified by multiple regression, but the correlation decreased gradually with the increase of canopy density of forest.

The difference of runoff and sediment production in several land use types was very distinct. If the runoff and sediment produced in *Ostryopsis davidiana* stand were both set as 1, then those of natural secondary forest were 1.34 and 0.57, *Robinia pseudoacacia* stand 4.54 and 2.05, *Pinus tabulaeformis* stand 5.98 and 4.49, mixed planting of apple trees and crops stand 17.14 and 3.96, respectively. But the amount decreased obviously after high-standard soil preparation for the last stand. Therefore, it is a wise policy to carry out closure and development of a self-restoration forest in the Loess Plateau such as arbor-shrub-grass compound forest or *O. davidiana* stand. At same time, in order to develop the region's economy and better execute the program for conversion from cropland to forest and grassland, orchard and

**Table 3** Gray correlation degree of each factor impacting sloping surface producing runoff and sediment

| Item                                 | Slope gradient<br>/(°) | Slop<br>aspect | Density<br>/(tree·hm <sup>-2</sup> ) | Canopy<br>density | Herb coverage<br>/% | Herb biomass<br>/(g·m <sup>-2</sup> ) | Litter biomass<br>/(g·m <sup>-2</sup> ) |
|--------------------------------------|------------------------|----------------|--------------------------------------|-------------------|---------------------|---------------------------------------|---|
| Runoff yield /(L·m <sup>-2</sup> )   | 0.555                  | 0.571          | 0.609                                | 0.639             | 0.629               | 0.565                                 | 0.639                                   |
| Sediment yield /(g·m <sup>-2</sup> ) | 0.416                  | 0.401          | 0.452                                | 0.531             | 0.548               | 0.786                                 | 0.693                                   |

mixed planting of apple trees and crops with high-standard soil preparation are better choices for Loess area.

Based on gray correlation analysis of the factors affecting runoff and sediment production in sloping land, the factors of canopy density and herb and litter biomass were the most significant ones, whose gray incidence degrees all exceeded 0.6. The factors of aspect and degree of slope were the significant ones, whose gray incidence degrees all exceeded 0.5. Consequently, mixed forest with multi-layer stand structure and shrub forest should be urgently developed in the vegetation re-construction of Loess area, which will help to increase coverage and litter thickness, and benefit to cut down the runoff and sediment dramatically in sloping land.

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