Deposition Velocity of PM2.5 in the Winter and Spring above Deciduous and Coniferous Forests in Beijing, China

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Abstract

To estimate the deposition effect of PM2.5 (particle matter with aerodynamic diameter <2.5 μm) in forests in northern China, we used the gradient method to measure the deposition velocity of PM2.5 during the winter and spring above a deciduous forest in Olympic Forest Park and above a coniferous forest in Jiufeng National Forest Park. Six aerosol samplers were placed on two towers at each site at heights of 9, 12 and 15 m above the ground surface. The sample filters were exchanged every four hours at 6:00 AM, 10:00 AM, 2:00 PM, 6:00 PM, 10:00 PM, and 2:00 AM. The daytime and nighttime deposition velocities in Jiufeng Park and Olympic Park were compared in this study. The February deposition velocities in Jiufeng Park were 1.2±1.3 and 0.7±0.7 cm s⁻¹ during the day and night, respectively. The May deposition velocities in Olympic Park were 0.9±0.8 and 0.4±0.5 cm s⁻¹ during the day and night, respectively. The May deposition velocities in Jiufeng Park were 1.1±1.2 and 0.6±0.5 cm s⁻¹ during the day and night, respectively. The deposition velocities above Jiufeng National Forest Park were higher than those above Olympic Forest Park. The measured values were smaller than the simulated values obtained by the Ruijgrok et al. (1997) and Wesely et al. (1985) models. However, the reproducibility of the Ruijgrok et al. (1997) model was better than that of the Wesely et al. (1985) model. The Hicks et al. (1977) model was used to analyze additional forest parameters to calculate the PM2.5 deposition, which could better reflect the role of the forest in PM2.5 deposition.

Introduction

Measuring the deposition effect of PM2.5 (particulate matter with aerodynamic diameter <2.5 μm) in forests is an important objective. This study is the first effort to estimate the deposition effect of PM2.5 in forests in northern China. Previous studies have been conducted in Europe and North America [1–2] but only one other study has been conducted in Asia. Kazuhide et al. [3] measured the deposition velocity of PM2.5 sulfate in the summer using the gradient method in a deciduous forest at the eastern foot of Mt. Asama, Nagano Prefecture in central, Japan. They obtained results that are similar to those measured in other parts of the world. Further investigations of deposition velocities in forests have been conducted in many sites in North America, Europe, Southeast Asia, and East Asia [4–6]. However, in East Asia deposition velocities in forests have only been studied in Japan and Chinese Taiwan locations [7–15].

The State Forestry Administration of China established this project to study the regulatory function and technology related to forest PM2.5. This study is a major project for exploring the role of the forest in PM2.5 deposition.

Particulate matter 2.5 (PM2.5) is the most important contributor to haze. Under certain conditions, haze can cause the attenuation of atmospheric visibility. The use of motor vehicles in Beijing has significantly increased in recent years: since the 1990s, the vehicle quantity has reached approximately 5.30 million [16]. Furthermore, the total amount of atmospheric pollution in Beijing is increasing, which may be partly due to the heavy use of firecrackers and fireworks on Chinese New Year and other similar occasions. Based on a report from the Ministry of Environmental Protection of China, the PM2.5 concentration reached 1000 μg/m³ in Beijing on the Chinese New Year due to the use of 313,000 boxes of fireworks [17]. The Chinese Government has been concerned about air pollution; thus, 35 environmental monitoring stations have been built in Beijing. These stations include 12 urban environmental monitoring stations, 11 suburban environmental monitoring stations, and 7 urban traffic environmental monitoring stations. A total of 24 hours of the measured data from all of these stations was published at http://zx.bjmemc.com.cn in 2013. In this study, we used the gradient method to survey temporal and spatial variations in PM2.5 concentration.
Experimental Section

1. Ethics Statement
This study did not involve any endangered or protected species. This work was conducted based on Forestry Standards “Observation Methodology for Long-term Forest Ecosystem Research” of the People’s Republic of China (LY/T 1952–2011).

2. Sites
The two field sites are depicted in Figure 1. One experiment site, Jiufeng National Forestry Park, is managed by the Forestry Committee of Beijing Forestry University and is available for teaching and research use by the university. It is located in Jiufeng National Forest Park in the Beijing Haidian District (40.06°N, 116.09°E). It is a typical rural sampling site.

The other experiment site, Olympic Forest Park, is managed by the Beijing Olympic Forest Park Development and Management Co., Ltd. It is located in a deciduous forest in the Olympic Forest Park in the Beijing Haidian District (40.258°N, 116.39°E). This site represents urban air pollution and is adjacent to Fifth Ring Road, one of the busiest roads in Beijing. *Populus tomentosa* is a winter-deciduous tree and is the dominant species in Olympic Forest Park. The dominant species in the Jiufeng National Forest Park is *Platycladus orientalis* evergreen. This site also contains *Pinus tabulaeformis*. The forests at both sites are classified as temperate forests, and flourish in similar climates.

The height of the trees was approximately 8 m around the tower in both sites. The displacement height ranged approximately from 4 m to 8 m (equations 1, 2 and 3). The roughness length ranged from 0.5 m to 1.5 m during the year for the Olympic and Jiufeng parks (equations 1, 2 and 3). According to measurements at the sites, the leaf area index (LAI) at the Jiufeng National Forest Park site was 3.1 and 3.8 in the winter and spring, respectively. The leaf area index (LAI) at the Olympic Forest Park site was 1.8 in the spring.

3. Sampling Program
Two experiment stations were built, one in each forest, with iron towers that measured approximately 16 m in height. Figure 2 depicts the setup of our experiment at both sites.

PM2.5 fluxes were obtained using an atmospheric particulate sampler (KC-6120 integrated air sampler, Qingdao, Laoshan Electronic Instrument Factory Co., Ltd.). PM2.5 was collected on glass fiber filters (MK360, Munktell&Filtrak GmbH, Sweden) at a flow rate of 100 L/min. The samplers were calibrated with the flow meter. Furthermore, the base of the filter film and the cutting head were ultrasonically cleaned with deionized water three times before each experiment.

Three aerosol samplers were placed on each of the two towers at heights of 9, 12 and 15 m above the ground. The sample filters in the atmospheric particulate sampler were changed at 6:00 AM, 10:00 AM, 2:00 PM, 6:00 PM, 10:00 PM, and 2:00 AM (i.e., three times during the day and three times during the night). The ultrasonic anemometer was placed on the iron tower at 15 m, and the meteorological instruments were placed on the iron tower at 9, 12 and 15 m. The sampling times occurred in February 2013 and May 2013. The experiment was performed in the winter from February 22 to 28 and in the spring from May 7 to 12 in 2013. After every sample was obtained, each sample filter was sealed in a clean membrane polypropylene filter box to avoid contamination.

4. Meteorological Data and PM10 Data
The meteorological data were measured by meteorological instruments in this study. The measured meteorological data included humidity and temperature (HMP45C, Campbell Scientific Inc., U.S.A.), wind speed and direction (014A/024A, Met One Instruments Inc., U.S.A.). An ultrasonic anemometer (Wind Master, Gill Instruments, Britain) was used to obtain friction velocity and the Monine-Obukhov length.

Some data (PM10 and PM2.5 concentrations) were obtained from the Beijing municipal environmental monitoring center, the agency’s official website is http://zx.bjmemc.com.cn/. The data...
were applied to calculate the concentration ratios of PM2.5 from PM10. Data is available in Data S1 for this manuscript.

5. Computation of PM2.5 Fluxes

In this study, the gradient method was used to estimate PM2.5 fluxes [18–20]. Table 1 lists all of the symbols and units used in this research. The equations 1, 2 and 3 were used to determine the \( d \) and \( Z_0 \).

\[
U(z) = \frac{u^*}{k} \ln \frac{Z-d}{Z_0} \quad (1)
\]

\( u(z) \) is the average wind velocity, \( u^* \) is friction velocity, \( k \) is Von Karman constant, \( d \) is roughness length, \( Z_0 \) is displacement height.

\[
f(d) = \frac{U(z_1) - U(z_2)}{U(z_1) - U(z_3)} = \frac{\ln(Z_1-d) - \ln(Z_2-d)}{\ln(Z_1-d) - \ln(Z_3-d)} \quad (2)
\]

\( U(z_1), U(z_2) \) and \( U(z_3) \) are the wind velocity at heights \( Z_1, \ Z_2 \) and \( Z_3 \), respectively. In this study we used 15, 12 and 9 m.

\[
g(d) = d - \frac{f(d)}{f'(d)} \quad (3)
\]

\( f(d) \) and \( g(d) \) are arbitrary function used in the iterative process and \( f' \) is the numerical derivative (the gradient between values in two iterations) of \( f(d) \). This equation set is used iteratively. First an initial value for \( d \) is assumed. Then, the value of \( g(d) \) is updated and used to determine the new value \( d \), then the updated \( d \) value is substituted into the equations (2) and (3) to get a new \( g(d) \). We assumed the process has converged once the absolute value of the difference between the updated \( g(d) \) and the previous one is less than 0.001. The final value of \( d = g(d) \).

The flux-gradient technique was used to determine the flux \( F \) from the measured vertical gradients of the concentration and the eddy diffusivity of sensible heat, as shown in equation (4).

\[
F = -u^* \varepsilon^* \quad (4)
\]

\[c^* = \frac{k \Delta c}{\ln \left( \frac{Z_2-d}{Z_1-d} \right) - \Psi_h \left( \frac{Z_2-d}{L} \right) + \Psi_h \left( \frac{Z_1-d}{L} \right)} \quad (5)\]

\[\Delta c = c(Z_3) - c(Z_1) \quad (6)\]

In this equation, \( L \) is the Monin-Obukhov length, \( \varepsilon^* \) is eddy concentration, \( \Delta c \) is the changes in the concentrations between \( Z_1 \) and \( Z_3 \). \( \Psi_h \) is the integrated stability correction function in atmospheric deposition in relation to acidification and eutrophi-
From equations (4) and (5), \( F \) can be expressed by equation (9):

\[
F = \frac{-ku^*\Delta c}{\ln\left(\frac{Z_3-d}{Z_1-d}\right) - \Psi_h\left(\frac{Z_3-d}{Z_1-d}\right) + \Psi_h\left(\frac{Z_2-d}{Z_1-d}\right)} \tag{9}
\]

\( u^* \) and \( L \) were averaged every 15 min, \( F \) was averaged every 4 h because \( \Delta c \) were from six periods: 6:00–10:00, 10:00–14:00, 14:00–18:00, 18:00–22:00, 22:00–2:00, and 2:00–6:00.

The deposition velocity, \( V_d \), was determined using the following equation adapted from Wesely and Hicks (1977) \[21\]:

\[
\Psi_h\left(\frac{Z_3-d}{L}\right) = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\arctan(x) + \frac{\pi}{2} \tag{7}
\]

\[
x = \left[1 - 16 \left(\frac{Z-d}{L}\right)^{0.25}\right] \tag{8}
\]
6. Empirical Models

We chose three empirical models with which to compare our measured data: the models proposed by Wesely and Hicks (1977), Wesely et al. (1985), and Ruijgrok et al. (1997) [21,22,23]. The model by Wesely et al. (1985) is a dry deposition model over grass, whereas the Ruijgrok et al. (1997) model is a dry deposition model over forest canopy. The Wesely and Hicks (1977) model is a dry deposition model over all canopies.

Slinn (1982) [24] and Wesely (1985) used the aerodynamic terms equation to express the deposition velocities of the aerosol particles. The following equation was used to calculate the deposition velocities, where $R_a$ is the aerodynamic drag, and $V_{ds}$ is the surface deposition velocity:

$$V_d \approx \frac{F}{c}$$

Furthermore, $R_a$ was calculated using the following equation, which is based on Erisman and Draaijers (1995) [25]. $u^*$ is the friction velocity, and $\Psi_h$ is the integrated stability function for heat.

$$R_a = \frac{\ln \left( \frac{Z_d}{z_0} \right) - \Psi_h \left( \frac{Z_d}{L} \right)}{k u^*}$$

Next, the Wesely and Hicks (1977) model was used for more complex parameters, where $u$ is the wind speed, $S_c$ is the Schmidt number, and $Pr$ is the Prandtl number:

$$V_d = \frac{1}{R_a + R_b + R_c}$$

$$R_a + R_b = \frac{u}{u^*} + \frac{2}{k u} \sqrt{\frac{S_c}{Pr}}$$

$$\frac{1}{R_c} = \frac{1}{R_s + R_m} + \frac{1}{R_m} + \frac{1}{R_{ds} + R_d} + \frac{1}{R_{ds} + R_g}$$

The resistances in the upper canopy included $R_s$ (the stomatal), $R_m$ (the mesophyll), and $R_{ds}$ (the outer surface resistances). The resistances in the lower canopy were the resistance to transfer by buoyant convection ($R_c$) and the resistance to the uptake by exposed surfaces ($R_{ds}$). The fourth term represents resistances to transfer ($R_{ds}$) and uptake ($R_{ds}$) on the ground [26].

The third value, $V_{ds}$ was initially presented by Wesely et al. (1985) and was fit to the grassland ecosystem in the United States. This value can be calculated using equations 16 and 17. The first
equation was fit to the stability condition \((L>0)\), and the second equation was fit to the instability condition \((L<0)\).

\[
V_d = \frac{u^*}{500} \tag{16}
\]

\[
V_d = \frac{u^*}{500 \left(1 + \left[\frac{300}{u^*} \right]^{2/3}\right)} \tag{17}
\]

Figure 4. The mean PM2.5 concentration at the various heights and sites. The mean PM2.5 concentration at the heights of 9 m, 12 m, and 15 m during the day and during the night in Jiufeng National Forest Park and Olympic Forest Park in February 2013 and May 2013. The error bars are the standard errors at the various heights. (A: Olympic Forest Park in spring. B: Jiufeng National Forest Park in spring. C: Olympic Forest Park in winter. D: Jiufeng National Forest Park in winter).

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Figure 5. The concentration ratios of PM2.5 from PM10 at the study sites.

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The third model was proposed by Ruijgrok and was fit to a European forest. If \( V_s \) is the deposition velocity due to sedimentation, then \( V_d \) is calculated using the following equation:

\[
V_d = \frac{1}{\frac{1}{V_{ds}} + R_d} + V_s
\]  
(18)

\[
V_{ds} = \frac{u^2}{u_b} E
\]  
(19)

\[ RH > 80, E = 0.05u^{0.28} \left[ 1 + 0.18\exp \left( \frac{RH - 80}{20} \right) \right] \]  
(21)

\[ RH \leq 80, V_S = 0.0067 \]  
(22)

\[ RH > 80, V_S = 0.0067\exp \left( \frac{0.0066RH}{1.058 - RH} \right) \]  
(23)

\[ RH \leq 80, E = 0.05u^{0.28} \]  
(20)

In the above equation, \( RH \) is the relative humidity, and \( u_b \) is the wind speed at the top of the canopy (approximately 9 m).

**Table 3.** Mean deposition velocities, friction velocity and Monine-Obukhov length.

| Daytime in Olympic in Feb. | Daytime in Jiufeng in Feb. | Daytime in Olympic in May. | Daytime in Jiufeng in May. |
|---------------------------|--------------------------|----------------------------|---------------------------|
| \( V_d \) (cm s\(^{-1}\)) | \( u^* \) (m s\(^{-1}\)) | \( L \) (m)               | \( u^* \) (m s\(^{-1}\)) | \( L \) (m)               |
| 0.02±0.03                 | 0.22±0.12                | −11.6±5.6                  | 0.01±0.01                 | 0.12±0.06                | 21.77±12.5                |
| 1.2±1.3                   | 0.39±0.23                | −15.5±7.4                  | 0.7±0.7                   | 0.29±0.13                | 20.6±12.8                |
| 0.9±0.8                   | 0.35±0.22                | −17.15±9.7                 | 0.4±0.5                   | 0.19±0.12                | 27.97±14.3               |
| 1.1±1.2                   | 0.42±0.25                | −15.9±7.8                  | 0.6±0.5                   | 0.31±0.18                | 22.8±6.4                 |

\( u^* \) and \( L \) in the daytime and nighttime during the study period (February and May 2013). All of the values are the mean±standard deviation.

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Results and Discussion

1. Atmospheric Conditions

Meteorological conditions greatly impact the concentration of PM2.5 [27]. Therefore, the impacts of the conditions are important to analyze. Table 2 summarizes the meteorological conditions of Jiufeng National Forest Park and Olympic Forest Park, including temperature, humidity, wind speed, and solar radiation. Figure 3 presents the relationships between the meteorological conditions. We observed several common patterns between Jiufeng National Forest Park and Olympic Forest Park. The humidity and temperature were higher in the Olympic Forest Park, but the concentration of PM2.5, the solar radiation, and the wind speed were lower.

2. PM2.5 Gradients

Testing the changes in aerosol concentrations at multiple altitudes is difficult. The differences between the altitudes were minimal. A paired t-test reveals that the concentration at 15 m was significantly (P<0.01) higher than the concentration at 9 m during the spring (vegetation with young leaves), whereas the concentrations were not significantly different in the winter (vegetation without leaves). To decrease the sampling error, we used the same instrument to measure the concentration seven times at the same height of 9 m (or 15 m).

Fig. 4 shows the average concentrations measured at the various heights, sites and times. The concentration at 15 m was greater than that at 9 m, and concentrations appeared to decrease with height. This observation indicates a downward flux of the particulate aerosols (top down). To decrease the sampling error, we used the same instrument to measure the concentration seven times at the same height of 9 m (or 15 m).

As shown in Fig. 5, the concentration ratios of PM2.5 to PM10 were 42% in spring and 59% in winter in Jiufeng National Forest Park and 49% in the spring and 66% in the winter in Olympic Forest Park. This indicates that the environmental conditions had an enormous impact on the concentration ratios of PM2.5.

3. The Concentration Ratios of PM2.5 from PM10

The concentration ratios of PM2.5 and PM2.5–10 (PM10 minus PM2.5) to PM10 reflect different sources of pollution among regions and seasons. In the winter, natural gas heating is used throughout Beijing instead of coal; however, there is a lower socioeconomic belt around Beijing that uses old-fashioned fireplace burning coal for heating [28–29]. This population’s reliance on coal heating is also responsible for the excessive sulfur dioxide discharge [30–31]. Another important source of pollution is the motor vehicle exhaust from the 5.3 million cars in Beijing [32].

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4. The Change in the PM2.5 Concentration

Fig. 4 illustrates the diurnal variation of the PM2.5 concentrations in various seasons. PM2.5 concentrations in the winter were much higher than those in the spring in Jiufeng National Forest.
Horváth et al. [41] believed that it was important to correct the measured values were larger than the modeled values. However, the reason for this ambiguity could be a sampling error, as indicated by the report of Kazuhide et al. [3]. Researchers from Japan suggested that velocities observed in this study were comparable to those reported in Kazuhide’s study [3]. The deposition velocities of the aerosol particles were strongly influenced by aerodynamic conditions. In other studies [36–37], lower PM2.5 concentrations were observed at special times, such as the 50th National Day in 1999, which can be attributed to specific procedures mandated by the government to reduce the emissions of PM2.5. Artificial simulation of rainfall was applied in the Che Gong Zhuang area on September 30, 1999. As a result, the PM2.5 concentration was notably low (50 μg/m²) [36].

The average PM2.5 concentration was 60% to 100% higher in the winter than in the spring, and 30% to 40% higher than the annual average [37] and was far greater than that of the EPA Ambient Air Quality Standard [38]. The deposition velocities during the day and night in Olympic Forest Park and Jiufeng National Forest Park were notably small in February because the vegetation in the forest lacked leaves. During February and May, the deposition velocities in Jiufeng were higher than in Olympic Forest Park. The main reason for this observation is that the PM2.5 capture rate of needle-leaved evergreen forests is higher than that of broadleaf deciduous forests [39].

This study revealed that deposition increased in the daytime, whereas it decreased in the nighttime in Olympic Forest Park and Jiufeng National Forest Park. This result is consistent with previous studies. In Norway, Netherlands, America, Canada, Portugal [40], and Japan [10], the deposition velocities of aerosol particles were measured at the tops of coniferous forests. The measured values were greater than the computations by the Ruijgrok et al. (1997) model [23] in Kazuhide’s study [3]. However, the deposition velocities observed in this study were comparable to those reported in Kazuhide’s study [3]. Researchers from Japan suggested that the reason for this ambiguity could be a sampling error, as indicated by the report of Kazuhide et al. [3].

The present study was conducted in Jiufeng National Forest Park and Olympic Forest Park in Beijing, China. To the best of our knowledge, this is the first report of the measurement of the deposition velocity of PM2.5 in China. This study also represents the first attempt to compare the deposition velocity in the city center with that in the suburbs. In general, the deposition was higher during the daytime than during the nighttime. Likewise, the deposition was higher in the suburbs compared with the urban area. The deposition velocities of the aerosol particles were significantly higher in Jiufeng National Forest Park than in Olympic Forest Park during the same time periods. This may be due to the greater friction velocity in Jiufeng National Forest Park. Furthermore, the deposition velocities of the aerosol particles were also influenced by the eddy diffusion coefficient of the sub-layer surface roughness, as indicated by the report of Kazuhide et al. [3].

Our results indicated that the deposition velocities of the aerosol particles were influenced by the friction velocity (Figure 6). The friction velocity was strongly influenced by the aerodynamic conditions [22,23,24,42]. Thus, the deposition velocities of the aerosol particles were strongly affected by aerodynamic conditions. These results are consistent with most recently reported results from other centers [22–24].

A potential sampling error resulted in larger measured values compared with the model values. Therefore, it was important to correct the model parameters to calculate the deposition velocities. Therefore, the deposition flux increased 56% during the day and increased 52% during the night. The increase in deposition flux during the day was greater than that at night. The same general patterns were observed with the deposition velocity.

5. Deposition Velocities

Table 3 lists the deposition velocities and relative parameters such as deposition velocity $V_d$ (cm s⁻¹), friction velocity $u^*$ (m s⁻¹), and Monine-Obukhov length $L$ (m), during the daytime and nighttime, in Olympic Forest Park and Jiufeng National Forest Park. A positive correlation exists between $u^*$ and $V_d$ (Figure 6). The deposition velocities during the day and night in Olympic Forest Park were notably small in February because the vegetation in the forest lacked leaves. During February and May, the deposition velocities in Jiufeng were higher than in Olympic Forest Park. The main reason for this observation is that the PM2.5 capture rate of needle-leaved evergreen forests is higher than that of broadleaf deciduous forests [39].

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A potential sampling error resulted in larger measured values compared with the model values. Therefore, it was important to correct the model parameters to calculate the deposition velocities.
of PM2.5 and to compare the calculated values of the models with the measured values.

The measured results were more consistent with the Ruijgrok et al. (1997) model than with the Wesely et al. (1995) model. Different models were applicable to different profiles of the forests in different regions. The Ruijgrok et al. (1997) model was more applicable to the coniferous and broadleaved forests in northern China.

Supporting Information

Data S1 Data S1 is the data of meteorological data and PM2.5 concentration. This data contain seven parts: 1. meteorological data1 include temperature,humidity,wind direction,wind speed et al in different height in Olympic Forest Park. 2. meteorological data2 include temperature,humidity,wind direction,wind speed et al in different height in Jiufeng National Forest Park. 3. met data include Monin-Obucov length and friction velocity. 4. PM2.5 DATA1 is the PM2.5 concentration in winter of Jiufeng National Forest Park. 5. PM2.5 DATA2 is the PM2.5 concentration in spring of Olympic Forest Park. 6. PM2.5 DATA3 is the PM2.5 concentration in winter of Olympic Forest Park. 7. PM2.5 DATA4 is the PM2.5 concentration in spring of Jiufeng National Forest Park.

(XLS)

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Author Contributions

Conceptualized and designed the experiments: F. Sun XLI. XY. Performed the experiments: F. Sun ZY. Analyzed the data: F. Sun XLI. XY. F. Shi. ZY. Contributed reagents/materials/analysis tools: XY. Wrote the paper: F. Sun XLI. XY.

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