Temporal and Spatial Variation and Influencing Factors of Soil Moisture in 
* Larix principis-rupprechtii* Plantation in 
Semiaрид Liupan Mountains, Northwest China

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Abstract: Understanding the temporal and spatial variation of soil moisture of forest and studying the effects of vegetation transpiration, forest floor evapotranspiration and meteorological factors on soil moisture are important to vegetation restoration, integrated forest-water management and the improvement of the eco-hydrological functions of forest/vegetation in the arid regions. A stand plot of *Larix principis-rupprechtii* plantation was established in the semiarid Dieiedigou small watershed on the north side of Liupan Mountains, Ningxia. Meteorological conditions, forest transpiration, forest floor evapotranspiration and soil moisture during July to October in 2013 were simultaneously monitored by automatic meteorological station, thermal diffusion probes, micro-lisometers and time domain reflectometry. The soil moisture was monitored in the layers of 0–20, 20–40, 40–60 and 60–80 cm, to explored the main factors affecting the soil moisture. The results showed that: (1) Affected by the random rainfall events, the soil moisture showed corresponding pulse variation. On the whole, the mean soil moisture (32.69%) of the surface layer (0–20 cm) was relatively lower than that of the layers followed (about 40.00%). The variation range of soil moisture decreased...
transpiration and forest floor evapotranspiration had a significant correlation with the soil moisture of the main root zone (0–60 cm) during the whole study period. (3) The correlation coefficients between soil moisture and all the influencing factors decreased with the increasing of soil depth, which were significant in the main root zone, but no longer significant in the soil layers below (60–80 cm). In summary, the soil moisture was affected by both the precipitation input and evapotranspiration output. The temporal variation of soil moisture in each soil layer was similar. However, the soil moisture of surface layer was low and with a larger variation range. The sensitivity and amplitude of soil moisture to the influencing factors decreased gradually with the increasing of soil depth.

Keywords: soil moisture; forest floor evapotranspiration; forest transpiration; meteorological condition; 
Larix principis-rupprechtii plantation

Soil water content is a major component of the soil—vegetation—atmosphere system. Soil moisture is closely related to the climate, vegetation, and the soil type. In this study, we investigated the effects of precipitation and evapotranspiration on soil moisture content in a Larix principis-rupprechtii plantation. Soil water content was measured at different depths and times, and the results showed a significant correlation with soil moisture and precipitation. The soil moisture content was affected by both precipitation and evapotranspiration. The temporal variation of soil moisture was similar in all soil layers. However, the soil moisture of the surface layer was low and showed a larger variation range. The sensitivity and amplitude of soil moisture to the influencing factors decreased gradually with the increasing of soil depth.

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In summary, the soil moisture content was affected by precipitation and evapotranspiration. The temporal variation of soil moisture was similar in all soil layers. However, the soil moisture of the surface layer was low and showed a larger variation range. The sensitivity and amplitude of soil moisture to the influencing factors decreased gradually with the increasing of soil depth.

1. Research Area

The study site is located in Xingyi City, Guizhou Province, China. The climate is humid subtropical with a mean annual temperature of 14 °C and an annual precipitation of 1200 mm. The soil is a typical red soil, which is rich in organic matter and nutrients. The vegetation is characteristic of the region, with a rich biodiversity.

2. Methods

2.1 Site Selection

The study site is located in a forest area in the Xingyi City, Guizhou Province, China. The site is characterized by a humid subtropical climate, with a mean annual temperature of 14 °C and an annual precipitation of 1200 mm. The soil is a typical red soil, which is rich in organic matter and nutrients. The vegetation is characteristic of the region, with a rich biodiversity.

2.2 Data Collection

Soil moisture content was measured at different depths and times using a soil moisture sensor. Precipitation data were collected from a nearby weather station. Evapotranspiration data were calculated using the Priestley-Taylor equation. The results showed a significant correlation between soil moisture and precipitation. The temporal variation of soil moisture was similar in all soil layers. However, the soil moisture of the surface layer was low and showed a larger variation range. The sensitivity and amplitude of soil moisture to the influencing factors decreased gradually with the increasing of soil depth.

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其海拔为 2055 m。坡向为北偏西 30°，下坡位，坡度约 11°；林分密度过为 1600 株/ hm²，在研究年份 2013 年的林龄为 25 年，林冠郁闭度 0.88，平均树高 10.1 m，平均胸径 10.56 cm；林分结构单一，林下灌木层不明 显，生长有少量草本等；林下草本层发育较好，盖度 0.78，主要有铁杆 Eğer、芨芨（Artemisia giralldii）、羽 叶毛 菊（Saussurea maximowiczii）、白 颖 菊（Carex rigescens）等。土层较厚，约 2 m 以上。

各种观测均在该样地进行，时间为 2013 年 7 月 15 日至 10 月 31 日。

### 2.2 土壤物理性质测定

在样地附近典型位置挖 3 个土壤剖面，分 0—20，20—40，40—60，60—80 cm 4 层，用体积 100 cm³ 的环刀取土，带回实验室后利用环刀法测定土壤容 重、孔度、持水量，稳定率等物理性质。各土层物 理性质见表 1。

<table>
<thead>
<tr>
<th>表 1 不同土层的土壤物理性质</th>
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<tr>
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<td>40—60</td>
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<td>60—80</td>
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</table>

### 2.3 气象条件监测

在林外开阔处架设 1 台 Wheatherhawk—232（Campbell Scientific, 美国）自动气象站，同步监测降水量 (P, mm)、空气温度 (T, °C)、气压 (AP, kPa)、阳光辐射强度 (ESR, W/m²)、风速 (W, m/s)、风向 (WD, °) 等，计算蒸发散水量 (VPD, kPa) [30] 和潜在蒸发散量 (PET, mm) [31]。同时，在样地内设置 1 台 LI—1400 小型自动气象站（LI—COR，美国），并连续监测 20—40 cm 深土层温度（℃）。

### 2.4 林木蒸腾和林地蒸散测定

在样地内选取 5 株干径通直，生长良好的优势木 或亚优势乔木样树，安装 SF—L 树干流液测定仪（Ecomatic, 德国）。由于林木长势高低不一，故选用 20 mm 长的探针，安装方法、检测程序及数据计算方法见文献[10]。利用 5 株样树流液密度均值作为林 分流液密度，基于枝条与边材的平均经验公式[32] 获得单株和林分的枝条面积，并以此为标量推估林分 蒸腾量（ES, mm）。在样地内选择代表草本层种类和 盖度及林冠遮蔽状况的地点 5 个，安装微型蒸散仪（内径 5 mm，深 35 cm，简底带筛孔，下方放置容器收集 细流水分），蒸散仪内筒装有未扰动的原状枯落叶、土 柱和草本植物。每天固定时间（8:00）称重 1 次，根据 前 2 天称重差值（kg）及 1 天内的降水量（mm）、渗 漏水量（mm）计算各日林地蒸散量（EF, mm）。

### 2.5 土壤湿度监测

采用 TDR 时域反射仪（Time Domain Reflectometry，德国）长期定位监测土壤湿度。在样地内选择 3 处典型点位安装 TDR 测管，每目固定时间（8:00）读数，依林木根系分布，分 0—20，20—40，40—60，60—80 cm 土层，将 3 个点位均值作为样地土壤体积分含水量。

### 2.6 数据处理

采用 Excel 2010 和 SPSS19.0 软件处理分析数据。

### 3 结果与分析

#### 3.1 降水量和土壤湿度的日变化

由图 1 可知，研究期间总降水量 412 mm，但集中在 7 月 15 日至 8 月 7 日（153 mm，占 38.11％）、8 月 22 日至 9 月 23 日（219 mm，占 53.16 ％）2 个时段，其余时间降雨很少，仅占 8.75％。受脉冲式降雨事件影响，各土层湿度呈对应变化，在降水间隔期受蒸散耗水影响而逐渐减少，其中表层（0—20 cm）变幅最大，其均值也低于其他各层，呈现土壤湿度变幅随土层加深而减小但均值增加的变化趋势。

#### 3.2 各土层湿度变化的统计分析

由表 2 可知，研究期间 0—80 cm 土层的体积含水量平均为 38.05％，极差为 17.44％。表层湿度均值 最小（32.69％），其下各层都在 40％左右，变化不 大。各层体积含水量最大值的湿度变化规律与均值 相似，最小值随土层加深逐渐增大，极差的土层变化 与最小值相反。在各月之间，0—80 cm 土层体积含 水量的均值和最大值分别为 8.75％，80—80 cm 相同，但 60—80 cm 土层体积含水量均值的月变化为 10 月 > 9 月 > 8 月，表层土 壤体积含水量的最大值和最小值均出现在 7 月 > 9 月 > 10 月 > 8 月。其他各层与 0—80 cm 相同；各土层体积含水量的极大值变化与 0—80 cm 相同。

在 7 月，各土层体积含水量的均值、最大值和最小值随土层加深呈元先升高后轻微降低的变化，峰值均出现在 20—40 cm。最小值的土层变化为先快速增加后缓慢
增加，极差表现出与最小值相反的土层变化。在 8月，各层体积含水量均值随土层加深逐渐增大，但增幅渐小；最大值表现出先增大后轻微降低的变化，峰值(44.63%)出现在 20－40 cm；最小值(极差)呈现出与均值相同(相反)的深度变化。在 9月，各层体积含水量均值、最大值、最小值随土层加深均呈现先升高后轻微降低的变化，最高值出现在 20－40，40－60 cm；极差的土层变化为先急剧减小后轻微减小。在 10月，各层体积含水量的均值、最大值、最小值、极差的土层变化与 9月相似。

图 1 降水量和各土层体积含水量的逐日变化

标准差与变异系数(CV)分别表示绝对变异和相对变异大小。

由表 2 可知，各土层的标准差均小于 7，7月与 9月均小于 10月，随土层加深逐渐减小。依据变异性强弱分别(CV<10%为中等；CV>10%为强)，8月属中等变异，7，9，10月属弱变异性；各土层变异性的月份差异与标准差相同，各月及研究期间 20－40 cm 和 8月的 20－40 cm 属中等变异性，其余均为弱变异性，随土层加深逐渐减小。

表 2 不同层次土壤湿度的统计特征

<table>
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<th>测定时间</th>
<th>土层深度/cm</th>
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<th>最小值/%</th>
<th>极差/%</th>
<th>平均值/%</th>
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<th>变异系数/%</th>
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3.3 各土层湿度的气象条件响应

由表 3 可知，在研究期间和不同月份(除 7月的土温和气压、9月的温度、风向和温度在蒸散外)基本呈现出气象因子对土壤湿度的作用随土层加深逐渐减弱。

研究期间，0－80 cm 平均体积含水量与气压相
象因子相关极显著（P＜0.01），40～60 cm 土壤湿度与温度和饱和水气压差相关极显著（P＜0.01），与潜在蒸散、太阳辐射和风向相关显著（P＜0.05），与其他气因子相关不显著（P＞0.05）；60～80 cm 土壤湿度与 20 cm 土壤温度显著相关显著（P＜0.05），与其他气因子相关不显著（P＞0.05）。

### 表 3 各土层温度与气象条件的相关系数

<table>
<thead>
<tr>
<th>测定时间</th>
<th>土层深度(cm)</th>
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<th>(T_{\text{min}})</th>
<th>(T_{\text{max}})</th>
<th>(T_{10})</th>
<th>(T_{20})</th>
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<td>-0.313</td>
<td>-0.209</td>
<td>-0.390</td>
<td>-0.325</td>
<td>0.283</td>
<td>0.378</td>
<td>0.210</td>
<td>-0.340</td>
<td>-0.382</td>
<td>-0.362</td>
<td>-0.281</td>
<td>-0.473</td>
</tr>
<tr>
<td></td>
<td>20~40</td>
<td>0.112</td>
<td>0.212</td>
<td>0.044</td>
<td>0.283</td>
<td>0.180</td>
<td>0.240</td>
<td>0.140</td>
<td>-0.230</td>
<td>-0.244</td>
<td>-0.237</td>
<td>-0.261</td>
<td>-0.361</td>
</tr>
<tr>
<td>8月</td>
<td>1~20</td>
<td>-0.361</td>
<td>-0.260</td>
<td>-0.378</td>
<td>-0.325</td>
<td>0.283</td>
<td>0.378</td>
<td>0.210</td>
<td>-0.340</td>
<td>-0.382</td>
<td>-0.362</td>
<td>-0.281</td>
<td>-0.473</td>
</tr>
<tr>
<td></td>
<td>20~40</td>
<td>0.112</td>
<td>0.212</td>
<td>0.044</td>
<td>0.283</td>
<td>0.180</td>
<td>0.240</td>
<td>0.140</td>
<td>-0.230</td>
<td>-0.244</td>
<td>-0.237</td>
<td>-0.261</td>
<td>-0.361</td>
</tr>
<tr>
<td>9月</td>
<td>1~20</td>
<td>0.140</td>
<td>0.277</td>
<td>0.128</td>
<td>0.280</td>
<td>0.255</td>
<td>0.175</td>
<td>0.125</td>
<td>-0.235</td>
<td>-0.235</td>
<td>-0.235</td>
<td>-0.240</td>
<td>-0.235</td>
</tr>
<tr>
<td></td>
<td>20~40</td>
<td>0.442</td>
<td>0.374</td>
<td>0.384</td>
<td>0.498</td>
<td>0.498</td>
<td>0.498</td>
<td>0.498</td>
<td>-0.498</td>
<td>-0.498</td>
<td>-0.498</td>
<td>-0.498</td>
<td>-0.498</td>
</tr>
<tr>
<td>10月</td>
<td>1~20</td>
<td>0.351</td>
<td>0.359</td>
<td>0.468</td>
<td>0.332</td>
<td>0.341</td>
<td>0.735</td>
<td>0.473</td>
<td>-0.193</td>
<td>-0.282</td>
<td>-0.378</td>
<td>-0.378</td>
<td>-0.378</td>
</tr>
<tr>
<td></td>
<td>20~40</td>
<td>0.520</td>
<td>0.520</td>
<td>0.468</td>
<td>0.332</td>
<td>0.341</td>
<td>0.735</td>
<td>0.473</td>
<td>-0.193</td>
<td>-0.282</td>
<td>-0.378</td>
<td>-0.378</td>
<td>-0.378</td>
</tr>
</tbody>
</table>

注: *P＜0.05; **P＜0.01; T为日均气温(℃); \(T_{\text{min}}\)为日最低气温(℃); \(T_{\text{max}}\)为日最高气温(℃); \(T_{10}\)为日均 20 cm 土温(℃); \(T_{20}\)为日均 40 cm 土温(℃); RH 为日均空气相对湿度(％); AP 为日均气压(kPa); PET 为日均潜在蒸散量(mm); ESR 为日均太阳辐射强度(w/m²); W 为日均风速(m/s); WD 为风向(º); VPD 为饱和水气压差(kPa)。

7月，表层土壤湿度与日最低温度和 40 cm 土温相关不显著（P＞0.05），与其他气因子相关显著（P＜0.05）；日均温与 40 cm 土温极显著（P＜0.01），日均温与 40 cm 土温相关显著（P＜0.05），与 40~60, 60~80 cm 土壤湿度与温度和气压相关显著（P＜0.01），与其他气因子相关显著（P＜0.05）。8月，表层土壤湿度与日均温（P＜0.05）；表层土壤湿度与日均温、40 cm 土温及饱和水气压差相关显著（P＜0.05），60~80 cm 土壤湿度与温度相关显著（P＜0.05），与 40~60, 60~80 cm 土壤湿度与温度相关显著（P＜0.05），与其他气因子相关显著（P＜0.05）。9月，表层土壤湿度与日均温、日最低温度、日均温及饱和水气压差显著（P＜0.01），日均温与 40 cm 土温相关显著（P＜0.05）。10月，表层土壤湿度与 40~60, 60~80 cm 土壤湿度与温度和气压相关显著（P＜0.01），与 40~60, 60~80 cm 土壤湿度与温度和气压相关显著（P＜0.01），与其他气因子相关显著（P＜0.05）。11月，表层土壤湿度与 40~60, 60~80 cm 土壤湿度与温度和气压相关显著（P＜0.01），与其他气因子相关显著（P＜0.05）。

### 3.4 各土层湿度对林木蒸腾和林地蒸散的响应

由图 2 可知，林木蒸腾和林地蒸散随日温度波动幅度较大，但整体呈逐渐减小趋势。研究表明林木总蒸腾为 58.96 mm, 7.8, 9, 10 月均值分别为 0.21, 0.71, 0.84, 0.49, 0.21 mm/d；而林地总蒸散为 160.39 mm, 7.8, 9, 10 月均值分别为 1.56, 2.16, 1.24, 0.95 mm/d。

由表 4 可知，研究期间和各月均表现为林木蒸腾和林下蒸散随日湿度变化的影响随土壤类型及温度变化而变化。研究表明 40~60 cm 土壤湿度与温度相关显著（P＜0.05），与 40~60, 60~80 cm 土壤湿度与温度显著（P＜0.05），与其他气因子显著相关显著（P＜0.01）。
月，表层和 0—80 cm 土壤湿度与两者及 20—40 cm 土壤湿度与林地蒸散相关极显著(P<0.01)，60—80 cm 土壤湿度与林木蒸腾相关显著(P<0.05)，其余各层与两者相关均不显著(P>0.05)。

4 讨论

4.1 土壤水分时空变化特征

在干旱地区，土壤湿度直接影响植被生长与分布，其时空变化主要受天气条件和蒸腾、植被特征、水分运移等因素的影响。土壤水分的损失途径包括表层下的植被蒸腾和土壤蒸发以及向下的渗漏(漏失)等，补给途径主要是降水和少量地表径流，因而脉冲性的降水输入直接导致土壤湿度变化呈波浪状。杨磊等[12]、唐敏等[11]研究典型植被和不同土地类型中的土壤湿度动态变化，其结果与本研究相同。

雨水在降雨林地区土壤的深层下移过程中，由于沿途不断补充土壤水分而使可继续下移的数量逐渐减小，植被根系数量沿土层深度增加而减少，使其吸收土壤水分的数量从表层向下也减少，表层土壤蒸发也是首先消耗表层和浅层土壤水分，这些作用机制共同导致土壤湿度的变幅从表层向下而逐渐减小(图 1)。在本研究中，表层土壤体积含水量总体上低于下层，这与黄土丘陵区和祁连山地区研究的结果一致，这可能与其气候差别(降水量、蒸散能力)和植被根系深度分布特点等有关。


4.2 土壤水分变化对影响因子的响应

受土地利用、微地形、气象条件、林木年龄、植被类型和生长耗水(植被蒸腾、土壤蒸发)、管理措施等的综合作用，土壤湿度的时空变化极为复杂。本研究主要讨论了土壤湿度变化受气象条件、林木蒸腾和林地蒸散等的影响。

Table 4 各层土壤湿度与林木蒸腾、林地蒸散的相关系数

<table>
<thead>
<tr>
<th>土层深度/cm</th>
<th>ES</th>
<th>7月</th>
<th>8月</th>
<th>9月</th>
<th>10月</th>
<th>EF</th>
<th>7月</th>
<th>8月</th>
<th>9月</th>
<th>10月</th>
</tr>
</thead>
<tbody>
<tr>
<td>0—20</td>
<td>-0.317</td>
<td>-0.588*</td>
<td>-0.284</td>
<td>0.013</td>
<td>-0.570*</td>
<td>-0.444</td>
<td>-0.539*</td>
<td>-0.360</td>
<td>-0.069</td>
<td>-0.737*</td>
</tr>
<tr>
<td>20—40</td>
<td>-0.217</td>
<td>-0.010</td>
<td>-0.274</td>
<td>-0.407</td>
<td>-0.287</td>
<td>-0.373*</td>
<td>-0.407</td>
<td>-0.287</td>
<td>-0.116</td>
<td>-0.500*</td>
</tr>
<tr>
<td>40—60</td>
<td>-0.210</td>
<td>-0.004</td>
<td>-0.066</td>
<td>-0.286</td>
<td>-0.246</td>
<td>-0.316*</td>
<td>-0.286</td>
<td>-0.246</td>
<td>-0.041</td>
<td>-0.274</td>
</tr>
<tr>
<td>60—80</td>
<td>-0.091</td>
<td>-0.087</td>
<td>-0.073</td>
<td>0.015</td>
<td>-0.428*</td>
<td>-0.156</td>
<td>-0.147</td>
<td>-0.125</td>
<td>0.045</td>
<td>-0.267</td>
</tr>
<tr>
<td>0—80</td>
<td>-0.262</td>
<td>-0.468</td>
<td>-0.224</td>
<td>0.005</td>
<td>-0.456*</td>
<td>-0.379*</td>
<td>-0.449</td>
<td>-0.289</td>
<td>-0.053</td>
<td>-0.667*</td>
</tr>
</tbody>
</table>

注：ES 为林木日蒸腾量 (mm)；EF 为林地日蒸散量 (mm)。
随土层加厚而逐渐减缓。

在研究期间，影响土壤湿度的气象因子主要是温度、潜在蒸发、太阳辐射和饱和水气压差。但是，影响各月份不同土层的土壤湿度变异的主导因子存在差异，可能是因水分输入不均衡（降雨分配不均）、各土层水分对林分蒸散的贡献差异、林木生长节律差异等共同作用的结果，但仍能看出温度是影响土壤湿度时空变化的主导因子。庄家等^{[15]}在南京市郊区东善桥林场的研究表明，林地和草地 0－30 cm 土壤湿度变化量主要受空气温度湿度等的影响，与本研究结果基本相同。从观测结果看，10 月的林木蒸腾和林地蒸散与各层土壤湿度的相关程度多数强于其他各月，可能是因 10 月降雨天数和降雨量均较少数造成的。

本文仅初步分析了生长中后期的土壤湿度对变化情况，未来需扩展研究的时尺时度，如加强多年、整个生长季的研究以及日变化研究。另外，本研究仅是通过相关分析而初步研究了土壤湿度对气象条件，蒸散散布变化的影响，以后应加强土壤水分平衡动态过程的数值划算。理解和量化立地特征、植被结构、地被物覆盖、土壤特性、气象条件（降水、温度、潜在蒸散）等对土壤水变化的作用机理。

5 结论

（1）受随机降雨事件影响，土壤湿度变化呈波浪状。表层土壤湿度较低，平均 32.69%，而其他土层均在 40% 左右，变异性程度随降雨输入增大和土层加深而逐渐减缓。

（2）影响土壤湿度的主导气象因子存在月份和土层深度差异。在整个研究期间为温度和饱和水气压差。在 7.8.9.10 月分别为土温和气压、土湿、温度和气压、温度和饱和水气压差；对各土层的主导气象因子均为温度。

（3）林木蒸腾和林下蒸散对土壤湿度的作用弱于气象条件。研究期间两者与主根系层（0－30 cm）土壤湿度相关显著，其中 10 月份两者对土壤湿度的作用强于其他月份；相关关系随土层加深和降雨增多而变弱。

（4）各因子对土壤湿度的影响随土层加深而变弱，在主根系层明显，以下土层不明显。

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