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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

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Name

学位論文題目：
Title of Dissertation
Throughfall and stemflow by rainfall and fog under different tree characters in a montane forest of Popa Mountain Park, Central Myanmar
(中部ミャンマー・ポッパ山林における異なる樹種を対象とした降雨と霧による林冠通過雨水量と樹幹流に関する研究)

学位論文要約：
Dissertation Summary

Montane forests provide 60-80% of the world's freshwater resources despite its coverage area is only 28% of the world's total forest area. Thus, montane forests have been getting increasing recognition from scientists for their hydrological services to sustain the water resources to communities living in the downstream areas. However, a rapid depletion of montane forest leads to water related issues. For instance, seriously decreased water resources after removal of montane forest have been reported in various parts of the tropics including Myanmar. In Myanmar, deforestation and forest degradation occur with a rapid rate due to land-use changes despite the government is focusing on the conservation of natural forests. Hence, a large-scale afforestation and reforestation program, intensively implemented in central dry zone of Myanmar, is implemented in the deforested and degraded forest area by expecting to gain more rainwater input.

Several studies have discussed that rainfall in a forest can be divided into three components: (1) throughfall (TF), i.e., rainwater that reaches the ground by passing through the small gaps within the canopies or intercepted rainwater dripping via the foliage, (2) stemflow (SF), i.e., rainwater that reaches the ground by flowing down along the branches and stems, and (3) interceptive loss (IL), i.e., rainwater that is intercepted by the canopies and does not reach the ground due to the evaporation loss from the canopy. In a rainfall partitioning, throughfall and stemflow can be measured directly, but interception loss is estimated from the differences between gross rainfall and net rainwater input (sum of throughfall and stemflow). Partitioning amount of throughfall, stemflow, and interception loss are region-specific and depends on numerous factors which are topographic, meteorological, and vegetative. Thus, rainfall partitioning is crucial to assess the net rainwater input of a region.

In Myanmar, however, there have been no scientific studies related to rainfall partitioning research. Therefore, this study was conducted in Popa Mountain Park (PMP) aiming to: (1) investigate the partitioning amount of net rainwater that reach to the ground, (2) examine the influencing factors on partitioning of net rainwater input, (3) investigate the importance of stemflow to soil water replenishment, and (4) monitor the impacts of land-use changes on the conservation of montane forest. Gross rainfall (Pg), throughfall (TF) under different canopies, stemflow (SF) at different tree types, and soil water content (SWC) at different places for different soil depths were measured in PMP for 125 days (from 30th Jun to 2nd Nov, 2019). Reference points for accuracy assessment of land-use land cover changes were collected during Feb and Mar in 2019. Canopy and tree characteristics such as canopy cover, leaf area index (LAI), crown area, crown thickness, tree diameter at breast height (DBH), height were measured in the site. Bark texture and crown shape were visually observed in the site.

Total gross rainfall during the entire observation period was 753.6 mm. This study showed that mean TF, SF, and IL rates were 58.7% (442.3 mm), 18.9% (142.4 mm) and 22.4% (168.8 mm) of total Pg, respectively. By comparing IL under three different Pg classes (Pg>10.0 mm, 10.0 mm ≥ Pg ≤ 50.0 mm, and Pg >50.0 mm),

this study found that IL did not have significant correlations with any Pg classes ($p > 0.05$). Moreover, IL did not have significant correlation with other climatic factors (solar radiation, air temperature, relative humidity, wind speed and wind direction) in PMP.

This study successfully partitioned total TF and total SF into TF and SF caused by Pg and fog. By comparing TF and SF in four different tree types (two for TF and two for SF), this study found that a sparser canopy resulted in larger TF by Pg than a denser one ($p > 0.05$). However, a denser canopy resulted in larger TF by fog ($p < 0.05$). TF rates from Pg (TF_{rain}/Pg) in the sparser and denser canopies were 54.5% and 51.5%, respectively, while those from fog (TF_{fog}/TF_{all}) were 15.2% and 27.2%, respectively. As a result, total TF rate (TF_{all}/Pg) in the denser canopy (70.7%) was significantly higher than that of the sparser one (64.3%). Shorter trees with small crowns and smooth bark (Type I) resulted in larger SF from Pg than taller trees with larger crowns and rougher bark (Type II) ($p < 0.05$). However, Type II trees resulted in larger SF from fog ($p < 0.05$). SF rates from Pg (SF_{rain}/Pg) for Type I and II trees were 17.5% and 12.2%, respectively, while those from fog (SF_{fog}/SF_{all}) were 22.2% and 39.5%, respectively. No significant total SF rates (SF_{all}/Pg) were found at Type I (22.5%) and II trees (20.1%).

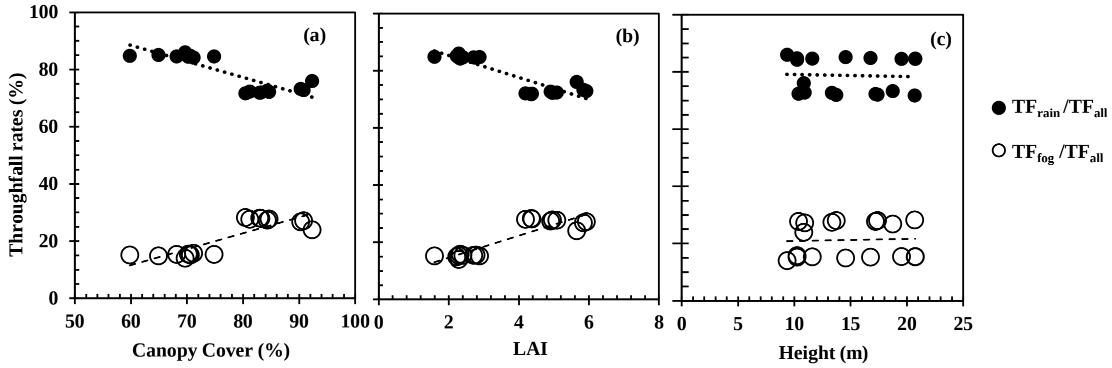

Fig. 1 Relationships of throughfall rates from rainfall and fog with (a) canopy cover, (b) LAI and (c) height.

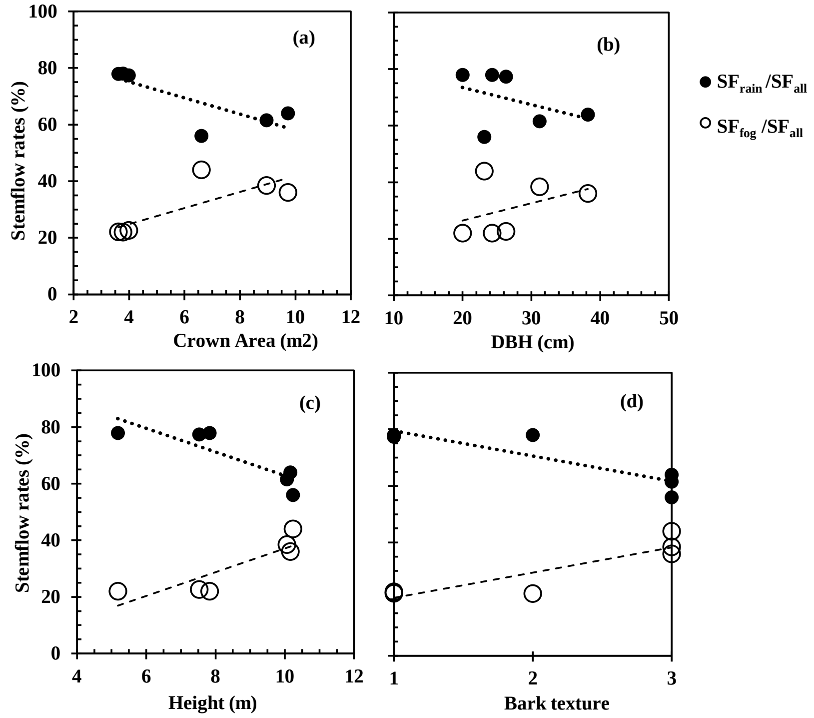

Fig. 2 Relationships of stemflow rates from rainfall and fog with (a) crown area, (b) DBH, (c) height, and (d) bark texture where 1 is defined as smooth, 2 for semi-rough and 3 for rough bark.

In this study, the influences of canopy cover, LAI and height on throughfall rates were investigated as shown in Fig. 1. Throughfall rates from rainfall (TF_{rain}/TF_{all}) were negatively correlated with canopy cover ($r = -0.85$, $p < 0.05$) and LAI ($r = -0.89$, $p < 0.05$). However, throughfall rates from fog (TF_{fog}/TF_{all}) were positively correlated with canopy cover ($r = 0.85$, $p < 0.05$) and LAI ($r = 0.89$, $p < 0.05$). Height had weak correlations with both throughfall rates ($r = 0.05$, $p > 0.05$). Figure 2 shows the relationships of stemflow rates with crown area, DBH, height and bark texture. Stemflow rates from rainfall (SF_{rain}/SF_{all}) were negatively correlated with crown area ($r = -0.86$, $p < 0.05$), DBH ($r = -0.51$, $p > 0.05$), height ($r = -0.89$, $p < 0.05$) and bark texture ($r = -0.91$, $p < 0.05$). However, stemflow rates from fog (SF_{fog}/SF_{all}) were positively correlated with crown area ($r = 0.86$, $p < 0.05$), DBH ($r = 0.51$, $p > 0.05$), height ($r = 0.89$, $p < 0.05$) and bark texture ($r = 0.91$, $p < 0.05$), respectively. Findings of this study confirmed that rainfall partitioning into throughfall and stemflow was mainly influenced by the tree characters. Forested mountain area is expected to have more net water input to the forest floor.

Most of the studies neglect SF due to its small partition amount from rainfall. However, some studies stated that even small amount of SF was important as a point source in maintaining SWC and recharging groundwater. Area without vegetation cover in a montane area, especially forest could increase a large amount of surface runoff with less amount of restored water to the soil. Some studies also stated that SWC and infiltration rates decreased with increasing distance from the tree trunks. To investigate the importance of stemflow to soil water replenishment, therefore, SWC was measured at two different points, i.e., near the tree and outside the canopy area for two soil depths (5 cm and 15 cm) under the same rainfall. In this study, measurement points for SWC were decided based on two facts: (1) the importance value index of the tree species observed in the experimental plot, and (2) an open space between the trees. Reason for selecting outside the canopy area was to avoid the effects of throughfall to SWC.

Mean SWC near the tree were 18.5% at 5 cm depth and 21.7% at 15 cm depth, respectively, while those for outside the canopy area were 11.4% and 9.0%, respectively. This study found that higher SWC was found near the tree than outside the canopy area ($p < 0.05$) for both soil depths (Fig. 3). In some periods, SWC near the tree continuously increased for several days even without rain (Fig. 3a). This increased SWC came from SF caused by fog. According to timely variation of Pg and SWC (Fig. 3a), SWC at 5 cm depth was higher than at 15 cm depth at the beginning of the observation period. This could be due to the unsaturated conditions of the soil. The delivered SF by the trees was absorbed by the uppermost layer (soil at 5 cm depth), rich in organic matters and litters. This condition could hinder the infiltration process if the soil was unsaturated after long-period of dry period.

By comparing SWC, this study found that different distribution pattern of SWC in soil profile at two different points. T-tests showed that SWC at 5 cm depth was lower than at 15 cm depth ($p < 0.05$) near the tree. This can be explained by soil type and properties. In the experimental site, the dominant soil types at 0-15 cm and at 15-30 cm are sandy loam and clay loam. Several studies have discussed that sandy loam soil has higher infiltration rate than clay loam soil, which can keep water for long hours. This property of clay loam soil led to have a high SWC at 15 cm depth near the tree. In case of outside the canopy area, however, SWC at 15 cm depth was significantly higher than SWC at 5 cm depth was significantly higher than SWC at 15 cm depth ($p < 0.05$). In an open area without vegetation cover, there was no point source to intercept rainwater and deliver them to the ground through SF. This condition consequently led to increase the amounts of surface runoff with less stored water to the soil through infiltration.

Infiltration rate was measured for 190 min at both points using double-ring infiltrometer method. Basic infiltration rate (I_B), a constant infiltration rate under the saturated condition, was determined from the measurements as shown in Fig. 4. I_B near the tree and outside the canopy area were 138.0 mm/h and 54.0 mm/h, respectively. Infiltration rate near the tree exceeded the amounts of the individual rain events helped to store more rainwater as SWC in deeper soil layers. In PMP, therefore, vegetative cover particularly forests are expected to have hydrological advantages in restoring water through a large amount of infiltrated SF to the soil.

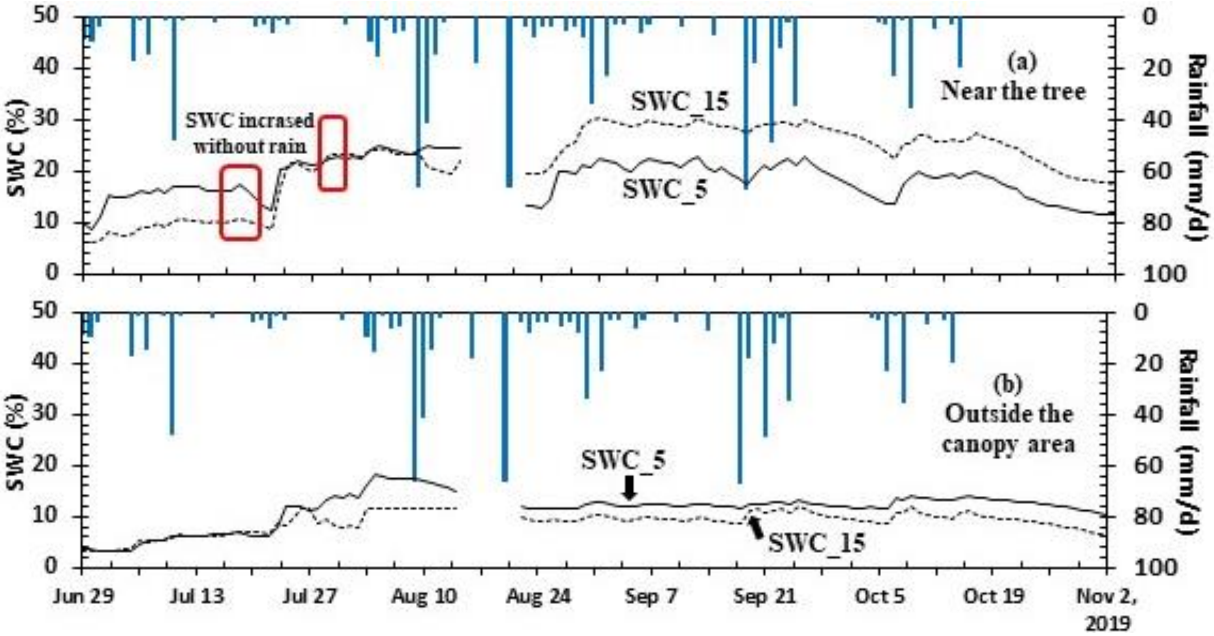

Fig. 3 Timely variations of rainfall and (a) soil water content near tree stand, (b) soil water content outside the canopy area for 5 cm (SWC_5) and 15 cm (SWC_15) under the same rainfall. The period with a lack of data was caused by battery error.

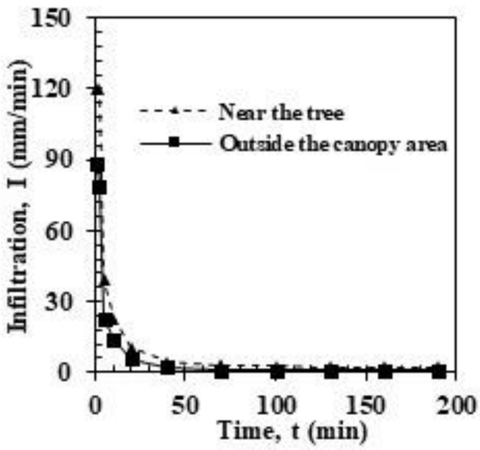

Fig. 4 Infiltration capacity for two different points measured at the experimental site

To monitor the impacts of land use land cover changes on the conservation of the montane forest, geographic information system (GIS) together with remote sensing technologies were applied in this study. According to land-use transition history of the study site, three Landsat level-2 images in the year of 1989, 2009, and 2019 were downloaded from the U.S. Geological Survey (USGS) web page. Satellite images applied in this study were selected by the degree of cloud-freeness and from the same season to minimize the discrepancies in the classification of land use classes. In this study, supervised maximum likelihood method by two special indices (normalized difference vegetation index, NDVI and bare soil index, BSI) was applied to interpret three Landsat level-2 images in PMP during 30 years (1989-2019). Training areas for each land-use land cover class (closed forest, open forest, other wooded land, crop/grass land and the others) were selected from the reference points collected during the field survey.

Overall accuracy for the classified land-use land cover maps of the Popa Mountain Park in the year of

1989, 2009 and 2019 (Fig. 5) were 86.51%, 85.32% and 87.85%, respectively with the Kappa coefficients of 0.83, 0.81, and 0.85. In 1989, the total area of closed forest, open forest, other wooded land, crop/grass land and the others were 469.5 ha (3.3%), 2967.1 ha (20.7%), 7023.6 ha (48.9%), 3595.0 ha (25.0%), and 303.3 ha (2.1%) of the total land area, respectively. In 2009, the area of closed forest, open forest, other wooded land, crop/grass land and the others were 71.3 ha (0.5%), 1288.2 ha (9.0%), 2143.7 ha (14.9%), 4763.9 ha (33.2%), and 6090.8 ha (42.4%) of the total land area, respectively. In 2019, the area of closed forest, open forest, other wooded land, crop/grass land and the others were 955.7 ha (6.7%), 2721.7 ha (19.0%), 4444.0 ha (30.9%), 5127.0 ha (35.7%), and 1110.3 ha (7.7%) of the total land area, respectively. In this study, the "from-to" change assessment was conducted to examine the changes from each land-use land cover class to another class.

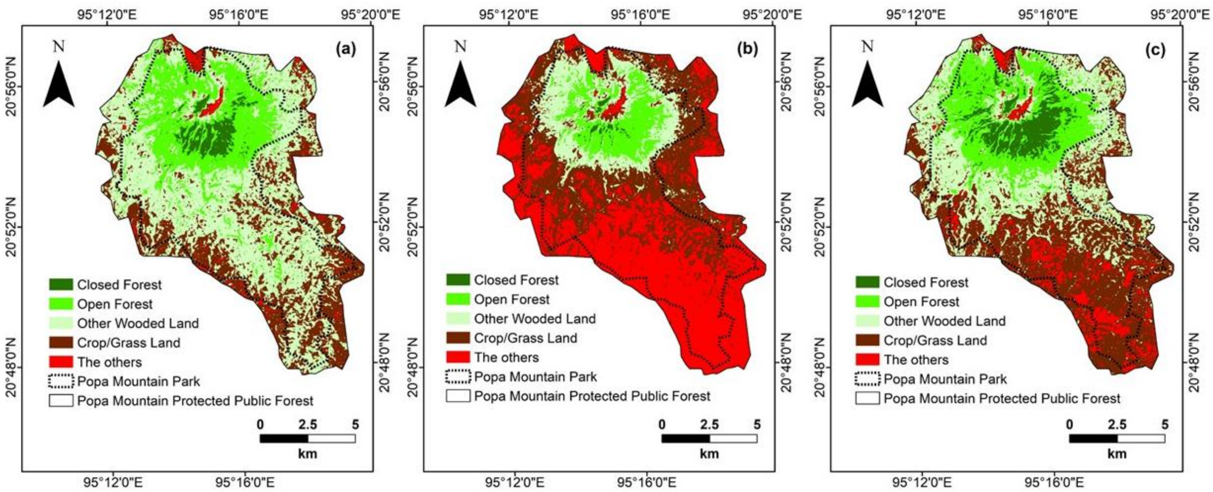

Fig. 5 Land-use land cover maps of the Popa Mountain Park by supervised maximum likelihood classification method for the year of (a) 1989, (b) 2009, and (c) 2019.

Figure 6 shows the changes of the respective land-use land cover class in PMP during 30 years (1989-2019). During the period between 1989-2009, closed forest areas in 2009 decreased 398.2 ha (2.8%) of the total area compared with those in 1989. Noticeable changes were found in open forest, other wooded land, crop/grass land and the others LULC classes. Open forest and other wooded land decreased 1678.9 ha (11.7%) and 4879.9 ha (34.0%) of the total area, respectively, while crop/grass land and the others increased 1168.9 ha (8.1%) and 5787.5 ha (40.3%) of the total area, respectively. During the period between 2009-2019, the area of closed forest, open forest, and other wooded land in 2019 increased 884.4 ha (6.2%), 1433.5 ha (10.0%) and 2300.2 ha (16.0%) of the total area, respectively, compared with 2009. The area of the others decreased 4980.5 ha (34.7%) but the area of crop/grass land increased 363.1 ha (2.5%). During the period between 1989-2019, closed forest areas in 2019 increased 486.2 ha (3.4%) of the total area compared with those in 1989. On the other hand, areas of open forest and other wooded land decreased 245.4 ha (1.7%) and 2579.6 ha (18.0%) of the total area, respectively, while areas of crop/grass land and the others increased 1532.0 ha (10.7%) and 807.0 ha (5.6%) of the total area, respectively.

According to the "From-To" change analysis, significant decreased in forest areas (closed forest, open forest, and other wooded land) through conversion to crop/grass land and the others was found in 2009. In 2019, there were recoveries in closed forest, open forest, and other wooded land, however, the areas of crop/grass land and the others still increased in compared with 1989. The main determinants of land use land cover changes in PMP were as follows; (1) the expansion of fruit orchards, the main livelihood of the region, and (2) fuelwood extraction and charcoal production, the main energy source for daily cooking in PMP. The recovery in forest area after 2009 was due to buffer zone establishment in 2010 which mitigated the dependencies on natural forests, and intensive afforestation and reforestation activities since 2011.

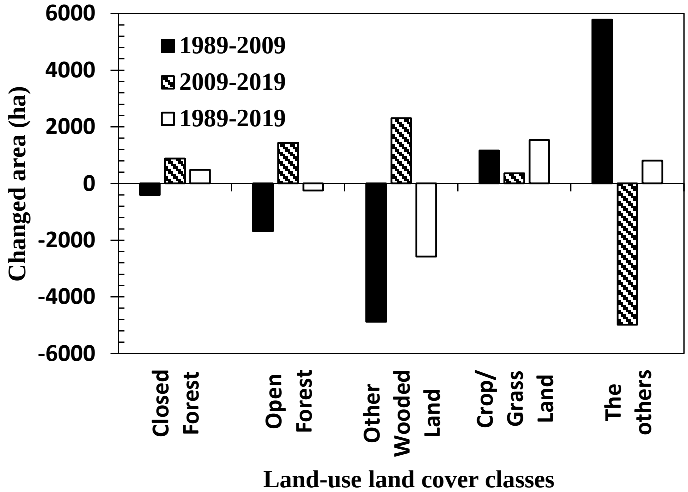

Fig. 6 Land-use land cover changes in Popa Mountain Park (PMP) for 30 years (1989-2019).

As a conclusion, montane forest in PMP resulted in large net water input from rainfall and fog. It should be prioritized to conserve this montane forest in order to reduce the water scarcity issue, but conservation strategy should be implemented in an inclusive way to meet the requirements of all stakeholders on the given resources and to have a strong participatory forest management. To provide a better sustainable park management, a consistency land-use management should be encouraged with a strong law enforcement in the core conservation zone. In buffer zone, following activities and actions should be encouraged: consistency land tenure to have strong a participatory forest management, introducing advanced agricultural technology to mitigate expansion of agricultural land, establishment of fuelwood plantations with high stand density and fast-growing species to meet the fuelwood demands in a shorter time. Besides, introducing the alternative energy sources such as using agricultural by-products should be encouraged to mitigate the dependencies on natural forests for the wood-derived energy. Stemflow is important as a point source to soil water replenishment, suggesting that area with vegetation cover replenished soil water content to deeper soil layers than non-vegetation area. Thus, afforestation and reforestation can be implemented as an environmental restoration approach. However, plantations with unsuitable tree species could harm the environmental balance of a region. This study suggested that three tree characteristics (denser canopy, shorter trees with small crowns and smooth bark, taller trees with larger crowns and rougher bark) should be considered for the afforestation and reforestation projects in PMP to enhance more net water input from the viewpoints of hydrological services.