Chapter 6

Summary and Conclusion

Objective of this study are to develop the optimized system measuring throughfall drops and to clarify the process for throughfall drop generation in forest canopies. I supposed meteorological factors and canopy structures as affecting factors on the process for throughfall drop generation, and estimated the influences of them, respectively.

In chapter 2, I newly developed and improved a laser drop-sizing gauge, named LD gauge, to be optimized measuring throughfall drops. The LD gauge realizes simultaneous, continuous, and multiple measuring of throughfall drops. When a raindrop passes through the laser sheet emitted by the transmitter, the output voltage from the receiver is reduced in proportion to the intercepted area. The voltage is converted into digital data with an A/D converter and stored on a PC connected to the LD gauge. Raindrop diameter is calculated from the relationship between the interception rate and the output voltage. The reliability of the LD gauge was confirmed by a calibration experiment using glass spheres and actual water drops.

In chapter 3, I reconfirmed and rearranged the characteristics of DSD and drop kinetic energy of throughfall. Throughfall and open rainfall drops were continuously and simultaneously observed within and outside a Japanese cypress (*Chamaecyparis obtusa*) plantation. Comparison of throughfall and open rainfall for one rainfall event suggested the following: 1) Throughfall drops were fewer in number, but larger in size, than open rainfall drops for one rainfall event; 2) Large drops were scarce in open rainfall but accounted for about half of the throughfall precipitation. Raindrops coalesce in the canopy; 3). The drop impact energy increased as large drops were produced.

Comparison of the two throughfall events suggested that the throughfall drops did not always have the uniform distribution in different events or in different time periods in one rainfall event, in contrast to the previous studies which resulted that throughfall drops had the uniform size distribution independent of rainfall intensity.

In chapter 4, I estimated the influence of canopy species and meteorological factors for throughfall drop generation. Raindrops were continuously measured in an open site and in three forest stands, Japanese cypress (CY), Japanese cedar (CD: *Cryptomeria japonica*), and sawtooth oak (SO: *Quercus acutissima*), simultaneously during three rainfall events. Drop size data obtained during the whole observation period were used in an hourly based data set and divided into three groups depending on three meteorological conditions: calm, heavy rain, and strong wind. Evaluating the influence of canopy species and meteorological factors using D_{50} and DSD differences revealed some throughfall-DSD characteristics.

First, throughfall had different DSDs among canopy species under conditions of little vibration of the canopy, with low rainfall intensity and wind speed; D_{50} values were 2.00, 2.93, and 3.60 mm in CY, CD, and SO, respectively. Differences were produced by the varying natural capacities of the canopies to produce large drips. Second, throughfall contained smaller drops under severe vibration of the canopy conditions, with high rainfall intensity and/or high wind speed, than under calm meteorological conditions. Vibration of the canopy led to reduced water coalescence and an increase in the spattering of rainwater from canopies. Wind speed had a greater effect on throughfall-DSD variations than did rainfall intensity. Third, the influence of meteorological factors was different among the canopy species; SO was readily influenced but CY was not.

Moreover, it was implied in the results that throughfall consisted of three components: free throughfall, drips and splash droplets. This study determined a process for generating throughfall-DSD that could explain the variations in throughfall-DSDs among canopy species and the influence of meteorological factors.

In chapter 5, I estimated the influence of canopy structures for throughfall drop generation. To estimate the influence of canopy structures for throughfall drop generation, the indoor laboratory experiment was conducted involving a transplanted Japanese cypress tree and water sprinklers. Throughfall amount and raindrops were measured at 32 points under four kinds of canopy structures created by the staged branch pruning. By the two steps of analyses of the experimental data, the followings were clarified.

First, the distance from the trunk affected the distribution of throughfall amount and intensity. The spatial variability of throughfall intensity was dominated by the distance from the trunk and generally increased as the radial distance from the trunk became further. The running component would exist in the process of rainwater flow in canopies. Rainwater applied around the center of the canopy may have spilled over to the edge of the canopy because of the canopy's conical shape.

Second, the canopy thickness affected the throughfall drop generation. The canopy thickness would determine the canopy storage and the probability to be re-intercepted the drips generated from the upper canopy layers. The time lag required to stabilize throughfall intensity became shorter with the distance from the trunk and with the branch pruning. When the measuring points were covered with canopy foliage, the abundance ratio of large drops with diameters > 3 mm increased with the distance from the trunk and with the branch pruning. Furthermore, the number and the ratio of drips with higher velocities increased with the branch pruning. Consequently, throughfall kinetic energy increased with the distance from the trunk and with the branch pruning.

Third, the first branch height affected the drop velocities of drips generated from the canopies. The branch pruning increased the velocities of drips.

Forth, the process of throughfall drop generation adjacent canopy edge was shown. Adjacent to the canopy edge, throughfall comprised larger drops because of thin canopy thickness, but the drips had lower velocities because they were almost generated from the lower layers. Consequently, throughfall kinetic energy generally increased with the distance from the trunk but the increasing trend was less clear than the throughfall intensity. The peak of throughfall intensity with the distance from the trunk appeared adjacent to the canopy edges but the peak of throughfall kinetic energy appeared more inner side of the canopy edges compared with the throughfall intensity.

As mentioned above, this study revealed the influence of meteorological factors and canopy structures for the process of throughfall drop generation in forest canopies. In particular, wind speed for meteorological factors and canopy thickness for canopy structures had major impact for throughfall drop generation. These findings help in determining the mean and the maximum rainfall amount, rainfall intensity, and rainfall erosivity of throughfall, which has large spatial variability to discuss the soil surface erosion process and the canopy interception process.

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論文内容の要旨

森林科学専攻

平成16年度博士課程　入学

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論文題目　Studies on the process of throughfall drop generation in forest canopies
（樹冠における林内雨滴の形成メカニズムに関する研究）

本研究は，林内雨滴の形成メカニズムを明らかにするために，林内雨滴の測定に適するレーザー雨滴計システムを開発し，構築されたレーザー雨滴計による多点同時連続雨滴測定から，林内雨の雨滴粒径分布・雨滴衝撃エネルギーの形成に与える気象要素・樹種・樹冠構造の影響を評価したものである．

第 1 章では，林内雨滴研究が必要とされる背景をまとめ，既往研究の成果及び課題を示し，本研究の目的を提示した．

林内雨滴の粒径分布と，それが地表面に与える衝撃エネルギーは極めて素過程的な測定項目であるが，裸地化した林床における表面侵食プロセス及び樹冠遮断蒸発プロセスを評価する上で重要な情報となる．林外雨滴については気象学・地形学的な観点から既往研究が数多くあるものの，林内雨滴についての研究例はそれほど多くない．これまでの研究により，林内は林外よりも大きな雨滴が発生し，林内の雨滴粒径分布は樹種や降雨強度に寄らず一定の分布型を持つとされている．

しかし林内雨滴に関する既往研究は手動雨滴観測に基づいているため，観測データの連

続性に欠けている．従って気象要素の時間変動に伴った林内雨滴の形成プロセスの変動を捉えていない可能性があり，林内雨滴の衝撃エネルギーについても概念的な議論に終始している．課題を解決するには雨滴の多点同時連続測定が必要であるが，林内でそれを実現できる測定技術がこれまでに存在していなかった．

そこで本研究では，林内雨滴の測定に適するレーザー雨滴計システムを開発し，林内雨滴形成に影響を与える要素として気象要素・樹冠構造を想定し，それらが林内雨滴形成に与える影響を評価し，それに基づいて林内雨滴の形成メカニズムを解明することを目的とした．

第 2 章では，本論文の方法論を提示した．

まず高性能レーザーセンサの使用・ハード面の改良・ソフトウェア開発を通して林内雨滴測定に最適化されたレーザー雨滴計システムを開発した．レーザー雨滴計は光学式雨滴計の一種であり，雨滴によるレーザー光線の遮光量が雨滴粒径と相関があるという原理を利用して，個々の雨滴の遮光率・遮光時間から雨滴の粒径・速度を求めている．開発されたシステムは従来の測器に比較して，小型で可搬性に富むため山地斜面への測器導入が容易であり，プログラミング制御により連続的かつ多点同時観測が可能という特徴を持つ．これらにより一雨を通した林内雨滴の定量的な評価，林外の気象要素の変動に応じた林内雨滴測定，同一気象条件下での林内雨滴の多点同時測定が可能となった．

2001 年にレーザー雨滴計（LD gauge version 1）を開発し，2002 年には改良型のレーザー雨滴計（LD gauge version 2）を開発した．各雨滴計はガラスビーズと水滴とを用いた室内での検定実験により精度を確認している．章の後半において，測器から得られたデータからの林内雨要素の計算手法を示した．

第 3 章では，林内雨滴の粒径分布及び衝撃エネルギーの特徴を把握するために，実際に林床の裸地化している壮齢ヒノキ人工林の林内外で雨滴の多点同時連続観測を行い，既往研究から得られている林内雨滴に関する定説について再確認と再評価を行った．

観測は 2001 年の 9–10 月に東京大学千葉演習林の袋山沢試験地にて行われた．ヒノキ人工林の林内外に測点を設け，2 つの降雨イベントにおいて降雨強度・雨滴の連続データを得た．林内外・イベント間での雨滴データの比較から，以下のことを確認した．

第 1 に，林内では林外に比べて雨滴は個数が減少して大粒径化した．林内雨量の約半分が自然降雨では生じることの少ない大雨滴により構成されていた．第 2 に，枝下高が十分に高い林内では，林外に比べて雨量が減少するにもかかわらず総雨滴衝撃エネルギーが増大することを再確認した．第 3 に，既往研究から得られている定説と異なり，林内雨の雨滴粒径分布が降雨イベント毎・降雨時間帯毎に変動することを示した．

第 4 章では，前章で示された林内の雨滴粒径分布の変動について，その要因を明らかにするために，異なる樹種・異なる降雨イベントで雨滴の多点同時連続観測を行い，樹種・気象要素が林内雨滴形成に与える影響を評価した．

観測は 2003 年の 7–8 月に東京大学田無試験地にて行われた．ヒノキ・スギ（*Cryptomeria* *japonica*)・クヌギ（*Quercus acutissima*）の3樹種の林内及び林外に測点を設け，気象条件の異なる3つの降雨イベントにおいて降雨強度・風速・雨滴の連続データを得た．得られたデータを1時間毎のデータセットとし，弱降雨弱風・強降雨・強風の3つの気象条件グループに分割した．気象条件グループ間・樹種間での雨滴データ比較から，以下のことを示した．

第1に，気象要素の影響の小さい弱降雨弱風条件において，林内の雨滴粒径分布は樹種ごとに異なった．ヒノキ・スギ・クヌギの順に林内雨滴は大きく，中央粒径D_{50}はそれぞれ2.00・2.93・3.60 mmであった．樹種ごとの葉の性質により大雨滴の作りやすさが異なることが推察された．第2に，気象要素により林内の雨滴粒径分布が変動した．林内雨滴は，弱降雨弱風条件に比べて，強降雨条件・強風条件で小粒径化した．特に風速の大小による変動が大きかった．風雨による樹冠振動が，樹冠内での雨水集合過程の未熟化・貯留雨水の飛散を引き起こし，その結果として林内雨滴が小粒径化するものと考えられる．第3に，気象要素の影響の受け方が樹種により異なった．もともと雨滴粒径の大きなクヌギは気象要素による変動が大きく，ヒノキでは気象要素の差異による雨滴粒径分布の変動が小さかった．更に，得られた結果を基に飛散雨滴の存在を明らかにし，林内雨が3成分（直達雨滴・滴下雨滴・飛散雨滴）により形成されることを示した．樹種・気象要素の差異による林内雨の粒径分布の変動を表現できる林内雨の形成プロセスを提示した．

第5章では，林内雨要素の空間分布を明らかにするために，移植ヒノキを用いた室内人工降雨実験により気象要素の影響を無視できる状況を作り，樹冠構造が林内雨滴形成に与える影響を評価した．

実験は，2005年9–10月に茨城県つくば市の防災科学技術研究所の大型降雨施設で行われた．施設内に樹高9.8mのヒノキを移植し，段階的な枝の切り上げにより4種類の異なる樹冠構造を人工的に与えた．各樹冠構造における枝下高は2, 3, 4, 5mであった．林内雨要素の空間分布を把握するために樹冠下に32箇所の測点を設けた．それぞれの配置は，幹から放射状に8方向，各方向に4箇所（幹から40, 100, 150, 200 cmの距離）である．降雨イベントとして，降雨強度の異なる2種類の降雨を連続的に与えた．各樹冠構造において合計120種類の雨量・降雨強度・雨滴の連続データを得た．

樹冠下の全ての測点に共通して，人工降雨で発生しない大きな雨滴が測定され，粒径3mm以上の雨滴は樹冠で生成される滴下雨滴とみなすことができた．また，降雨開始直後は降雨が樹冠に遮断されるために林内雨の立ち上がりは遅れ，林内降雨強度が安定するまでに時間を要した．

樹冠構造の影響を2段階の解析により評価した．まず枝を切り上げていない樹冠構造のデータの比較から，幹からの距離が林内雨要素の空間分布に与える影響を評価した．次に，枝の切り上げが林内雨形成に与える影響を評価した．枝の切り上げは枝下高の上昇だけでなく，樹冠厚・樹冠投影面積の減少という樹冠構造の変化を引き起こすため，それぞれの視点から樹冠構造の影響を評価した．これらの評価から以下のことを明らかにした．

第 1 に，林内雨の雨量・降雨強度は空間的なばらつきが大きかったが，そのばらつきが幹からの距離で整理され，幹から遠ざかるにつれて雨量・降雨強度が増大することを示した．これは幹近傍に降った降雨の一部が樹冠上を移動し，樹冠縁に向かって流れ込むことによって引き起こされるものと考えられる．

第 2 に，枝下高の上昇により樹冠からの滴下雨滴の速度が上昇した．

第 3 に，樹冠厚により林内雨要素が変動し，樹冠厚の減少が林内の雨滴衝撃エネルギーの増大を促すことを示した．まず樹冠厚の減少は樹冠貯留量を減少させた．それにより降雨強度が安定するまでに要する時間が減少し，林内雨量が増大した．また，樹冠厚の減少は樹冠上層で形成される滴下雨滴が樹冠下層で再遮断され飛沫化する可能性を減少させた．それにより林内雨を構成する粒径 3mm 以上の雨滴の存在比が上昇し，樹冠上層で形成される速度の大きな雨滴の個数・存在比が上昇した．樹冠縁から遠い測点では，幹から遠ざかるにつれて同様の傾向が見られたが，それは各測点距離の上層に存在する樹冠厚の差異により引き起こされたものと考えられる．結果として，林内の雨滴衝撃エネルギーは，枝の切り上げ・幹からの距離に伴い増大した．

最後に，樹冠縁付近での林内雨形成メカニズムを示した．樹冠縁付近では，幹近傍からの雨水流れ込み成分により降雨強度が大きかった．また樹冠が薄いために粒径 3mm 以上の大雨滴の存在比が大きかったが，滴下雨滴の大半が樹冠下層で形成されるため，その速度は比較的小さかった．それにより林内の降雨強度のピークは樹冠縁付近で見られるものの，林内の雨滴衝撃エネルギーのピークは樹冠縁よりも内側に現れた．

以上の章を要約して第 6 章とした．