	ﾌﾞﾗﾝﾄ ｱﾚｸｻﾝﾃﾞﾙ ｸﾘｽﾃｨｱﾝ
氏　　　名	**BRANDT, Alexander Christian**
本籍（国籍）	ドイツ連邦共和国
学位の種類	博士（農学）
学位記番号	連研 778 号
学位授与年月日	令和２年９月２５日
学位授与の要件	学位規則第５条第１項該当課程博士
研究科及び専攻	連合農学研究科　生物生産科学
学位論文題目	**Influence of snow dynamics on mountainous forest soil hydrology cycle（積雪動態が森林土壌の水循環におよぼす影響）**
学位審査委員	主査　山形大学教授　村山　秀樹
	副査　加藤　千尋(弘前 助教),武藤　由子(岩手 准教授),Lopez Caceres Maximo Larry(山形 教授)

論文の内容の要旨

Snow covers provide one of the most important water reservoirs on earth. Snowmelt in spring distributes water to plants, animals and humans, assuring the life of all living organisms. This process is particularly important in regions with little precipitation in spring, when plants start to transpire and soils start to dry due to increasing air temperatures. These regions rely on snowmelt water from mountains in sufficient quantity to bridge the time of little precipitation. In times of climate change and especially global warming, many regions around the world suffer droughts because snowfall in winter decreased significantly, and therefore the total amount of accumulated snow before spring did, too.

One region which uses snowmelt water intensively is Tōhoku region in Japan. Two thirds of the surface is covered by forests, which are mainly growing in the Ōu Mountain range, which divides Tōhoku region into West and East. The plains closer to the Japan Sea and the Pacific are mainly used for rice farming. Hence, the demand of water for trees in the forest and for paddy fields is high in spring. Since the mountains, especially on the western side, are receiving heavy snowfall in every winter, the amount of water stored in the mountains results in long-running snowmelt processes, lasting until June or July in every year. However, winter precipitation and snow accumulation decreased in the last decades, and air temperature in winter, especially in the Asahi Mountain Range of Yamagata prefecture, is around 0° C. This temperature implies that small differences in air temperature make a difference between snow accumulation and snowmelt, and the timing of precipitation determines the proportion of rain and snow. Since winter precipitation is high, with usually more than 1500 mm, snow depths of more than three metres are common in the mountains. It was found that the snow depth varied in the last years. Years with high snow depth were followed by a year with small snow cover two years later. Small temperature differences can then result in significant changes of water supply to the Shōnai plains, the coastal area of Yamagata.

The hydrological cycle in Shōnai and the Asahi mountains was subject of this study in order to understand the mechanisms in mountainous forests in winter and to detect changes in snow cover and snow dynamics over the last decade. Meteorological data, soil physical properties and soil moisture were continuously monitored in the Yamagata University Research Forest (YURF) in order to run a model for soil moisture estimations, which can be used for various applications. The modelling software used, HYDRUS 1D, calculates soil moisture, snow accumulation and other parameters using the data obtained from field and laboratory work.

The recent winter (2019/2020), with high air temperature and without heavy precipitation events, resulted in the shallowest snow cover in YURF which was measured. Snow depth was combined with snow density, which was higher in years with greater snow depth, because snow was compacted more in those years. Furthermore, snow at the surface melted on days with temperatures of more than 0°C and moved downwards in the snowpack. Water refroze in deeper layers of the snowpack, where it changed the snow crystal structure and increased the snow density. The same process was observed after rain on snow events. Knowing the snow density after those events means knowing the amount of water which will be supplied to the Shōnai plains in spring. Modelling of snow density for the snow accumulation period and also for the snowmelt period was performed for every winter starting in the year 2011. Using precipitation data and degree-day factors (DDFs), accurate calculations for the snow water equivalent (SWE) of the snowpack were carried out.

Rain on snow events were not only causing increases in snow density, but were also found to affect soil moisture under the snowpack. In order to measure these effects, soil moisture was monitored at three spots of a slope, vegetated with Japanese cedar (Cryptomeria japonica). Two winters with significantly different snow depth were measured and analysed in this thesis in order to understand the relation between snow cover and rainwater infiltration. Soil moisture was also affected by numerous small rain events of less than 10 mm in the winter 2019/2020, where the maximum snow depth was 1.3 m. In contrast to the highly variable soil moisture in this winter, water infiltrated the soil only a few times in the winter 2018/2019, when the snow cover was 3 meters at its maximum. Further it was found that different parts of the slope receive different amounts of water. While most water reached the soil surface at the top and at the bottom of the slope, soil at the slope was less affected by rain on snow events. Consequently lateral flow of water in the snowpack downwards the slope was of higher rate than vertical flow into soil.

Infiltration of the snowpack by water resulted in a constant soil moisture level at the matric potential of the soil. High precipitation in autumn filled most pores of the soil, and the last pores to reach field capacity were filled in early winter. Rain on snow events and partial snowmelt supplied water to fill quickly draining pores. However, due to high sand contents and high hydraulic conductivity, soil never became saturated. Soil moisture increased insignificantly in spring during snowmelt, which caused higher surface runoff of snowmelt water and less subsurface runoff. Soil moisture decreased significantly shortly before snowmelt ended. Trees started to transpire, and increasing soil temperature caused evaporation. Soil moisture reacted immediately to rain events in summer and autumn. However, soils in YURF had high water repellency, resulting in higher surface runoff when the soil was dry. Runoff measurements confirmed that surface runoff was higher after dry periods and when the rain event was heavy.

Significant differences in soil physical properties were found between the soils in YURF and the soils of the second study site in Kaminoyama city. Soils at the Kaminoyama sites contained more clay and silt and were therefore able to store water and nutrients better than the soils in YURF, which results in better fertility. The experiments were done in order to characterise the efficiency and yield of wine production. Since soils in Kaminoyama were better evolved than soils in YURF, the potential for agriculture and fruit cultivation was, based on the soil physical properties, significantly higher.

The application of the HYDRUS 1D model for YURF was found to be a good approach but introduced also some difficulties. Differences in between model and reality were small in seasons without snow cover. In contrast, thick snow cover caused problems for the model, resulting in overestimation of soil moisture contents in winter. Snow depth was not predicted correctly either. The best results for soil moisture modelling were obtained for the top of the slope, where water moves vertically in the snowpack. However, in general the model worked well and can be improved in the future, also by the use of the more sophisticated versions HYDRUS 2D and 3D.

In conclusion, this study demonstrated water storage and movement in soil, and the potential for using models for the calculation of hydrological processes. Winter precipitation became more important, since a shift in the amount of snowfall is followed by smaller SWE in the Asahi Mountains. The results confirm changing climate conditions and introduce new methods for the estimation of water availability.

積雪は、地球上で最も重要な貯水方法の１つである。春の融雪は植物や動物に水を供給し、すべての生物の生命を保証する。この過程は、植物が蒸散を始め、気温の上昇で土壌が乾燥し始める春に降水量の少ない地域で、特に重要である。これらの地域は山からの雪解け水に依存しており、降水量が少ない期間も十分な水量を確保することができる。気候変動、とりわけ地球温暖化によって世界中の多くの地域で干ばつが起こっている。また、冬の降雪量が大幅に減少し、その結果春さきの積雪量も減少している。

東北地方は、雪解け水を多く使っている地域であり、中心を縦に走る奥羽山脈周辺の森林が３分の２を占める。日本海側と太平洋側の平野は水田として利用されている。したがって、水は森林の樹木と水田に使われるため、春の水の需要は高くなる。東北地方特に日本海側は大雪に見舞われるので、山に蓄えられた水の量は多く、毎年 6，7 月まで長期にわたって融雪過程が起こっている。しかしながら冬の降水量と積雪量はここ 10 年で減少し、冬の気温も朝日連峰（山形県）でさえ 0 ℃付近である。これらは、気温のわずかな違いが積雪と融雪のバランスに変化をもたらすとともに、雨と雪の割合を決定する降水(雪)の時期が変化することを意

味している。たいてい冬の降水量は 1,500mm を超えるため、山では 3mを超える積雪深が一般的である。この積雪深は毎年変化しており、積雪量の多い年の 2 年後に積雪量の少ない年になる傾向がみられる。このようなことから、山形の海岸地域においては気温の小さな差が庄内平野への水の供給に大きな変化をもたらす可能性がある。

過去 10 年間の雪や天気の動態を調べるために、庄内地方と朝日連峰における水の循環を研究した。山形大学演習林(YURF)で取得した気象データならびに、測定した土壌物理特性と土壌水分データを水分モデル HYDRUS1D に入力した。このモデルで推定した土壌水分や積雪深など、様々なパラメーターを演習林の実測値と比較した。

2019-2020 は気温が高く、降水量も多くなかったため、ここ 10 年で積雪深は一番低かった。また、雪は雪自体の重みで圧縮されるため、積雪深は雪の密度にも影響をおよぼし、積雪深の高い年は低い年より雪の密度は大きくなることを確認した。温度が 0 ℃以上の日は、雪の上部で溶けた水が積雪の中に浸透し、下部で再び凍ることで結晶組織が変化し、雪の密度が増加した。同じプロセスは雨の日にも起こった。雪の重さが分かれば、春の雪解け水の量を推測できると考えられた。そこで、2011 年冬から毎年、積雪の期間と融雪の期間に雪密度の測定を行うとともに、降水量データと Degree-Day Factor を使用して、積雪相当水量（SWE）の正確な計算を行った。

冬の降水は雪密度を増加させるだけでなく、雪の下の土壌水分にも影響をもたらす可能性がある。そこで、山腹の杉林に 3 つのサンプリングポイントを設け、土壌水分を測定した。また、積雪と雨水の浸透との関係を理解するために、積雪深が大きく異なる 2 つのシーズンで測定を行い、そのデータを分析した。2019-2020 年の最大の積雪深は 1.3mと低く、1 日の降雨が 10 ㎜以下の場合も土壌水分にしばしば影響した。2018-2019 年の最大の積雪深は 3mであり、水は土壌に数回しか浸透しなかった。さらに、斜面の場所によって供給される水の量が異なることが判明した。雨水は斜面の上部と下部の土壌表面には到達したが、斜面途中の土壌は雨水による影響は少なかった。このことから、水は積雪の中を垂直に移動し土壌へ到達するよりむしろ、積雪の中を通り下部へ移動すると考えられた。

冬の雪解け水の浸透により土壌のマトリックポテンシャルを保ち、土壌水分を一定に保つことができた。秋の高い降水量は土壌における大半の孔隙を埋め、初冬に残った孔隙が埋まった。冬の雪解け水と雨水が土壌の大きな孔隙を埋めたのである。しかし、砂の量が多く、水伝導性が高いことから、土壌は決して飽和状態にはならなかった。雪解けの終わりに土壌水分はすぐに大幅に減少した。これは、樹木の蒸散が始まったことと、土壌温度が上昇し蒸発が始まったためである。夏と秋では、雨が土壌水分にすぐに影響を与えた。それでも YURF の土壌は撥水性が高いため、土壌が乾燥しているときに地表面からの水の流出量は多くなった。乾燥の後および雨が激しく降っているときに、地表面での流出量がより高いことが確認された。

土壌の物理的な特性の有意な差は、上山市のブドウ園と YURF との間にもみられた。上山市のブドウ園は、YURF と比較して粘土とシルトが多いため、水分と栄養素を、より保持することができ、これが肥沃につながった。この結果は上山市におけるワイン生産を特徴付けることに利用された。上山市の土壌は、物理的な特性の点で、より成熟していたことから、YURF より果樹の栽培に適していると考えられた。

YURF において HYDRUS１D モデルは良い結果を示したが、様々な問題も見つかった。雪がない時期は、モデルで推定した土壌水分と実際の土壌水分がほとんど同じレベルであった。これに対して、冬の積雪深が高い場合、土壌水分含有量を過大評価するという結果となった。

積雪深はモデルでも正しく推定されなかった。土壌水分モデルにおいて最も良い結果は斜面の上部でみられた。これは水が雪の中を垂直に流れたためである。このモデルは将来 HYDRUS 2D と 3D へバージョンアップすることにより、より良いものになっていくであろう。

以上の結果より、水の貯蓄や土壌中での流れを明らかにするとともに、水文学的プロセスの計算モデルを使用できる可能性を示した。降雪量の変化ならびに朝日連峰における SWE の低下により、積雪量はより重要になってきている。本論文では、東北地方の気候が変化していることを確認し、利用可能な水と雪の量を推定するための新しい方法を提示した。

論文審査の結果の要旨

Snowmelt in spring distributes water to plants, animals and humans, assuring the life of all living organisms. This process is particularly important in regions with little precipitation in spring. These regions rely on snowmelt water from mountains in sufficient quantity to bridge the time of low precipitation. Under climate change, many regions around the world have experienced a decrease in snowfall and in consequence the snow depth. In North-eastern Japan, along the Japan Sea forests as well as agricultural fields rely strongly on snowmelt water in spring and even early summer. However, winter precipitation and snow accumulation has decreased in the last decades, and air temperature in winter, especially in the Asahi Mountain Range of Yamagata prefecture has also increased. This implies that small differences in air temperature can have a significant impact on snow accumulation and snowmelt as well as on the timing of precipitation, which determines the proportion of rain and snow. Since winter precipitation is high, with usually more than 1500 mm, snow depths of more than three metres are common in the mountains. The hydrological cycle of an evergreen forest in the Asahi mountains was the subject of this study in order to understand the distribution of water in winter and spring in relation to changes in snow cover and snow dynamics over the last decade. Meteorological data, soil physical properties and soil moisture were continuously monitored in the Yamagata University Research Forest (YURF) in order to run a model for soil moisture estimations mainly in winter but also along the other seasons. The model HYDRUS 1D, calculates soil moisture, snow accumulation and other parameters using the data obtained from field and laboratory work.

The recent winter 2019/2020 had high air temperature and few precipitations events resulted in the shallowest snow cover in YURF in record. Higher snow depths resulted in higher snow densities because of compactation. Furthermore, snow at the surface melted on days with temperatures higher than 0°C and moved downwards in the snowpack. Water refroze in deeper layers of the snowpack, where it changed the snow crystal structure and increased the snow density. The same process was observed after rain on snow events. Rainwater infiltrated the snow and moved downwards in the snowpack, increasing the snow density. Modelling of snow density for the snow accumulation period and also for the snowmelt period was performed for every winter starting in the year 2011. Using precipitation data and degree-day factors (DDFs) accurate calculations for the snow water equivalent (SWE) of the snowpack were carried out.

Rain on snow events did not only cause increases in snow density, but were also found to affect soil moisture under the snowpack. In order to measure these effects, soil moisture was monitored at three spots of a slope, covered by Japanese cedar (Cryptomeria japonica) trees. Two winters with significantly different snow depth were measured and analysed in in order to understand the relation between snow cover and rainwater infiltration. Soil moisture was also affected by numerous small rain events of less than 10 mm in the winter 2019/2020, where the maximum snow depth was 1.3 m. In contrast to the highly variable soil moisture in this winter, water infiltrated the soil only a few times in the winter 2018/2019, when the snow cover was 3 meters at its maximum. Furthermore, different parts of the slope received different amounts of water. While most water reached the soil surface at the top and at the bottom of the slope, soil at the slope was less affected by rain on snow events, suggesting that the lateral flow of water in the snowpack downwards the slope was of higher rate than vertical flow into soil. Rain on snow events and partial snowmelt supplied water to fill quickly draining pores. However, due to high sand contents and high hydraulic conductivity, soil never became saturated. Soil moisture increased insignificantly in spring during snowmelt, which caused higher surface runoff of snowmelt water and less subsurface runoff. Soil moisture decreased significantly shortly before snowmelt ended as forest transpiration started and soil temperature increased. Soil moisture reacted immediately to rain events in summer and autumn. However, soils in YURF had high water repellence, resulting in higher surface runoff when the soil was dry. Runoff measurements confirmed that surface runoff was higher after dry periods and when the rain events were heavy. The application of the HYDRUS 1D model for YURF was found to be a good approach but introduced also some difficulties. Hydrus modelled and measured soil moisture values showed small differences in summer. In contrast, thick snow cover caused problems for the model, resulting in the overestimation of soil moisture contents in winter. The best results for soil moisture modelling were obtained for the top of the slope, where water moves vertically in the snowpack.

In conclusion, this study demonstrated water storage and movement in soil, and the potential for using models for the calculation of hydrological processes. The results confirm changing climate conditions and introduce new methods for the estimation of water availability.

学位論文の基礎となる学術論文

1. Brandt A.C., Zhang Q., Lopez C.M.L., Murayama H., 2020. Soil Temperature and soil moisture dynamics in winter and spring under snowfall conditions in north-eastern, Japan. Hydrological Processes. DOI: 10.1002/hyp.13794.