131. Jahrgang (2014), Heft 1, S. 45–62

Austrian Journal of Forest Science
Centralblatt für das gesamte Forstwesen

Soil moisture and soil temperature dynamics at the tree line of Mount Rax, 1999-2010

Bodenfeuchte- und Bodentemperatur-Dynamik an der Baumgrenze der Rax, 1999-2010

Roland Koeck[1,*], Eduard Hochbichler[1], Christian Holtermann[2],
Herbert Hager[3]

Key words: drinking water protection, *Pinus mugo*, subalpine pasture, soil moisture, soil temperature, forest hydrology

Schlagwörter: Trinkwasser-Ressourcenschutz, *Pinus mugo*, subalpine Almflächen, Bodenfeuchtigkeit, Bodentemperatur, Waldhydrologie

Abstract

On the karstic Mount Rax which is part of the drinking water protected area (DWPA) of the city of Vienna, dwarf pine (*Pinus mugo* Turra) and subalpine pasture vegetation were compared on the basis of three hydro-meteorological parameters. The focus of the study was the investigation of the differences between these two representative vegetation types for the upper subalpine zone, considering soil temperature, soil moisture and snow cover. In order to accomplish this task, two long-term monitoring plots were installed with automatic measurement units and have been in use for the last

---

[1] University of Natural Resources and Life Sciences, Department of Forest- and Soil Sciences, Institute of Silviculture, Peter Jordanstr. 82, 1190 Vienna, Austria.
[2] Sellenygasse 2-4/52, 1020 Vienna, Austria.
[3] University of Natural Resources and Life Sciences, Department of Forest- and Soil Sciences, Institute of Forest Ecology, Peter Jordanstr. 82, 1190 Vienna, Austria.
* Corresponding author: roland.koeck@boku.ac.at

fifteen years. Aspects from observation period 1999 to 2010 are displayed in this paper. With these measurements it was possible to identify differences between dwarf pine and subalpine pasture vegetation, which are of hydro-meteorological importance. During winter seasons soil frost beneath dwarf pine vegetation was mostly prevented or mitigated providing optimal infiltration conditions for melting water in spring. Beneath subalpine pasture vegetation significant soil frost occurred during some winter seasons while it was also absent during others depending on the formation of a solid snow pack in early winter periods. Snow accumulation in early winter was enhanced by the roughness of dwarf pine as snow was often blown off by winds from pasture areas. In spring snow melted earlier on dwarf pine areas than on pastures. The differences between the two vegetation types served as a basis for the establishment of water protection management concepts which focused on the mitigation of erosion processes or on a more balanced spring water discharge during snow ablation periods. Results of these ongoing measurements at the tree line of Mount Rax are relevant for drinking water protection purposes.

Zusammenfassung

Auf dem Karstgebirgsstock der Rax, welcher Teil des Quellenschongebiets der Stadt Wien ist, wurde Latschenbuschwald (*Pinus mugo* Turra) mit subalpiner Almflächen-Vegetation auf der Ebene von hydro-meteorologischen Parametern verglichen. Der Fokus der Studie lag in der Erforschung der Unterschiede zwischen den beiden für die obere subalpine Höhenstufe repräsentativen Vegetationsformen auf der Ebene von Bodentemperatur, Bodenfeuchtigkeit und Schneebedeckung. Um dies zu bewerkstelligen, wurden zwei Langzeit-Versuchsflächen mit automatischen Messeinrichtungen installiert, welche aktuell bereits seit 15 Jahren in Betrieb sind. In diesem Paper werden Aspekte der Messperiode 1999-2010 dargestellt. Mit den Messungen wurde es möglich, Unterschiede von hydro-meteorologischer Bedeutung zwischen den beiden Vegetationsformen zu identifizieren. Während der Winterhalbjahre war Bodenfrost unter Latschenvegetation zumeist entweder nicht vorhanden oder wurde abgeschwächt, wodurch optimale Infiltrationsbedingungen für die Schneeschmelze während der Frühlingsperioden gegeben waren. Unterhalb subalpiner Almflächenvegetation trat während einiger Winterhalbjahre deutlicher Bodenfrost auf, während andere durch die Abwesenheit einer Bodenfrostentwicklung gekennzeichnet waren, was jeweils von der Bildung einer soliden Schneedecke während der Frühwinterperioden abhängig war. Die Schneedecken-Akkumulation in den Frühwinterperioden wurde durch die Rauigkeit der Latsche gefördert, während die Schneedecke auf den subalpinen Almflächen oftmals durch Starkwinde abgeblasen wurde. Während der Frühlingsperioden schmolz die Schneedecke auf den Latschenflächen rascher ab als auf den Almflächen. Die Identifikation der Unterschiede zwischen den beiden Vegetationsformen diente als grundlegende Wissensbasis für die Ableitung von Managementkonzepten für den Trinkwasser-Ressourcenschutz, welche beispielsweise auf die Entschärfung von Erosionsprozessen oder auf die Förderung einer ausgeglichenen Quellenschüttung während der Schneeschmelzperiode ausgerichtet sind. Dadurch erlangen die laufenden Messungen an der Baumgrenze der Rax Bedeutung für die Zwecke des Trinkwasser-Ressourcenschutzes.

1. Introduction

Mount Rax is part of the drinking water protected area (DWPA) of the city of Vienna which has an extension of 943 km^2 and is situated within the North-Eastern Limestone Alps of Austria. Vienna receives about 95 % of its water supply from the karstic alpine springs in the DWPA. The quality of the water for the city of Vienna is high not requiring additional filtration and can be supplied with the application of only moderate chlorination. Two water mains transport the water by gravitational forces more than 200 km to the urban center. In order to guarantee the level of quality and supply safety of the drinking water sound management concepts for the DWPA are required (Richards et al 2012).

Dwarf pine communities (*Pinus mugo* Turra) and subalpine pasture areas are the most common vegetation types within the upper subalpine zone of Mount Rax, covering 8.9 % and 7.5 % of the whole DWPA respectively. The upper subalpine area of the DWPA faced land use change during the last several decades due to the abandonment of various subalpine pastures. This brought forth the expansion of dwarf pine communities on Mount Rax (Koeck et al 2001; Dirnböck et al 2003). Despite the abandonment of some pastures the impact of alpine pastoral systems can still be regarded as eminent in shaping the landscape (Hofer 2007). Also climate change could indicate shifts of the two mentioned vegetation types as air and soil temperature can be used as predictors for the tree-line position in landscape (Gehrig-Fasel et al 2008). The influence of vegetation types and land use categories on hydrology is regarded as significant (Dirnböck and Grabherr 2000; DeFries and Eshleman 2004; Koeck 2008), hence the upper subalpine zone with dwarf pine or subalpine pasture areas form a crucial management intervention zone for water protection purposes.

For example snow cover (Lundberg and Koivusalo 2003; Murray and Buttle 2003) and soil temperature (Körner 1999) can be influenced by vegetation cover. The leaf area index of vegetation types determines the level of snow interception or sunlight interception (Hedstrom and Pomeroy 1998; Kang et al 2000). Snow cover that lasts throughout the entire winter season usually will prevent soil horizons from freezing (Aulitzky 1961; Isard and Schaetzl 1998). Soil temperature influences the infiltration conditions for snow melt or precipitation into the soil especially if soil frost is present (Woo and Marsh 2005; Shanley and Chalmers 1999).

The purpose of this paper better understand the hydro-meteorological behaviour of dwarf pine communities and subalpine pasture areas. Comparison between those vegetation types on hydrological behaviour is scarce or missing. Hydrological knowledge about the two vegetation forms is very crucial for drinking water protection purposes within the DWPA. Data presented in Koeck et al (2002) were based on two years of measurement, while the mission of this paper is to extend this study into the period of 1999-2010.

2. The research sites

Mount Rax is situated at the easternmost edge of the North-Eastern Limestone Alps of Austria and the test sites can be found at 47° 42.90′ Northern latitude and 15° 42.71′ Eastern longitude. This area is a karstic mountain massif ranging from 450 m ASL up to 2007 m ASL where the most common bedrock types are limestones and dolomites (Mandl et al 2002). The climate is temperate sub-oceanic with mean annual temperatures of 6.5 °C and mean annual precipitation of 1294.2 mm, all measured in 612 m asl and within the period 1971-2000 at Schwarzau/Gebirge (ZAMG 2014). In 1850 m asl, two hydro-meteorological monitoring sites were installed at the upper subalpine vegetation zone in order to compare a dwarf pine plot (DP) with a subalpine pasture plot (PA) at the level of the measured hydro-meteorological parameters. The potential natural vegetation of the monitoring area is a dwarf pine forest on carbonate rock (*Rhododendro hirsuti-Mugetum prostratae, Adenostyles alliarae* variant Mayer 1974; Koeck et al 2001). Within the dense growth of dwarf pine (*Pinus mugo* Turra) which reaches average heights of about 2.3 m, some scattered spruce trees (*Picea abies* Karst.), and larch trees (*Larix decidua* Mill.) have established themselves with average heights between 3 m and 4 m. The subalpine pasture areas were established by the influence of alpine pastoral systems, which exerted their maximum impact during the last century but still can be regarded as land use systems which are shaping the landscape (Hofer 2007). The soil type on both experimental plots is chromic cambisol (‘Kalkbraunlehm’, Nestroy et al 2000) with depths between 70 cm and 100 cm. Soil material is loam in the upper soil horizons and clayey loam in the lower soil horizons. The soils are characterized by low contents of coarse material within the upper soil layers, but in horizons deeper than 25 cm the content of coarse bedrock material is rapidly increasing. The humus form on the pasture plot is mull, on the dwarf pine plot shallow layers of mull-like moder have accumulated. The experimental plots are situated on a level site where the underlying bedrock type is limestone.

3. Materials and methods

In both long term experimental plots a comparable set of hydro-meteorological instruments were installed. Due to restrictions regarding the DWPA, the remote location and monetary limitations, only few or no repetitions of the instrumentation were accomplishable. These limitations were acceptable and consequently the focus of the monitoring sites was chosen to be long-term data acquisition and monitoring.

Air temperature was measured at 2 m above the ground using Rotronic Pt-100 sensors. Also soil temperature was measured with Pt-100 sensors in 5 cm, 15 cm, 30 cm, and 45 cm depths on each of the two plots. Bulk precipitation was measured at the PA plot with a Delta-T tipping bucket gauge with 0.2 mm resolution. Snow depth was measured during some winter seasons following a snow course scheme.

Volumetric soil moisture content Θ was measured with theta probes from Delta-T Devices Ltd., which are frequency domain sensors. The theta probes were installed both in 20 cm and 35 cm depth with two repetitions for each plot. For the theta probes the generalised calibration equation which was provided by the manufacturer was used. It uses different calibration parameters for organic and mineral soils and the achievable accuracy lies between ± 5 % of volumetric water content (Delta-T Devices, Ltd. 1999). According to v. Wilpert et al (1999) the provided calibration equation showed sufficient accuracy, if the probes were installed within homogeneous soils free from stones. This requirement was fulfilled by placing the theta probes in homogeneous soil sections, where no stones were encountered, also providing close contact between soil material and sensor brackets.

Data was recorded by MiniCube data loggers (EMS, Brno) which recorded the mean of 20 individual measurements every 10 minutes. The measurement cycles were conducted throughout the whole year including throughout the winter. Energy supply for the measuring equipment was provided by solar panels.

The description of differences regarding the hydrological behaviour between the two vegetation cover types was the main research question. Hence the comparison of time series between the two plots and descriptive statistic were selected as appropriate methods for data analysis.

For a better understanding of the seasonal differences, the year was stratified into summer season and winter season, the first lasting from the 1st of May until the 31st of October, the latter lasting from the 1st of November until the 30th of April of the following year. This seasonal split conforms to the vegetation period and the snow pack duration within the subalpine zone of Mount Rax.

4. Results

The measurements started in November 1999 and are still ongoing. Within this paper, selected measurement periods from 1999 to 2010 are displayed which illustrate the differing behaviour of these two vegetation cover types of the subalpine zone. The soil temperature and soil moisture dynamics showed contrasting dynamics during different winter seasons. One characteristic winter season was 1999/2000 (Koeck et al 2002) which showed a pronounced soil frost formation at the subalpine pasture plot (PA) where soil temperatures reached values close to minus 4 °C. Soil temperatures at the dwarf pine plot (DP) remained above freezing throughout almost the entire winter (Fig. 1).

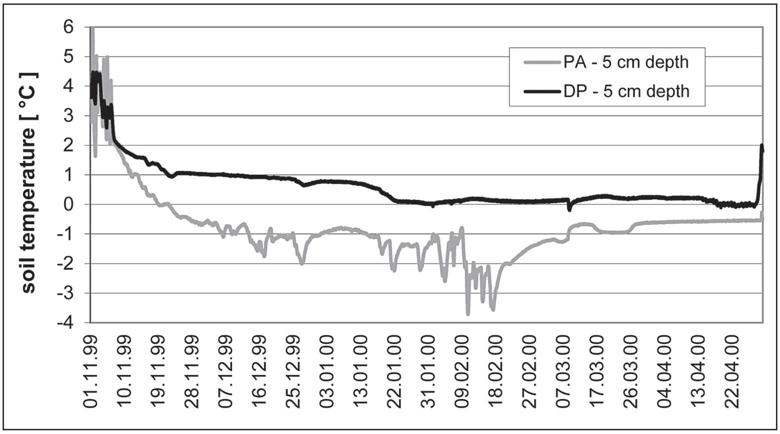

Figure 1: Sequence of soil temperature in 5 cm depth during the whole winter season 1999/2000, compared between the subalpine pasture plot (PA) and the dwarf pine plot (DP).

Abbildung 1: Sequenz der Bodentemperatur in 5 cm Tiefe während des gesamten Winterhalbjahres 1999/2000, verglichen zwischen den subalpinen Versuchsflächen Alm (PA) und Latsche (DP).

The end of the winter season in April 2000 was characterized by a relatively cold period, which lasted until 14th of April 2000 (see Fig. 2 A). The mean air temperature during the period from the 1st to the 14th of April was -2.1 °C. Starting from the 15th of April, a pronounced snow ablation period commenced and was characterized by maximum air temperatures around 13 °C (Fig. 2 A) and by a mean air temperature of 5.7 °C from the 15th to the 30th of April. These air temperatures initiated the snow ablation process whose effects can be seen at the DP plot by pronounced daily courses of both soil temperature (see Fig. 2 B) and soil moisture (see Fig. 2 C). When DP soil moisture reached its daily maximum, soil temperature reached its daily minimum. These dynamics can be explained by infiltration of cold melting water into the soil horizons. The drastic increase of soil temperature at DP at the end of April was caused by the end of the snow ablation period. Soil temperature during this period reached levels above 2 °C (Fig. 2B). In contrast, soil temperature and soil moisture at PA plot did not show pronounced daily courses during this snow ablation period. The soil at the PA plot was still frozen and covered with snow showing temperature levels around minus 0.5 °C (Fig. 2 B + C).

During the winter of 2007/2008 the dynamics of soil moisture and soil temperature showed different characteristics. Soil frost on both PA and DP plot was absent and soil temperature at DP was slightly higher than at the PA plot (Fig. 3). At the end of the winter season in April 2008 air temperature reached levels significantly above freezing during several periods thus beginning the snow ablation season (Fig. 4 A). The snow ablation process was reflected on both PA and DP by pronounced daily courses of soil temperature and soil moisture (Fig. 4 B + C). The only difference between PA and DP was that the peaks of soil moisture were slightly higher in the case of DP. The daily maximum of soil moisture coincided again with the daily minimum of soil temperature, now indicating at both PA and DP infiltration of melting water into the soil horizons.

Table 1: Monthly mean of Air Temperature (AT) and Soil Temperature (So) in 5 cm depth at both pasture (PA) and dwarf pine (DP) plot during January, 2000-2010 (values in °C)

Tabelle 1: Monatliche Mittel der Lufttemperatur (AT) und der Bodentemperatur in 5 cm Tiefe auf den Versuchsflächen Alm (PA) und Latsche (DP) im Jänner, 2000-2010 (Werte in °C)

	2000	2001	2002	2003	2004	2005[1]	2006	2007	2008	2009	2010
AT	-7.86	-5.37	-4.68	-7.48	-9.23	-9.78	-7.04	-3.37	-3.88	-6.83	-8.71
So-PA	-1.21	-2.66	-0.62	-0.46	-1.07	-3.60	*	-0.40	0.66	-0.05	-0.88
So-DP	0.46	-0.06	-0.16	-0.41	0.23	0.60	0.57	-0.23	1.16	-0.14	-1.26
1 values 2005 from 11.1. to 10.2., others from 1.1. to 31.1. ; *no data due to data logger problems											

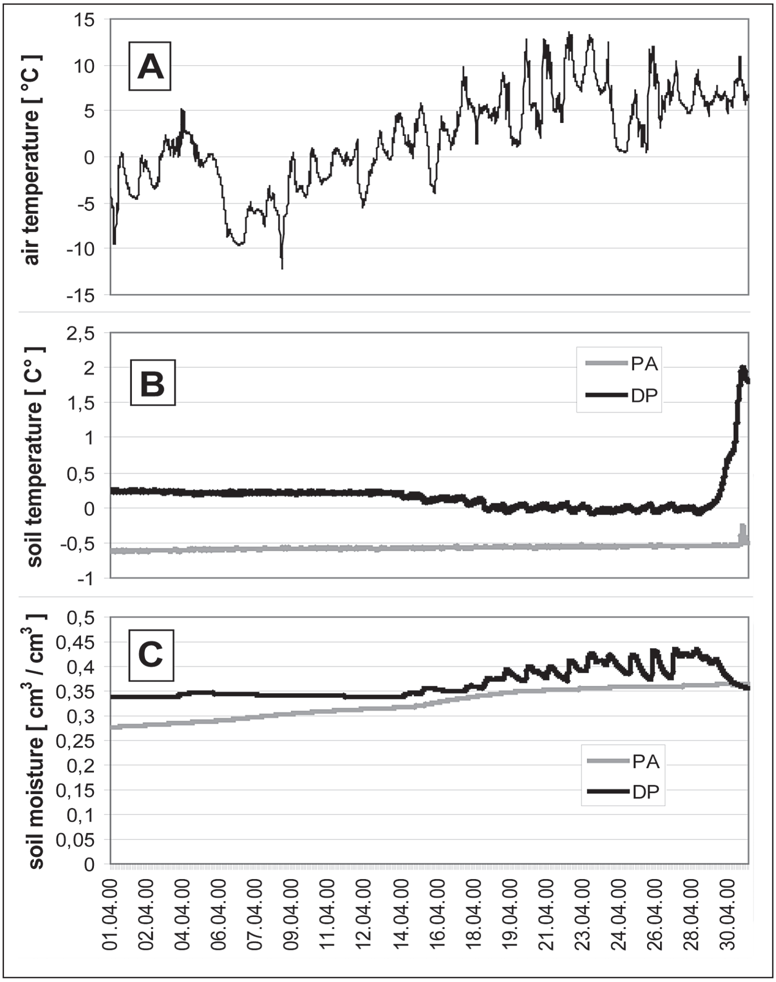

Figure 2: Air temperature (A), soil temperature in 5 cm depth (B), and soil moisture content in 20 cm depth (C) during the snow ablation period in April 2000, compared between the subalpine pasture plot (PA) and the dwarf pine plot (DP).

Abbildung 2: Lufttemperatur (A), Bodentemperatur in 5 cm Tiefe (B) und Bodenfeuchte-Gehalt in 20 cm Tiefe (C) während der Schneeschmelzperiode im April 2000, verglichen zwischen der subalpinen Versuchsflächen Alm (PA) und Latsche (DP).

Mean soil temperature in January from 2000-2010 showed that only in January 2008 soil frost formation at PA did not take place. During the other years soil was frozen there constantly. In most of the cases soil temperature at PA was lower than at DP (Tab.1).

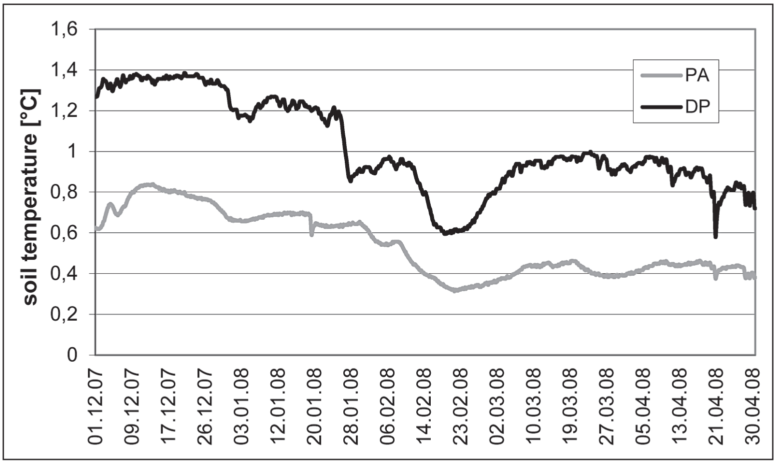

Figure 3: Sequence of soil temperature during the winter season 2007/2008, from 1. 12. 2007 until 30. 4. 2008, compared between the subalpine pasture plot (PA) and the dwarf pine plot (DP).

Abbildung 3: Sequenz der Bodentemperatur während des Winterhalbjahrs 2007/2008, vom 1.12. 2007 bis 30.4. 2008, verglichen zwischen den subalpinen Versuchsflächen Alm (PA) und Latsche (DP).

These results provide a broader view of the soil temperature and soil moisture dynamics at Mount Rax during winter seasons than the results presented in Koeck et al (2002), where the shorter measurement period did not cover winter seasons where soil frost was absent at both subalpine plots. A wide scope of climatically differing winter seasons was presented on the level of time series in Koeck (2008).

During summers the differences between PA and DP were rather uniform, soil temperatures were generally higher at PA compared with DP. During July and August 2003 the level of soil temperature at DP was up to 6 °C lower than at PA (Fig. 5). The course of soil moisture was governed by precipitation events and long lasting dry spells. It became evident that during long lasting dry spells like in August 2003 volumetric soil moisture decreased faster below dwarf pine vegetation than below pasture vegetation (Fig. 5).

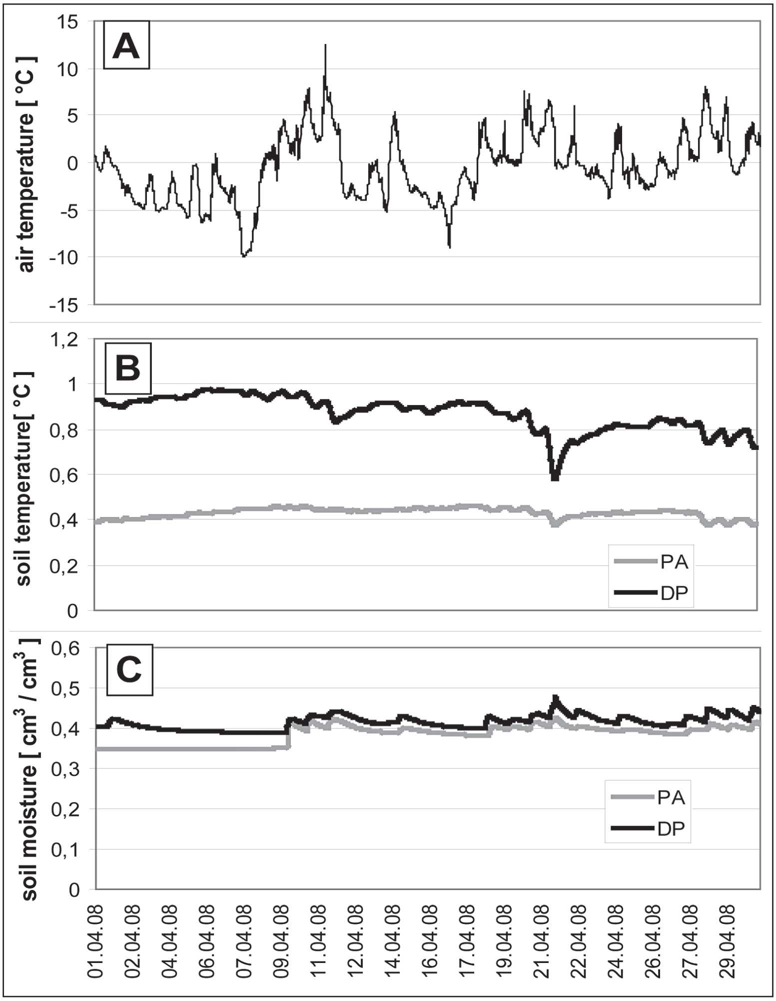

Figure 4: Air temperature (A), soil temperature in 5 cm depth (B) and soil moisture content in 20 cm depth (C) during the snow ablation period in April 2008, compared between the subalpine pasture plot (PA) and the dwarf pine plot (DP).

Abbildung 4: Lufttemperatur (A), Bodentemperatur in 5 cm Tiefe (B) und Bodenfeuchte-Gehalt in 20 cm Tiefe (C) während der Schneeschmelzperiode im April 2008, verglichen zwischen den subalpinen Versuchsflächen Alm (PA) und Latsche (DP).

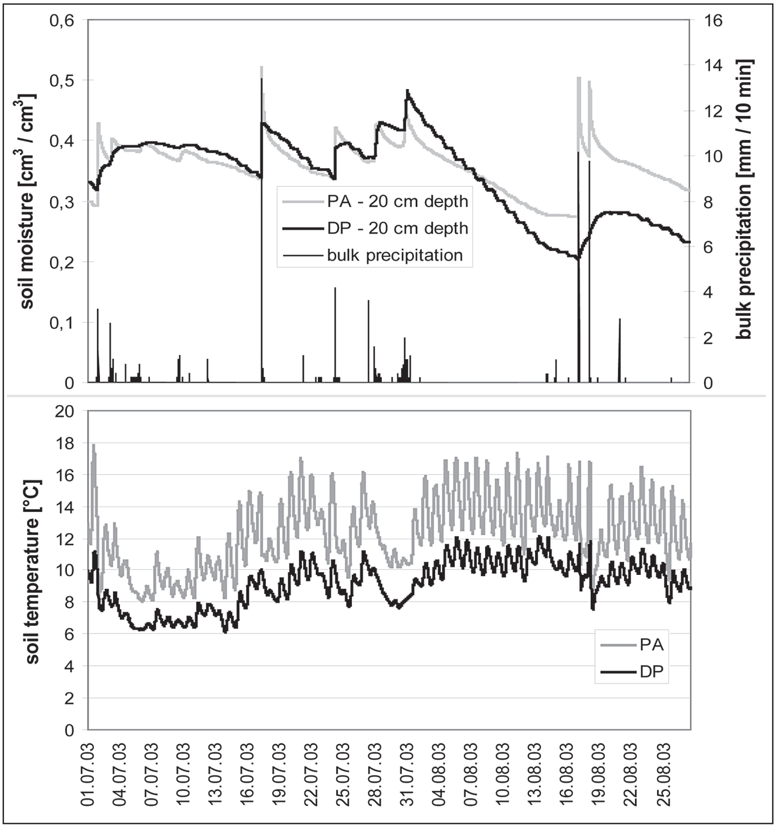

Fig. 5: Sequence of soil temperature in 5 cm depth, soil moisture in 20 cm depth and bulk precipitation compared between pasture plot (PA) and dwarf pine plot (DP) from 1.7. to 28.8. 2003.

Abbildung 5: Sequenz der Bodentemperatur in 5 cm Tiefe, des Bodenfeuchte-Gehalts in 20 cm Tiefe und des Freiland-Niederschlags, verglichen zwischen den subalpinen Versuchsflächen Alm (PA) und Latsche (DP), vom 1.7. bis 28.8. 2003.

5. Discussion

The infiltration of snow melting water into the soil at the dwarf pine plot (DP) took place during all measured winter seasons shown by pronounced daily courses of soil moisture and soil temperature. In contrast infiltration was inhibited in the case of the subalpine pasture plot (PA) e.g. during the winter season 1999/2000 (Fig. 2), where the soil horizons were frozen during this period (Fig. 1). Almost during all measured periods (January is selected as the reference month as it represents the winter halfway point) soil temperature in 5 cm depth was lower at PA than at DP. Only the years 2009 and 2010 showed slightly lower temperatures at DP (Tab. 1). The fact that snow melt water or precipitation water may easier infiltrate into soils without ground frost than into frozen soils was highlighted by Shanley and Chalmers (1999). Also other authors refer to the obstruction or reduction of infiltration of water into frozen soils (Gray et al 2001; Hardy et al 2001; Hinkel et al 2001; Stähli et al 2001). The cause for the differences in soil temperature between PA and DP can be found in differing snow pack accumulation during the early winter season. Dwarf pine branches have the ability for an efficient snow interception which was leading to higher snow accumulation at the DP plot during most of the monitored early winter seasons. In contrast, early winter snow may be blown off by winds from subalpine pasture areas which also can be seen by lower snow depths at the PA plot at these times (data not displayed here, see e.g. in Koeck 2008). The accumulation of a solid snow pack in early winter season in the case of the dwarf pine plot (DP) leads to a thermal insulation and also to a prevention of radiative cooling of the soils (Körner 1999) which both can prevent soils from severe freezing (Stadler et al 1996; Sutinen et al 1999). Radiative cooling only can take place on surface. If soils are covered by snowpack they cannot be cooled by emission of radiation. This combined effect was observed during most of the monitored winter seasons (Tab. 1) leading to significantly differing soil temperature and soil moisture dynamics at DP and PA plot (Fig. 1 + 2). The facilitation of snow pack formation by shrub vegetation and the subsequently higher soil temperatures below shrubs in comparison with open land during winter seasons were also reported by Sturm et al (2001).

But during some of the winter periods, most pronounced in the season 2007/2008, the formation of a solid snow pack during early winter took place at both DP and PA leading to the prevention of soil frost at both experimental plots (Fig. 3 and Tab.1). This resulted in the situation that in spring time the infiltration of melting water into the soils was possible without any hindrance at both DP and PA plot (Fig. 4). Early snowfall during this winter season may have occurred with higher temperatures and without the impact of strong winter storms facilitating the formation of a solid snow pack also at PA plot. Snow pack formation generally shows a high variation between winter seasons, which may be due to the differing weather situations during each of the winters, a fact which also was reported by several authors (Isard and Schaetzl 1998; Hebertson and Jenkins 2003). The fact that the soils below dwarf pine (DP) may have a higher content of macro-pores due to the higher amount of plant root channels and favourable humus conditions may also contribute to better infiltration conditions for melting water in spring periods.

The snow ablation periods in spring were characterized by a faster snow melt process at the DP plot. Snow pack at the PA plot lasted longer into spring than at DP plot (snow course data not displayed here, see e.g. in Koeck 2008). This process can be explained with the dark dwarf pine branches which facilitate a lower short wave albedo value in the course of snow ablation. If the dark branches are already situated close to the snow surface, more short wave radiation may already be absorbed by them, thus emitting infrared radiation, for which snow is nearly an ideal absorber. If the dwarf pine branches finally rebound from the snow pack due to snow ablation and the elasticity of dwarf pine, the dark branches can emit the infrared radiation directly to the snow layers beneath facilitating a faster snow melt process at the DP plot than at the PA plot. The differences between the two vegetation cover types were analysed at a flat site of the Mount Rax plateau excluding variation in snow pack formation caused by topography.

The dynamics of soil temperature during summer seasons compared between DP and PA were of different structure (Fig. 5). Due to the shading effect of the crown cover of dwarf pine, soil temperature was up to 6 °C lower at DP compared with PA. In general, dwarf pine vegetation showed a dampening effect on soil temperature during summers. Kang et al (2000) referred to the thermal dampening effect of a closed forest canopy on soil temperature. The important effect of soil temperatures in the rooting zone of tree species on the formation of the tree line was reported by Körner and Paulsen (2004). Especially within densely stocked dwarf pine communities the germination of spruce or larch may be hindered due to the cooler soil temperatures below this vegetation type facilitating the dominance of dwarf pine at this altitude range also in future periods. This effect was also reported by Dullinger et al (2005). The faster decrease of volumetric soil moisture in 20 cm depth below dwarf pine in contrast to pasture vegetation like shown in figure 5 could be caused by a higher transpiration rate of *Pinus mugo* which according to Kutschera and Lichtenegger (2002) shows a concentration of roots within the upper soil layers.

The described effects of *Pinus mugo* vegetation cover on hydro-meteorological parameters proves its suitability for water protection purposes at the specific subalpine forest sites. Its characteristics in early winter snow accumulation and the acceleration of snow ablation processes combined with the good infiltration conditions for snow melt water in spring periods may contribute to a more balanced spring discharge and also to a possible mitigation of erosion processes. During summer periods the good infiltration conditions for precipitation water and the root-network of dwarf pine also contribute to the prevention of soil erosion. The stabilization of the fragile karstic soil- and humus formations is a central concern of the integral drinking water protection strategy within the DWPA (see e.g. in Richards et al 2012).

On the other hand the presence of subalpine pasture vegetation also contributes to an extension of the snow ablation period in late spring. The possible higher plant species biodiversity through the presence of subalpine pastures is a factor which also may be considered (Pornaro et al 2013).

It can be then be concluded that an adequate areal distribution between dwarf pine and pasture vegetation cover seems to be the most appropriate solution for water protection purposes. However, the impacts of dwarf pine on hydrology seem to be more desired within the DWPA and the processes of pasture abandonment and climate change could additionally contribute to an increase of the dwarf pine area within the upper subalpine zone in future.

It also has to be considered that monitoring of soil temperature dynamics at the tree line provides useful data for the documentation of climate change effects and possible consequences for soil organic matter due to increased or decreased soil temperatures, to which e.g. Hagedorn et al (2010) or Prietzel and Christophel (2014) referred.

Twelve years data analysis provided insights into the hydrological behaviour of the two vegetation cover types which could never be accomplished with only two or three years of measurement duration.

6. Conclusions

The comparison between subalpine pasture vegetation (PA) and dwarf pine vegetation (DP) showed characteristic differences on the level of hydro-meteorological variables like soil moisture, snow depth and soil temperature. The analysis of twelve years of monitoring at the test plots provided deeper insights into the hydrological behaviour of the two vegetation cover types for differing weather conditions in both winter and summer seasons.

The prevention or mitigation of soil frost beneath dwarf pine vegetation favoured the infiltration of snow melt water into the soil. This is of interest for water protection purposes because ground water recharge and the delivery of karstic spring water can be influenced positively. Consequently the prevention of the erosion processes is important for source water protection. The afforestation of *Pinus mugo* as control measure for subalpine areas which are prone to erosion and also as snow accumulation belts for early winter periods can be recommended as part of water protection management concepts. Due to the fact that snow pack duration on subalpine pasture areas under the absence of major snow pack translocation through high winds was in general longer than on dwarf pine areas, the significance of the pasture areas can be found in their role to provide a longer lasting snow storage effect and a resulting prolonged melt water release during spring. Both PA and DP vegetation can contribute to a more balanced spring water release. Therefore a mosaic of dwarf pine areas and subalpine pasture areas with an adequate areal distribution can be regarded as optimal for water protection. The role of dwarf pine vegetation may be more desired within the DWPA as its contribution to erosion control is higher. Also the effect of pasture abandonment and climate change could contribute to an increase of *Pinus mugo* in its areal extension. We conclude that the measurements at the tree line of Mount Rax showed relevant results for the management of the drinking water protected area as they provided some insights into the differing hydrological behaviour of the two analysed vegetation types. Long-term data acquisition and monitoring are of importance within this context.

Acknowledgements

We want to express our gratitude to the city of Vienna for supporting the investigations. Our special gratitude is communicated within this context to the Municipal Departments ‘Vienna Water’ (MA31) and ‘Forestry Office and Urban Agriculture’ (MA49). Further we also want to thank the European Regional Development Fund (ERDF) for supporting past and current projects, like KATER II or CC-WaterS. We also express our acknowledgments to all the people, who have supported the research activities on Mount Rax. We thank Adam Moreno for reviewing the paper and for English editing.

References

Aulitzky H. (1961). Die Bodentemperaturverhältnisse an einer zentralalpinen Hanglage beiderseits der Waldgrenze. Archiv f. Meteor., Geophy. u. Bioklimat., Serie B: All. und biol. Klimatologie, Band 10, 4. Heft.

De Fries R, Eshleman K N. (2004). Land-use change and hydrological processes: a major focus for the future. Hydrological Processes 18, 2183-2186.

Delta-T Devices Ltd. (1999). Theta Probe Soil Moisture Sensor, User Manual. Burwell, Cambridge, England.

Dirnböck T, Grabherr G. (2000). GIS assessment of vegetation and hydrological change in a high mountain catchment of the Northern Limestone Alps. Mountain Research and Development 20 / 2, 172-179.

Dirnböck T, Dullinger S, Grabherr G. (2003). A regional impact assessment of climate and land-use change on alpine vegetation. Journal of Biogeography, No. 30, 241-252.

Dullinger S, Dirnböck T, Koeck R, Hochbichler E, Englisch T, Sauberer N, Grabherr G. (2005). Interactions among tree-line conifers: different effects of pine on spruce and larch. Journal of Ecology 93, 948-957.

Gehring-Fasel J, Guisan A, Zimmermann N E. (2008). Evaluating thermal treeline indicators based on air and soil temperature using an air-to-soil temperature transfer model. Ecological Modelling 213, 345-355.

Gray D M, Toth B, Zhao L, Pomeroy J W, Granger R J. (2001). Estimating areal snowmelt infiltration into frozen soils. Hydrological Processes 15, 3095-3111.

Hagedorn F, Martin M, Rixen C, Russ S, Bebi P, Zürcher A, Siegwolf R, Wipf S, Escape C, Roy J, Hättenschwiler S. (2010). Short-term responses of ecosystem carbon fluxes to experimental soil warming at the Swiss alpine tree line. Biogeochemistry 97, 7 – 19.

Hardy J P, Groffman P M, Fitzhugh R D, Henry K S, Welman A T, Demers J D, Fahey T J, Driscoll C T, Tierney G L, Nolan S. (2001). Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. Biogeochemistry 56, 151-174.

Hebertson E G, Jenkins M J. (2003). Historic climate factors associated with major avalanche years on the Wasatch Plateau, Utah. Cold Regions Science and Technology 37, 315-332.

Hedstrom N R, Pomeroy J W. (1998). Measurements and modelling of snow interception in the boreal forest. Hydrological Processes 12, 1611-1625.

Hinkel K M, Paetzold F, Nelson F E, Bockheim J G. (2001). Patterns of soil temperature and moisture in the active layer and upper permafrost at Barrow, Alaska: 1993-1999. Global and Planetary Change 29, 293-309.

Hofer I. (2007). Die Alm- und Weidewirtschaft des Rax-, Schneeberg-, Schneealpe- und Hochschwabgebietes. [Master thesis] Vienna, Austria: Institute of Geography, University of Vienna.

Isard S A, Schaetzl R I. (1998). Effects of winter weather conditions on soil freezing in southern Michigan. Physical Geography Vol. 19, Issue 1, 71-97.

Kang S, Kim S, Oh S, Lee D. (2000). Predicting spatial and temporal patterns of soil temperature based on topography, surface cover and air temperature. Forest Ecology and Management 136, Issues 1-3, 173-184.

Koeck R, Mrkvicka A, Weidinger H. (2001). Bericht zur Forstlichen Standortskartierung im Revier Rax, Forstverwaltung Nasswald der Quellenschutzwälder der Stadt Wien, Niederösterreich. Österreichische Nationalbibliothek, Wien.

Koeck R, Härtel E, Holtermann C, Hochbichler E, Hager H. (2002). Soil Moisture Dynamics Related to Vegetation Cover in the Subalpine Zone of the Northeastern Calcareous Alps in Austria. Results of Case Studies in the Rax Area. Centralblatt für das gesamte Forstwesen 119, Heft 3-4, 297-306.

Koeck R. (2008). Waldhydrologische Aspekte und Waldbaukonzepte in karstalpinen Quellenschutzgebieten in den nördlichen Kalkalpen. [PhD dissertation] Vienna, Austria: Department of Forest- and Soil Sciences, Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna.

Körner C. (1999). Alpine plant life. Springer Verlag, Berlin, Heidelberg, Stuttgart.

Körner C, Paulsen J. 2004. A world-wide study of high altitude treeline temperatures. Journal of Biogeography 31, 713-732.

Kutschera L, Lichtenegger E. (2002). Wurzelatlas mitteleuropäischer Waldbäume und Sträucher. Leopold Stocker Verlag, Graz.

Lundberg A, Koivusalo, H. (2003). Estimating winter evaporation in boreal forests with operational snow course data. Hydrological Processes 17, 1479-1493.

Mayer H. (1974). Wälder des Ostalpenraumes. Gustav Fischer Verlag, Stuttgart.

Murray C D, Buttle J M. (2003). Impacts of clearcut harvesting on snow accumulation and melt in a northern hardwood forest. Journal of Hydrology 271, 197-212.

Nestroy O, Danneberg O H, Englisch M, Geßl A, Hager H, Herzberger E, Kilian W, Nelhiebel P, Pecina E, Pehamberger A, Schneider W, Wagner J. (2000). Systematische Gliederung der Böden Österreichs. (Österreichische Bodensystematik 2000). Mitt. D. Österr. Bodenkundl. Ges., Heft 60, Wien.

Pornaro C, Schneider M K, Macolino S. (2013). Plant species loss due to forest succession in Alpine pastures depends on site conditions and observation scale. Biological Conservation 161, 213-222.

Prietzel J, Christophel D. (2014). Organic carbon stocks in the forest soils of the German Alps. Geoderma 221-222, 28-39.

Richards, W H, Koeck R, Gersonde R, Kuschnig G, Fleck W, Hochbichler E. (2012). Landscape-scale forest management in the municipal watersheds of Vienna, Austria and Seattle, USA: Commonalities despite disparate ecology and history. Natural Areas Journal 32, 199-207.

Shanley J B, Chalmers A. (1999). The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont. Hydrological Processes 13, 1843-1857.

Stadler D, Bründl M, Wunderli H, Auckenthaler A, Flühler H. (1996). Measurement of frost-induced snowmelt runoff in a forest soil. Hydrological Processes 10, 1293-1304.

Stähli M, Nyberg L, Mellander P E, Jansson P E, Bishop K H. (2001). Soil frost effects on soil water and runoff dynamics along a boreal transect: 2 simulations. Hydrological Processes 15, 927-941.

Sturm M, McFadden J P, Liston G E, Chapin F S III, Racine C H, Holmgren J. (2001). Snow-shrub interactions in arctic tundra: a hypothesis with climate implications. Journal of Climate 14, 336-344.

Sutinen M L, Holappa T, Ritari A, Kujala K. (1999). Seasonal changes in soil temperature and snow-cover under different simulated winter conditions: Comparison with frost hardiness of Scotts pine (*Pinus sylvestri*) roots. Chemosphere: Global Change Science 1, 485-492.

v. Wilpert K, Nell U, Lukes M, Schack-Kirchner H. (1998). Genauigkeit von Bodenfeuchtemessungen mit „Time Domain-Reflektrometrie“ und „Frequency Domain-Sensoren“ in heterogenen Waldböden. Z. Pflanzenernähr. Bodenk., 161, 179-185.

Woo M K, Marsh P. (2005). Snow, frozen soils and permafrost hydrology in Canada, 1999-2002. Hydrological Processes 19, 215-229.

ZAMG (2014). Zentralanstalt für Meteorologie und Geodynamik, Wien: Klimadaten von Österreich, 1971-2000. Verfügbar via Internet: www.zamg.ac.at / Klima – langjährige Klimadaten.