SZENT ISTVÁN UNIVERSITY

WATER CYCLE IN FORESTS AND GRASSLANDS

The main points of the thesis

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1. THE ANTECEDENTS AND AIMS OF THE WORK

The demand for nature-based forestry is increasing with social and environmental changes. The aim of nature-based forestry is to maintain natural, mixed-species and uneven-aged forests simulating natural forest processes. Gap dynamics is the natural process when gap is created in the canopy as one or some trees fall down and after that new trees repopulate the gap. It can be simulated with small extent, group-like cutting that can expand from one tree to some dozen of trees. Knowledge on gap regeneration ecology is essential for understanding the forest processes and nature-based forest management so its research is important from ecological, environmental protection and forestry aspects. Gaps generate considerable changes in microclimate, biogeochemical cycle and vegetation at the forest floor. Gap effects are often studied, but in most cases from the aspect of tree regeneration. From abiotic factors, mainly the light conditions are studied that shows the most visible changes. Changes in herb vegetation, soil moisture and soil temperature are less discovered. Results that can be found in the literature are obtained at various spatial and time resolutions. In the frame of NAT-MAN EU FP6 research project we aimed at a complex research on soil moisture, soil temperature, light conditions and vegetation at fine spatial scale, involving analysis of relationships between these factors. We assumed that soil water content increases in the gaps compared to the closed stand because of microclimatic changes and decreased plant water use. Our main questions were the following: 1) is there significant difference between the water content of the upper soil layer in the gaps and in the closed forest stand, and in the two different sized gaps (diameter of half and one and a half tree length) in the first, second and fifth year after gap creation? 2) what is the fine scale spatial pattern of soil moisture and soil temperature like in the gaps? 3) is there relationship between the spatial pattern of soil water content, relative light intensity and herb species?

Forests have a great effect on soil hydrological properties and water cycle. Among others they facilitate water infiltration into the soil, the litter increases the soil water retention, the canopy protects soil against heavy rainfalls, so forests play an important role in soil protection and flood prevention in rainy mountain areas. As a result of great extent treatments like deforestation water cycle can change significantly. Knowledge on these changes is important from the aspect of prevention of harmful effects and of management and land use planning. I compared the soil hydrological properties and soil water content dynamics of a forest and a secondary grassland developed on a cutting area in Mátra Mountains. In their area heavy rainfalls are frequent and a flood have occurred and caused serious damage recently. My questions were the following: 1) are there differences between properties influencing water cycle of the forest soil and the grassland soil? 2) is there difference between soil water content dynamics of the grassland and the forest? 3) to what extent does the canopy decrease the amount of rain reaching the forest soil surface? 4) is there relationship between throughfall and precipitation amount and intensity, and canopy closure?

The evapotranspiration (ET) is the water balance element of which determination is the most difficult. Its measurement requires specific, expensive instruments. Precise measurement of different physical properties or the water balance is needed for it. Therefore, its direct measurement is not suitable for routine applications, it is rather useful for testing of indirect methods (as models simulating water balance elements). For model calibration generally soil water content or estimated ET data are used as reference, measured ET data are rarely available. Direct measurement of ET gives an opportunity to improve model calibration using ET data as input or comparing the measured and the simulated ET. Using the latter method, with data measured in the frame of Carbomont and Greengrass FP5 and Carboeurope IP FP6 projects by SZIU Institute of Botany and Ecophysiology I aimed at describing the water cycle of two different grasslands with SWAP soil water flow model. My other main aim was to estimate the two elements of ET, evaporation and transpiration that are difficult to distinguish. Many researchers study the relationships between ET and weather parameters, and based on them, empirical relations, models are created. The precision of ET determination can be highly improved by considering soil water content and vegetation factors. Most studies are limited to the vegetation period or short periods, more years long observations are rare. In my work the temporal dynamics of ET was studied in a four years period. I searched for relations between ET, weather parameters, soil water content and leaf area index (LAI). Data measured in the frame of Carbomont and Greengrass FP5 and Carboeurope IP FP6 projects by SZIU Institute of Botany and Ecophysiology were analysed.

2. MATERIALS AND METHODS

The research was carried out at three sites.

1. In the Börzsöny Mountains in the area of Királyrét Forestry in a closed beech stand (*Melitti-Fagetum*) developed on eroded brown forest soil with clay illuviation and in artificial gaps created in the beech stand in the winter of 2000/2001. The gaps have a diameter of half and one and a half tree length („small" and „large" gaps, area: 0,1 and 0,02 ha).
2. In piedmont area in the Mátra Mountains, in a forest stand dominated by Turkey oak and in a secondary grassland next to it, developed in a clearing where ploughing was given up about 20 years ago, both developed on Ramann brown forest soil.
3. In Bugacpuszta, in the territory of the Kiskunsági National park, in an arid sand grassland (*Cynodonti-Festucetum pseudovinae*) developed on humic sandy soil. It has been grazed extensively for 20 years.

In the gaps in the beech stand in Börzsöny Mts. the water content of the upper soil layer was measured with capacitive probes (IMAG and BR-30) in the first (2001), second (2002) and fifth year (2005) after gap creation. The measurements have been carried out twice in 2001 and with three weeks frequency from April to June in 2002, along 1-1 slope and contour line direction transect running through the gap centre and below the closed stand. The measurement distance was 0.5 and 1 m. Soil water content was measured in a grid once in about every three weeks from June to October in 2002 and in April 2005 in a small and in a large gap, and in June 2005 in three small and two large gaps. Soil temperature was measured simultaneously with soil moisture measurements along transects and with the first grid measurement. Coverage of the herb layer species was registered in circle shaped sampling units with 20 cm radius located around the soil moisture measurement points.

The difference between soil water content of the gap, the gap edge and the closed stand was tested with variance analysis. It was tested with statistical methods if there is difference between soil temperature of the gap and the closed stand, the soil water content of the small and the large gap (at the same measurement dates), variance of soil water content in the gaps and in the closed stand, in the small and in the large gap. It was also tested with statistical methods if there is correlation between cover of herb species, soil water content and (the diffuse and direct component of) relative light intensity. The spatial pattern of soil water content, soil temperature and diffuse and direct relative light intensity were compared.

Soil water content has been measured with ECH2O capacitive sensors in one soil pit in the grassland and in three soil pits in the forest in Mátra Mts. in depths of 15, 25, 35, 45 and 55 cm during two years (2005-2006). Texture, plasticity index according to Arany and humus content of the 0-10, 10-20, 20-40, 40-60 and 60-80 cm soil layers, water retention curve and bulk density of the 0-5, 20-25 and 40-45 cm soil layers were determined in 1-1 soil pits in the forest and in the grassland in 3-3 repetitions. The near-saturated hydraulic conductivity was measured with mini disk infiltrometer.

Rainfall and throughfall has been measured with tipping bucket rain gauges in the grassland and in the forest, respectively, between 2005 and 2007. The canopy closure above the throughfall measurement sites was estimated upon photographs taken of the canopy from the top of the rain gauges. The correlation between throughfall, rainfall intensity and amount, and canopy closure were tested with linear regression.

The water cycle of the grasslands in Mátra Mts. and Bugac were analysed for a four years period. The weather and evapotranspiration data were obtained from the micrometeorological station operated by the SZIU Institute of Botany and Ecophysiology. Soil water content monitoring has been carried out with Campbell FDR sensors at the stations, in 3, 8, 14 and 20 cm soil depths in the Mátra site and in 3, 10 and 30 cm depths in Bugac. Soil water cycle of the grasslands was simulated with the SWAP deterministic model. Correlations between ET and weather parameters (radiation, air temperature, vapour pressure deficit and wind speed), soil water content and - in Bugac – the leaf area index (LAI) were analysed with statistical methods.

3. RESULTS

3.1 Results related to the gaps in the beech forest in Börzsöny Mountains

We obtained extensive information about effects of so small sized gaps (with diameter of half and one and a half tree length, that is 15-20 m and 35-40 m, respectively) for the first some years after gap creation in the studied beech forest that had not been studied in Hungary before.

In the autumn of the first year after gap creation and in the second year the soil water content was significantly higher in the gaps than below the closed canopy at all measurement dates except one, after a larger spring rainfall event. The soil water content of the gaps did not differ from that of the closed stand at the spring measurement date of the fifth year after gap creation when the soil was in wet condition. At the summer measurement date in the same year the similar gap effect as in the previous years could be shown, even expanded the study for two large and three small gaps.

There was no difference between the two gap sizes considering the average and the standard deviation of soil water content. The standard deviation was larger in both gap sizes than in the closed stand at every measurement dates, therefore as a result of creating both gap sizes wetter and more heterogeneous water supplied habitats came off compared to the closed stand.

The spatial structure of the soil water content in the gaps is changing in time (both correlation range and sill). The range is similar to the gap diameter in case of the gap with a diameter of half tree length („small gap") but it is smaller in the gap with a diameter of one and a half tree length („large gap"). As the correlation range is the range within which the samples are dependent (belong to the same population), the soil water content within the small gap can be considered to be homogenous, but it is different outside of the gap. The soil water content in the large gap is heterogeneous. In accordance with this, clear gradient-pattern can be observed based on the grid measurements in the small gap but in the large gap also smaller scale patches ("microhabitats") could be seen.

The gap edge on the score of soil moisture can be set along the tree trunks bordering the gap. The spatial pattern of the soil water content differ from that of the direct component of relative light intensity from more aspect, but it shows relationship with the spatial pattern of the diffuse component. The soil temperature did not differ between the gap bounded based on the bordering tree trunks and the closed stand, but it showed relationship with the relative light intensity. It increased even below the closed stand around the gaps, similarly as the relative light intensity which strengthens the "expanded gap" theory.
The soil water content was proved to be an important factor in the spatial pattern formation of herb species. From the species groups distinguished based on the frequency in the light intensity zones – as we had expected – the group of species most frequent in the centre of both gap sizes (at places with different relative light intensity but similar soil moisture) all showed correlation with soil water content, but most of the other species, too. Only two species, characteristic for beech forests, a weed species and beech seedlings did not show correlation with soil moisture. The cover of most of the species correlated with the diffuse component of the relative light intensity. The direct component showed correlation only with two species that were frequent in the large gap centre. Negative

correlation was showed between the presence of beech seedlings and diffuse component of relative light intensity.

3.2 Results related to the soil and water cycle of the grassland and forest in Mátra Mountains

The site has brown forest soil. Its texture is clay except for the upper 10 cm layer of the grassland soil which is clayey loam. The spatial variance of soil water content of the 10-20 cm soil layer was high in the forest. That of the deeper layers is smaller. The soil water content dynamics was similar in the grassland and in the forest. From the dry summer period the soil water content decreased more in the forest than in the grassland only in the soil layers deeper than 20 cm, which can be related to the deeper tree roots. The water supply of the upper 20 cm soil layer was similar at the two sites, but that of the upper 50 cm layer was smaller in the forest at the end of the dry summer period.

The characteristics of rainfall events influencing interception (precipitation amount and intensity) were revealed for two years. The monthly sums of the interception and stemflow ("net precipitation") were determined as the difference between gross rainfall and throughfall for three years. Studying the throughfall during three years I experienced that it has high spatial and temporal variance. It is interesting that throughfall sometimes was higher than gross rainfall measured in the grassland. The reason can be the difference between the rainfall in the grassland and above the forest in about 100 m distance from each other or the partially increased amount of throughfall caused by the redistribution of rainfall by the canopy. The latter can happen because water is led to the forest floor by the canopy spatially unevenly, gathered at some places, plus expanded in time – water can be dropping from the canopy also after the rainfall events.

There was correlation between monthly throughfall and gross rainfall in two out of three studied vegetation periods. Monthly throughfall correlated with the monthly mean rainfall intensity in the spring-summer period of two studied years. When the autumn months were taken into the analysis the correlation had weakened, which probably shows the effect of defoliation. Correlation was founded only in two out of five studied months between the monthly throughfall measured at more locations in the forest and the canopy cover estimated for the given months for the measurement locations. The reason for the absence of a general relationship between the studied factors can be that throughfall is also influenced by further vegetation parameters beyond canopy closure, such as canopy water holding capacity, canopy and branch structure. These characteristics can have high spatial variance because the forest is composed of many tree species and there are intraspecific differences among tree individuals, too.

3.3 Results related to the water cycle of the grassland in the Mátra Mountains and in Bugac

In the two grasslands with different species composition and habitat I concluded which factors evapotranspiration is affected by in different time periods, based on data measured at the micrometeorological station of the SZIU Botanical and Ecophysiological Institute. It was showed that in time periods when ET differed between the two grasslands the differences are caused principally not by the weather parameters but by the so called surface factors (soil and plant properties). The ET decreasing effect of soil water content could be showed in some time periods. In other periods it can be assumed that the smaller soil hydraulic conductivity and the different plant functioning could decrease the ET compared to the atmospheric evaporative demand more in the grassland in which ET is smaller.

It was showed with more data analysing methods that soil water content limited the ET when it was smaller than 28 V/V% (pF 4.2) and than 12 or 13 V/V% (depending on the year) (~ pF 3.4) in the grassland in the Mátra Mts. and in Bugac, respectively. Close correlation was found between the ET and the leaf area index (LAI) in the Bugac grassland in the four analysed years. It was the strongest in the droughty year of 2003. The residuum of the estimated ET values from the ET(LAI) function and of the measured ET values showed correlation with radiation, air temperature and vapour pressure deficit in three out of the four analysed years, and in two years with soil water content, so the effect of these factors could be shown.

The SWAP model was adapted successfully for the description of both grasslands. During the adaptation for dry/droughty weather areas it was shown that the soil water content smaller than wilting point has caused larger error than the acceptable in the simulation of soil water content dynamics in some soil layers in some time periods, because the model does not handle this soil moisture condition. The weekly water supply change generally could be simulated more accurately than the daily soil water content. Anyway, the daily measured and simulated soil water content mostly agreed with acceptable accuracy. The model simulated the annual ET with acceptable error in general and it approximated the seasonal dynamics also well. The monthly ET values were already estimated with large error in more cases and even more the daily values. So only careful conclusions can be drawn based on the monthly and daily simulated water balance elements but the annual and seasonal water balance elements can be determined with acceptable accuracy with SWAP model. So I estimated the annual sum of evapotranspiration elements, evaporation and transpiration that can be separated with difficulty. The model was used for testing the saturated hydraulic conductivity values determined with different methods in the grassland in Mátra Mts. and the estimated hydrophysical parameters (water retention curve, saturated hydraulic conductivity) in the Bugac grassland and for generating the saturated water content of the upper soil layer in Bugac, too.

The practical experiences about the BR-30, the IMAG and the ECH2O capacitive soil moisture sensors and the Campbell FDR sensors during my work are summarized.

3.4 NEW SCIENTIFIC RESULTS

Results related to the gaps in the beech forest in Királyrét

1. The soil water content increasing effect of gap creation could be shown in the first, second and fifth years after gap creation. Neither the soil water content nor its variance differed between the two sized gaps but its spatial pattern was different. The spatial structure of soil water content – depending on the gap size – is changing in time. The border of the gap can be set along the tree trunks around the gap or maximum in 1-2 m distance from them in direction of the gap centre.
2. The soil temperature showed close correlation with the relative light intensity and changed similarly to it even below the closed stand around the gaps.
3. The spatial pattern of most analysed plant species is in relationship with soil water content. The relation can not be linked to species groups distinguished based on frequency in the relative light intensity zones.

Results related to the soil and water cycle of the grassland and the forest in Mátra Mountains

4. The soil water content dynamics in the grassland and in the forest was similar in the studied time periods. Differences in water supply were shown only in layers below the upper 20 cm that includes the main root mass of the grass and only at the end of the dry summer period (the soil water content decreased more in the forest).
5. The monthly throughfall was varying in the forest, it was the 32-100% of the monthly gross rainfall. Its spatial variance was high and it decreased during defoliation. The monthly throughfall showed correlation with the rainfall intensity in the two studied vegetation periods, but with the precipitation amount only in one out of the three analysed vegetation periods and with the canopy closure only in some months, which shows that the throughfall is affected by its influencing factors in a complex way.

Results related to the water cycle of the grassland in the Mátra Mountains and in Bugac

6. The temporal dynamics of evapotranspiration was usually similar in the two grasslands. The differences are mainly caused not by the weather parameters but the soil water content and vegetation parameters. The soil water content limited the ET to a measurable extent when it was smaller than 28 V/V% (pF 4.2) and than 12 or 13 V/V% (depending on the year) (~ pF 3.4) in Szurdokpüspöki and in Bugac, respectively.

7. There is close correlation between the evapotranspiration and the leaf area index (LAI) in the Bugac grassland. The correlation equation rather underestimates the evapotranspiration in case of dry soil conditions and overestimates it in wetter soil. The residuum between the measured and the estimated evapotranspiration can be explained by the soil water content, the radiation, the air temperature and the vapour pressure deficit.

8. The SWAP soil water flow model was adapted successfully for the two grasslands. It was shown that the soil water content permanently smaller than wilting point causes larger error than the acceptable in the simulation in some time periods, because the model does not handle that soil moisture condition. The monthly and daily ET sums were estimated with large error by the model in many cases but the annual ET sum and also the seasonal dynamics were approximated well. So estimation was given using the model for the annual evaporation and transpiration values and for the annual variation of their proportion.

4. CONCLUSIONS AND PROPOSITIONS

The study of the artificial gaps in the beech forest concerns only some years after gap creation which is a short period compared to the time scale of forest development. Anyway, it gives detailed information about the initial phase of gap regeneration from which numerous conclusions can be drawn.

The soil water content increasing effect of gaps could have been shown until the fifth year after gap creation. With gap regeneration the difference between the gap and the closed stand will expectedly decrease but the vegetation and the soil water content can change in different ways in certain gaps.

The spatial structure of soil water content in the gaps was different along the slope and the contour line and also changing in time. The relationships between soil water content and plant species is changing in time, too, so reliable consequences cannot be drawn by a single measurement. This strengthens the necessity of appropriate repetition number of soil water content measurements in time and space.

As a result of creation of both gap sizes patches with more diverse water supply develop compared to the closed forest that give habitat for plant species with various water demand. So these gaps can play an important role in maintaining species diversity. There was no significant difference between the soil water content of the small and large gaps, only its spatial pattern was different, unlike to relative light intensity. As a consequence, in practice the choice between the two gap sizes affects the light conditions more than soil water content.

A definite border between the gap and the closed stand cannot be set based on soil moisture neither along the canopy nor along the trunks. Its reason can be that the joint effect of more factors controls soil water content. The trunks (or rather the roots) take their effect on soil moisture through water uptake and the canopy affects interception.

The use of circle shaped vegetation sampling units with 20 cm radius in the correlation analysis between soil moisture and herb layer species resulted in small frequencies because of the small vegetation cover. This made the statistical analysis difficult but because of the high spatial variability of soil water content it was even a good choice to refer the measured values for such small areas.

The effects of gap size and location within the gaps can be explained by relative light intensity and soil water content data, which verifies the importance of these factors in colonization of plant species. The most common plant species belong to the group of sun plants according to the Collins Pickett's categorization. The group can be further classified based on the location within the gaps and on correlations with light intensity and soil moisture.

The joint investigation of soil moisture, relative light intensity, soil temperature and the undergrowth has shown that the border between the gaps and the closed forest set based on the different features can be different. Therefore, if we define a gap, it is necessary to define that it is bounded on the basis of what factor.
The long-term continuation of the gap studies can give information that practice may use for the planning of group selection harvest.

Some properties of the upper 40 cm soil layer significantly differ between the grassland and the forest (e.g. clay and humus content), which partly explains the differences in soil water retention curve but it is also influenced by the measurement difficulties resulted from the high clay content of the soil of the forest. By comparing the soil water content dynamics of the grassland and the forest I concluded that the soil water content decreasing effect of interception in the upper 20 cm soil layer in the forest is balanced by the shading effect and by the high water retention of the A-layer with higher organic matter content and of litter.
The ratio of throughfall to gross rainfall and the sum of interception and stemflow calculated as the difference of gross rainfall and throughfall were determined for the early summer-autumn periods of three years. As their spatial variance has proven to be significant, their measurement in more repetition could result in more accurate determination.
General relationships between throughfall, rainfall amount and intensity and the canopy closure could not been shown. This points to the assumption that interception (the rate of water amount intercepted by canopy) is influenced by many factors in a complex way. This is also shown by that the relations between interception and rainfall characteristics are widely studied but relations are not even clear. Further results that can be used in the evaluation of the effects of land use on water cycle can be obtained by more complex study of water cycle in the forest.

The assumed effect of the functioning difference between the grassland in Bugac and that in Mátra Mts. based on the correlation analysis between evapotranspiration, weather parameters and soil water content is verified by the net gas exchange studies of PINTÉR ET AL. (2007). This shows that for the fully comprehensive knowledge on the factors regulating the ET interdisciplinary research is needed including studies on soil, weather and vegetation factors.
The advantage of the presented water cycle modelling studies is that two types of reference data (soil water content and ET) were available for calibration and evaluation, which gave an opportunity for more accurate model fitting. The long-term and detailed measured soil water content data enabled the analysis of soil water cycle modelling at different (daily, weekly, monthly and annual) time scales.
The SWAP model was successfully adapted for the two grasslands. By comparing the measured and simulated soil water content and evapotranspiration data it was concluded that only careful conclusions can be drawn from the monthly and daily simulated data, but the annual water balance elements can be determined with acceptable accuracy. So I could estimate the annual sum of the elements of evapotranspiration, evaporation and transpiration and the model can be used for simulating the different effects (weather situations and changes - climate change, drought, management – mowing, grazing) on the water cycle of the grasslands in the future.
As in case of the clayey soil of the Mátra site the measurement error of ±3% cannot be guaranteed for the whole period the calibration method of STANGL et al. (2009) is suggested.

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