Fuzzy Modelling of Below - Canopy Precipitation in Pine Forests as a Tool for Scaling up Water and Element Fluxes from Measurement to Ecosystem Level*

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1 Problem

Investigations of processes governing water and element fluxes in forests can be carried out at few selected investigation plots and with a small number of repetitions only. Due to the great variety of complex ecosystems like forests it proves to be hard transferring results of such local case studies to extensive parts of forest area as a precondition for scientifically founded management recommendations. On the other hand, forest structures can be mapped area-covering at reasonable cost. Therefore, the investigation of the relationships between structure and process at a series of forest sites which represent typical structural patterns seems to be a reliable method to quantify water and element fluxes in forests on a regional scale (JENSSEN et al. 1994).

Water and element balances are estimated by in-situ measurements at the boundaries of ecosystem compartments. Canopy throughfall and water flows at various soil depths are measured at different horizontal positions of the respective investigation plot. However, forests are marked by a considerable spatial heterogeneity with respect to vegetation and soil structure even on the scale of an investigation plot that was chosen as a homogeneous part of its surroundings. Water and element flows depend on the spatial distribution of structural elements sensitively (BORMAN and LIKENS 1979, KREUTZER 1985, v.WILPERT and MIES 1991, JENSSEN 1996). Usually it cannot be presupposed a priori that a chosen gauge distribution represents a certain structural pattern on a larger scale. Furthermore, there is no chance to establish investigation programs representing at least most widespread ecosystem structures.

Scaling up spatially disaggregated fluxes to ecosystem level proves to be a crucial challenge to forest ecology that requires appropriate model tools (HAUHS 1990, JARVIS 1993). The approach outlined in this paper is based on the assumption that the available measurement devices are distributed in a systematic or random manner on various investigation plots. At each measurement point a series of structural data is recorded and local relations between structure and process are analyzed. This way structural properties controlling the measured fluxes decisively can be elaborated. Regarding large-scale ecosystem structures as mosaics of local structural elements,

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their overall water and element balances can be obtained by area-weighted puzzling of local fluxes (fig. 1).

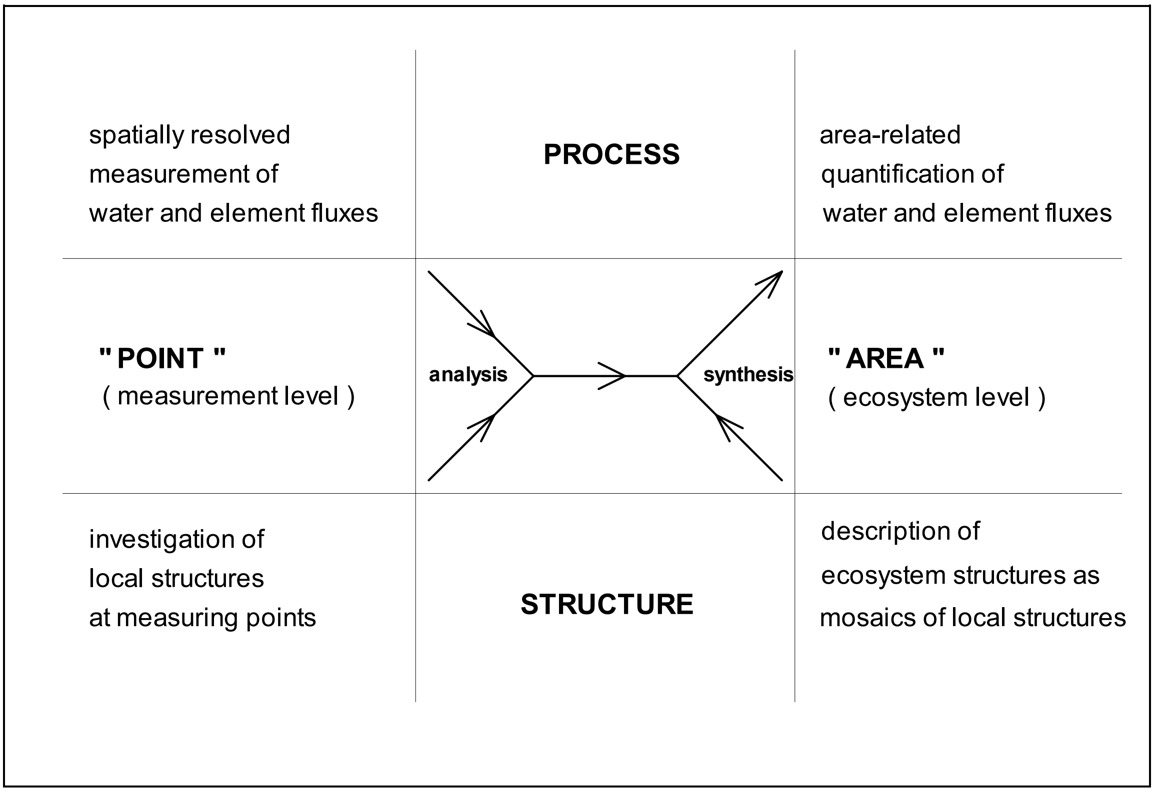

Figure 1: Based on the analysis of local relations between structure and process at the level of measuring points, water and element balances of area-covering forest ecosystems can be synthesized as area-weighted puzzles of local structural elements.

The sketched approach requires an appropriate methodology permitting

- an aggregated and flexible description of complex and manifold „mesostructures“ which have to be considered on measurement level,
- an event-related quantification of the multiple nonlinear dependencies of the spatially resolved processes under consideration on mesostructural parameters in spite of a limited data basis usually not justifying statistical foundations,
- compatibility of mesostructural description on measurement level with macrostructural description on stand or ecosystem level.

As will be demonstrated in this paper, a fuzzy approach is suited to meet these demands. As an example I will refer to the modelling of horizontally resolved below-canopy precipitation (throughfall) in Northeast German pine forests. Below-canopy precipitation controls processes in the compartments of ground-covering vegetation and forest soil to a large extent. For that quantification of its distribution patterns proves to be an important prerequisite for scaling up water and element fluxes from measurement to ecosystem level.

2 Quantification of local canopy structures by fuzzy sets

Provided identical above-canopy weather conditions net precipitation impinging on the rain gauges is varied by canopy structure. From the knowledge of microclimatic processes a physically substantiated choice of canopy parameters with possible influence on interception loss and precipitation allocation can be made.

For describing the structural peculiarities above rain gauges it is obvious to make a distinction between canopy elements like crown core, crown margin, or canopy gap. Each of these elements is marked by a series of similar structural properties and can be expected to show similar behaviour with respect to precipitation throughfall. However, an exact definition and mutual demarcation of the respective scopes by the help of few physically measurable quantities like needle density or distances from stem and idealized crown margin appears to be very problematical for several reasons. Furthermore, the transitions between these canopy elements are fluently. For that the canopy section above each gauge was documented by a video camera and afterwards evaluated by an estimated number between 0 and 1. A 0 denotes a central position inside a gap, a 1 describes a crown core with normally maximum density of needles and branches close to the stem, whereas values around 0.5 denote the inner and outer crown margin. Arbitrary graduations between these benchmark figures can be substantiated by a mutual comparison of different recordings. Furthermore, the main exposure of the respective canopy element with respect to the point of the compass was determined. Additionally, a series of parameters characterizing structure of adjacent trees was recorded including, e.g., crown area, gap area, crown transparency, needle surface or sociological position of trees.

In order to model main structural determinants of the precipitation allocation it seemed to be helpful to perform an aggregation of the measured or guessed data via a decomposition of their range of values in fuzzy sets according to the notion of ZADEH (1965) which is demonstrated exemplarily in figure 2. Thereby I restricted myself to the definition of triangular and trapezoidal fuzzy sets covering the range of values of the respective structural variables completely. E.g., a rain gauge the canopy position of which was estimated by the number 0.4 belongs to the crown margin with a membership of 0.6, to the gap with a membership of 0.4, but it definitely not belongs to the crown centre. It is important to emphasize that these degrees of membership do not correspond to probabilities. The degree of membership quantifies the possibility that the corresponding canopy position can be described by the terms crown margin or gap with respect to a series of characteristic properties. The fuzziness results less from the impreciseness of measurement or guess but rather from the difficulty to define the structural terms unambiguously.

The domain of a certain parameter can be partitioned into fuzzy sets in an arbitrary way. For example it could be meaningful to distinguish between inner and outer crown margin provided both scopes display a clearly different behaviour with respect to canopy throughfall. The fuzzy sets have not to be symmetrical or even bell-shaped like a normal distribution but may reflect nonlinear dependencies. The introduction of fuzzy sets offers a convenient and flexible opportunity to deal with the quantification of complex and manifold canopy structures.

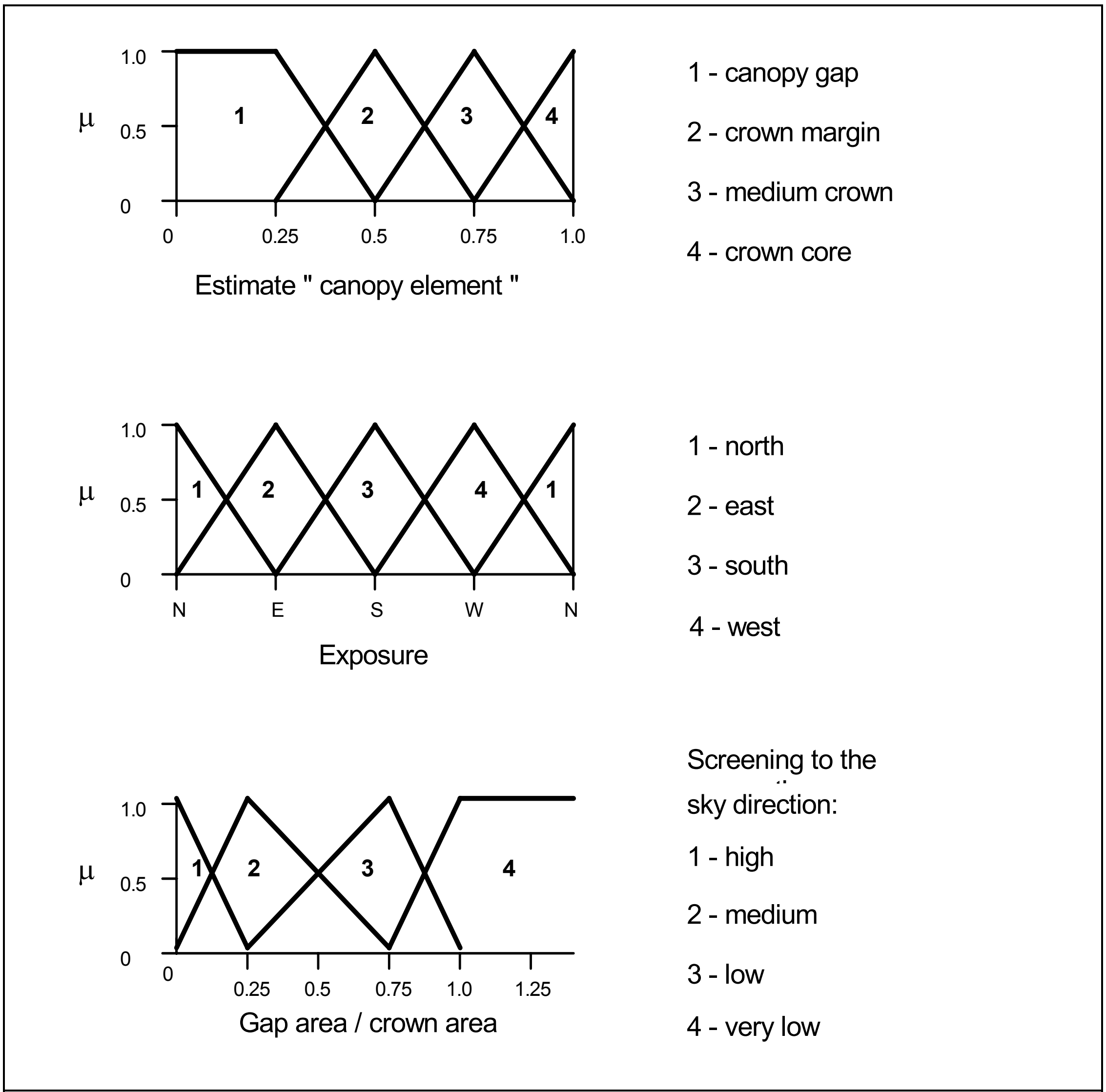

Figure 2: Decomposition of the range of value of some important structural variables into fuzzy sets. The fuzzy sets are defined by their membership functions.

3 Modelling below-canopy precipitation by systems of fuzzy rules

The fuzzy sets defining essential structural properties of canopy can be used to derive systems of fuzzy rules allowing a highly resolving modelling of precipitation underneath tree canopy. Such rule systems are excelled by a high transparency and can be interpreted easily since each fuzzy set does have a lingustic meaning.

Each rule consists of a number of presuppositions (structural properties) and a corresponding inference or rule answer (ratio of below- to above-canopy precipitation). Two possible rules could be:

1. Beneath a **crown margin** with **western exposure** and **low screening to the west** the ratio of below-canopy to above-canopy precipitation amounts to $\mathbf{Y_1}$.

2. Beneath a **crown margin** with **western exposure** and **medium screening to the west** the ratio of below-canopy to above-canopy precipitation amounts to $\mathbf{Y_2}$.

The presuppositions are defined as fuzzy sets according to figure 2 whereas the rule answers are real numbers in our case. Hence the formal structure of a rule r consisting of I presuppositions and the inference Y_r can be written as:

$$(S_{r,i} : i=1,...,I) \;\rightarrow\; Y_r$$

After setting up a system of presuppositions $S_{r,i}$ the inferences Y_r will be obtained from a training set L consisting of as much as possible (N) case cites:

$$L = \{(x_{1,n},...,x_{i,n},...,x_{I,n}, y_n) \,;\, n=1,..,N\}$$

The $x_{i,n}$ denote the values of the structural parameters X_i at gauge n whereas y_n stands for the corresponding precipitation ratio measured by the gauge. For each n the degree of fulfilment $\nu_{r,n}$ of rule r is provided by the product of membership degrees of the presuppositions $S_{r,i}$:

$$\nu_{r,n} = \prod_i \mu_{S_{r,i}}(x_{i,n}) \tag{1}$$

Rule answers Y_r are calculated as means over all gauges n weighted by the corresponding membership degrees:

$$Y_r = \frac{\sum_n \nu_{r,n} * y_n}{\sum_n \nu_{r,n}}$$

Now the rule system is quantified completely and can be used for modelling the below-canopy precipitation y_m at an arbitrary location m that is defined by the values $x_{i,m}$ of the structural parameters X_i. According to (1) the membership degrees $\nu_{r,m}$ with respect to all the rules r can be calculated for the model point m. Finally the model output is obtained as follows:

$$y_m = \frac{\sum_r \nu_{r,m} * Y_r}{\sum_r \nu_{r,m}} \tag{2}$$

This way the amount of precipitation incident upon a certain spot of forest floor will be modelled by comparison of the canopy structure above it with those structural configurations represented by a set of fuzzy rules. For elaborating a rule system it is suitable to divide the available dataset into training and test sets. The definition of fuzzy sets as well as their combination to fuzzy rules can be varied until a good agreement of measurements and model outputs has been achieved.

4 Applications of the model

The model is suited to provide local precipitation inputs to arbitrary spots on the investigation plots where other flows as, e.g., soil water fluxes, element contents of soil water, evapotranspiration of ground-covering vegetation, or gaseous exhalations out of forest soil are measured. Fig. 3 shows a canopy map of a Scots pine investigation plot that was thinned out considerably due to atmospheric nitrogen input. Throughfall was measured at 12 positions marked on the map.

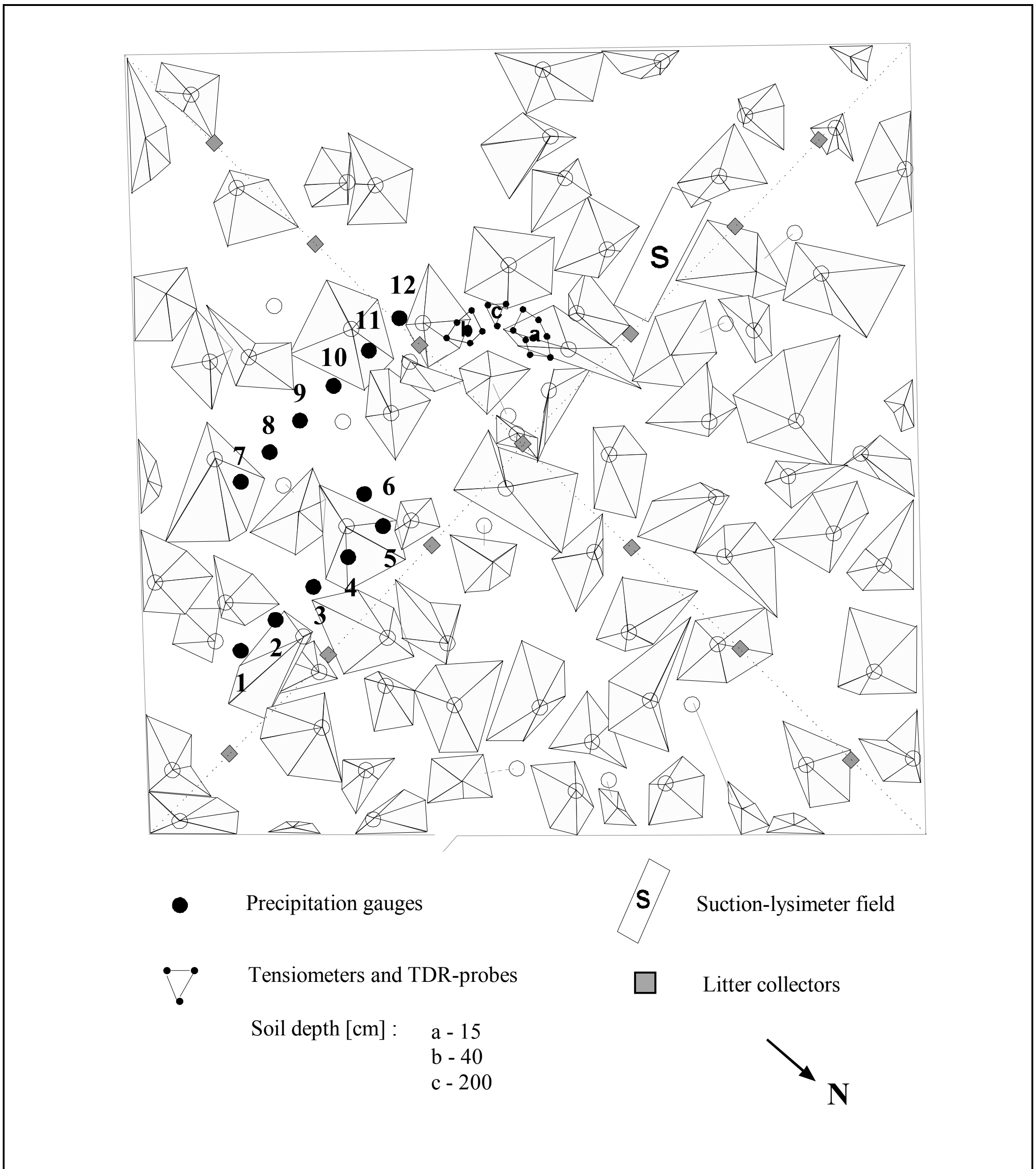

Figure 3: Canopy map of a Scots-pine investigation plot. Positions of the 12 precipitation gauges are marked by the labelled dots.

The high spatial variability of below-canopy precipitation (fig. 4) forbids to use the unweighted average of all the 12 gauge measurements as presumed precipitation input to the tensiometers, time-domain-reflectometry-probes, or the suction lysimeters. However, these inputs can be modelled more accurately by a system of fuzzy rules describing the dependency of throughfall on local canopy structure. For testing model accuracy it is appropriate to reproduce the precipitation values of the 12 rain gauges by a system of fuzzy rules which was parametrized with the help of a training set consisting of data obtained on other investigation plots.

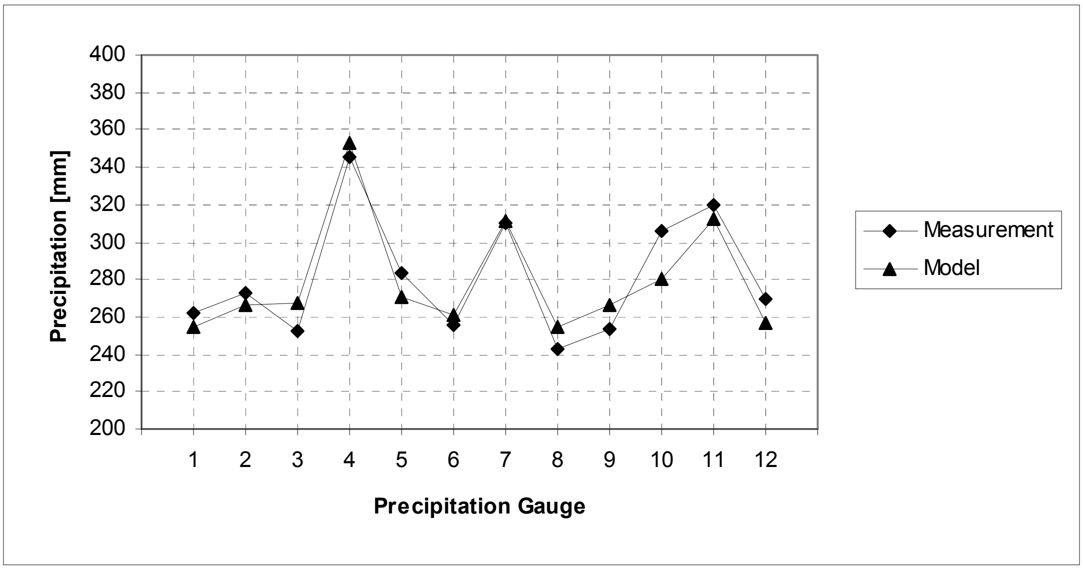

Figure 4: Comparison of modelled and measured precipitation amounts of the 12 gauges shown in fig.3 from may till september 1993. Above-canopy precipitation amounted to 348 mm during this period. The training set comprised 96 measuring points on 8 other investigation plots.

Figure 4 shows the result of such a model calculation. Obviously the applied rule system describes basic relations between local canopy structure and precipitation throughfall correctly. These relations can be obtained from the applied rule system a part of which is displayed in figure 5. It turns out that during growth period 1993 (which was characterized by low interception losses and mainly western winds) most rain fell to forest floor underneath eastern crown cores of detached trees, whereas rain minima occurred within canopy gaps. Correspondingly, fuzzy systems can be parametrized for a series of different structural configurations during arbitrary measurement periods.

Finally, the transition from local fuzzy relations between structure and process to the quantification of water or element flows of area-covering forest structures will be demonstrated briefly. Figure 6 shows a mean precipitation pattern for Scots pine stands with a degree of canopy cover of 0.5 that was obtained from an area-weighted puzzle of local canopy elements. The pattern was synthesized from eight different canopy elements defined by combination of fuzzy sets (gap centre, eastern gap edge, a.s.o.) the frequency distribution of which was determined empirically from a series of stands with canopy cover around 0.5. The area above the precipitation curve defines the total interception loss of the tree-layer structure under consideration.

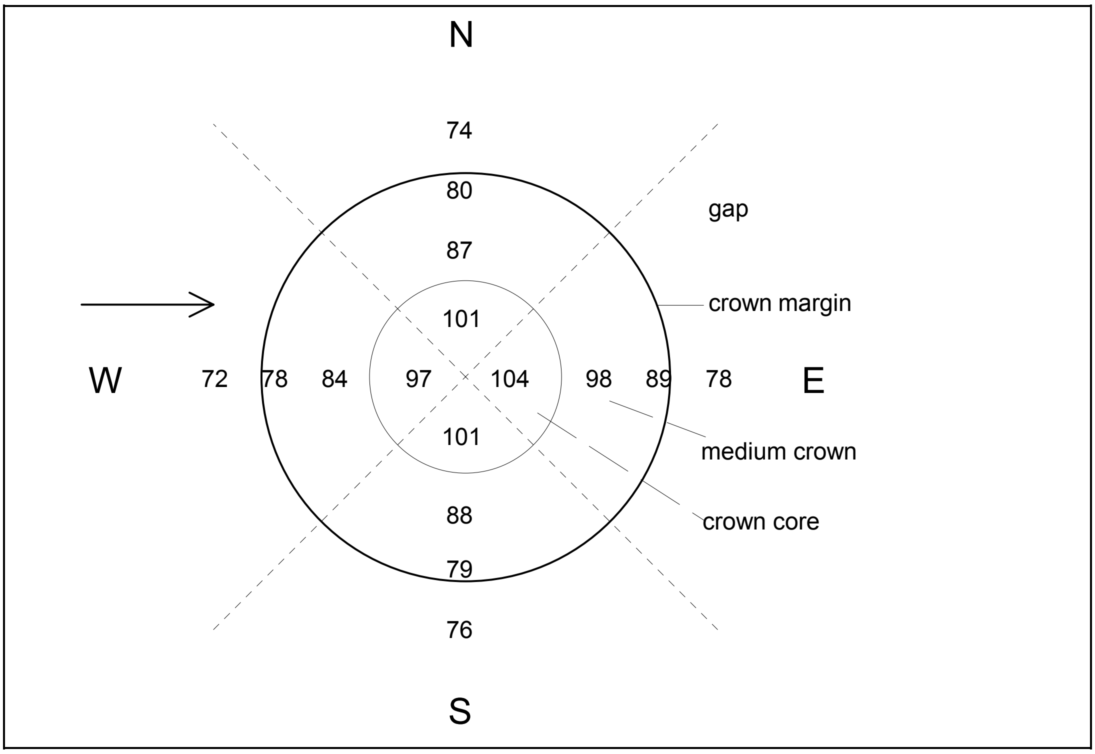

Figure 5: Part of the rule system based on fuzzy sets defined in fig.2 and used for the model application shown in fig.4. The numbers denote the percentage of below- to above-canopy precipitation for a tree with „very low screening to the west and to the east“ during the period from may till september 1993.

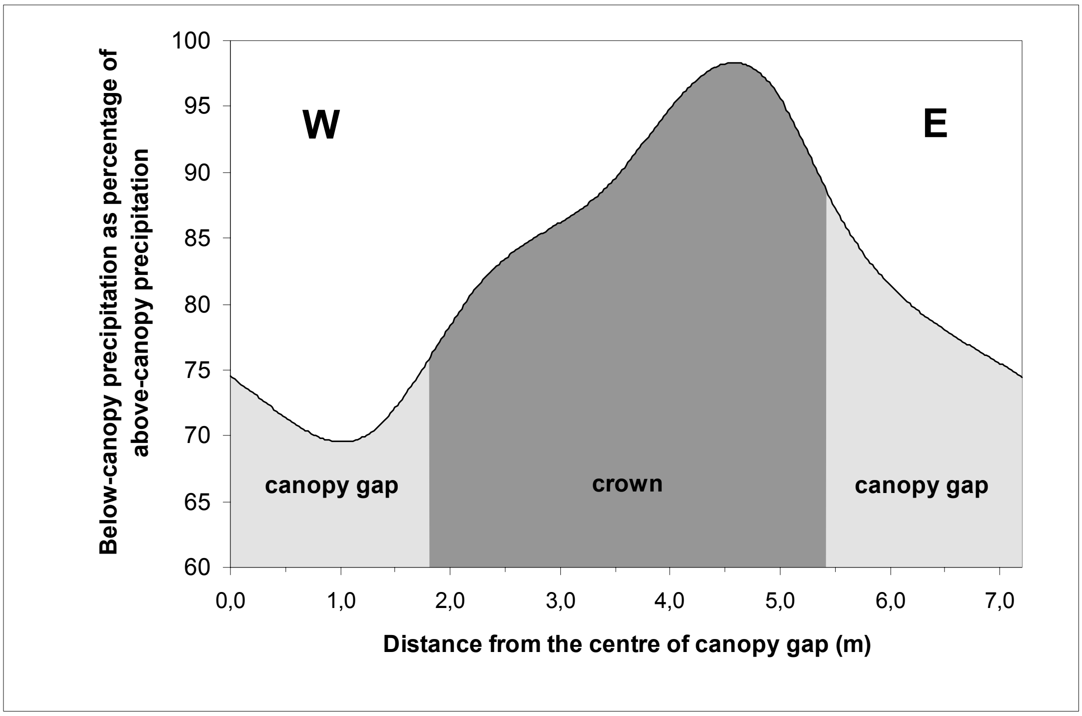

Figure 6: Pattern of below-canopy precipitation in medium-aged Scots pine stands with a degree of canopy cover of 0.5 in the interior Northeast-German lowlands during growth period 1993 (JENSSEN

1996). The pattern was obtained from an area-weighted synthesis of fuzzy inferences corresponding to local canopy elements.

By the help of the outlined modelling approach annual interception loss as well as precipitation redistribution in Scots pine stands of the Northeast-German lowlands were calculated from the degree of canopy cover and precipitation amount, i.e. from parameters which can be obtained area-covering from remote sensing data and weather stations, respectively. Model application yielded new insights into distribution patterns of net precipitation underneath Scots pine canopies with consequences for silvicultural practices. The results were presented elsewhere in detail (JENSSEN 1996). Future work is dedicated to the investigation of total water balances of Scots pine ecosystems of different structure.

5 Conclusions

The fuzzy approach presented in this paper proves to be a tool for scaling up water and element flows from measurement to ecosystem level. Starting from a local analysis of relationships between flows and structural properties at a series of measurement points a synthesis of water and element balances of ecosystem units which can be mapped area-covering becomes possible.

Application of fuzzy models offers some important advantages in solving this problem. Fuzzy sets are well suited to perform an aggregated and flexible description of complex and manifold structures at the level of individual measuring points. Different macroscopic structures can be composed of substructures defined by these sets easily. Fuzzy-rule based models are characterized by a high transparency and can be interpreted easily. A disadvantage consists in the considerable effort involved in the optimization of fuzzy rule systems. At present stage of model development only rule inferences can be learnt from the training set of data whereas rule presuppositions are optimized „by hand“. A considerable improvement could be achieved by combining the fuzzy model with principles of neural networks disposing of inherent learning capabilities (NAUCK et al. 1994) .

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