The use of lysimeters in forest hydrology research in north-east Germany

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Abstract

Broad areas of the northeast German lowlands are characterised by low precipitation, distinct periods of summer drought and sandy soils with low water retention capacity. In this region, forest hydrology research looks into the influence of differently structured forest on the landscape hydrology, and on the components of the hydrologic equation. The aim is to provide scientific guidance in the development of productive forests that enhance the quantity and quality of seepage water. In unconsolidated rock substrate lysimeters can be used to measure seepage and evaporation. The use of different types of lysimeters in the Eberswalde region has a tradition of more than 100 years. In 1972, nine new large-scale lysimeters with a depth of 5 m and a surface area of 100 m^2 (10 x 10 m) were installed near Britz, near Eberswalde, and were planted with the tree species Scots pine, European beech, European larch and Douglas fir at plant spacings corresponding to those adopted in forestry practice.

In this region, groundwater recharge under forests is affected considerably by tree species. In deciduous European beech, and European beech mixed stands at the polewood stage (ca. 20- to 60-years old), seepage rates of 15 % to 25 % of open field precipitation are found, whereas the seepage rates recorded in Scots pine stands of the same age are insignificant. In Scots pine stands, the ground vegetation evaporation ranges between 20 % and 35 % of the precipitation depending on its composition and ground coverage. In particular, a dense grass cover of *Calamagrostis epigejos* limits the amount of soil water available to plants during the growing season substantially, and ultimately, can limit tree growth. These results can be obtained with the assistance of specially developed weighable lysimeters.

Keywords: Climate change, lysimeter type, water budget, tree species, Brandenburg, Calamagrostis epigejos

Zusammenfassung

Der Einsatz von Lysimetern in der forsthydrologischen Forschung in Nordostdeutschland

Das nordostdeutsche Tiefland ist in weiten Teilen geprägt durch geringe Niederschläge, ausgeprägte sommerliche Trockenphasen und Sandböden mit geringer Wasserhaltkapazität. Die forsthydrologische Forschung in der Region befasst sich mit dem Einfluss unterschiedlich strukturierter Wälder auf den Landeswasserhaushalt und auf die Teilglieder der Wasserhaushaltsgleichung. Ziel ist, den Aufbau solcher produktiver Wälder wissenschaftlich zu begleiten, die sich positiv auf die Menge und Qualität des Sickerwassers auswirken. Im Lockergesteinsbereich sind Lysimeter geeignete Messeinrichtungen zur Ermittlung von Sickerung und Verdunstung. Der Einsatz von Lysimetern unterschiedlicher Bauart hat im Raum Eberswalde eine über hundertjährige Tradition. 1972 wurden am Standort Britz bei Eberswalde neun Großlysimeter mit einer Tiefe von 5 m und einer Oberfläche von 100 m^2 (10 x 10 m) angelegt, die mit den Baumarten Kiefer, Buche, Lärche und Douglasie in praxisüblichen Verbänden bepflanzt wurden.

Die Grundwasserneubildung unter Wald wird in der Region entscheidend von der Baumart beeinflusst. Winterkahle Buchen- und Buchen-Mischbestände weisen im Stangenholzalter (Alter ca. 20 bis 60 Jahre) eine Sickerungsrate von 15 % bis 25 % des Freilandniederschlags auf, während in Kiefernbeständen gleichen Alters keine nennenswerte Sickerung zu verzeichnen ist. In Kiefernbeständen verdunstet die Bodenvegetation je nach Zusammensetzung und Bodenbedeckung zwischen 20 % und 35 % der Niederschläge. Insbesondere dichte Grasdecken mit *Calamagrostis epigejos* begrenzen die maßgeblich die pflanzenverfügbare Bodenwassermenge innerhalb der Vegetationsperiode und können zu Einschränkungen des Baumwachstums führen. Diese Ergebnisse wurden mit Hilfe speziell entwickelter wägbarer Lysimeter erzielt.

Schlüsselwörter: Klimawandel, Lysimetertypen, Wasserhaushalt, Baumarten, Brandenburg, Calamagrostis epigejos

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1 Introduction

Given its current low precipitation levels and predominantly sandy soils with low water retention capacity, the lowlands in northeastern Germany are regarded one of the country's regions with the highest vulnerability to a climate change bringing more frequent and more intense drought periods in the future (Schröter et al., 2005). In northeastern Brandenburg, the long-term annual precipitation of about 570 mm is well below the overall national average of 780 mm (Müller, 2002).

With a forested area of 1.1 million ha, covering 35.3 % of its surface area, Brandenburg, including Berlin, is the state with the fourth largest forest area in Germany (BMELV, 2008). The forest has a major effect on the landscape hydrology as a consequence of its multi-layered structure and its expanse. Therefore investigations into relationships among site, forest structure and water regime in the region are of particular interest. In view of the anticipated intensification of drought in wide areas of northern and central Germany as a consequence of climate change, the forest hydrology studies presented here may provide some direction for many other regions in Germany, particularly investigations of water consumption and forest growth in the case of declining water resources during the growing season.

This review paper provides a historical outline of forest hydrology research at Eberswalde, an overview of current and future research activities, and a summary of the most important results.

2 The use of different types of lysimeters

Lysimeters are appropriate for ascertaining the water budget of individual plants and stands. Due to the existing site conditions, the use of different types of lysimeters in investigations around Eberswalde has a long tradition (Table 1).

2.1 The Drachenkopf lysimeter

Already in 1907, the first investigations into the water budget of young trees were conducted with very small-scale lysimeters on Drachenkopf Mountain, in Eberswalde. In 1929, these small-scale lysimeters were replaced by a larger weighable station consisting of three lysimeters, which, in 1954, were supplemented by four additional lysimeters. To our knowledge, the Drachenkopf research station is the oldest lysimeter station used for forest hydrological purposes in the world (Müller, 2008). The weighable lysimeters have a surface area of one square meter and a depth of 1.5 m (Figure 1). The square lysimeter tanks are installed to cover the same ground surface area, and overgrown with vegetation corresponding to the surrounding vegetation for investigation. The Drachenkopf lysimeters are filled with soil, and hence represent disturbed lysimeters. The soil substrate is medium-grained sand with a horizon sequence corresponding to the sandy brown earths typical of the region.

The lysimeter balance scales are located in the cellar, where seepage water also is recorded.

The investigations focus on the determination of the water budget components, evaporation, transpiration and seepage, under defined weather and soil conditions for different types of vegetation.

The quantity of seepage water found under conditions of low regional precipitation was of particular interest because only this component of precipitation, which flows into the groundwater, is of hydrological use.

In addition to quantifying seepage water, lysimeters are an excellent means for determining plant evaporation (ET). Evaporation is the remainder after subtracting the seepage (S) and the change in soil moisture (dM) from precipitation (P) in the hydrologic equation (1).

$$ET = P - S - dM \quad (1)$$

Table 1:

Types of lysimeters used in forest hydrology research at Eberswalde

Year	1907	1929	1966	1972	1994	2005	2009
Site	Eberswalde "Drachenkopf"	Eberswalde "Drachenkopf"	Liepe	Britz	study sites	Britz "Postluch"	Eberswalde open field laboratory "Drylab"
Lysimeter type	smallest-scale lysimeter	small-scale lysimeter	sub-surface lysimeter	large-scale lysimeter	small-scale lysimeter	groundwater lysimeter	small-scale lysimeter
Weighability	non-weighable	weighable	non- weighable	non- weighable	weighable	weighable	non- weighable
Soil	disturbed	disturbed	undisturbed	disturbed	undisturbed	undisturbed	disturbed
Surface area	500 cm^2	1 m^2	500 cm^2 1500 cm^2	100 m^2	1 m^2	1 m^2	2 m^2
Depth	1.0 m	1.5 m	5 m	5 m	1.8 m	2.0 m	1.5 m

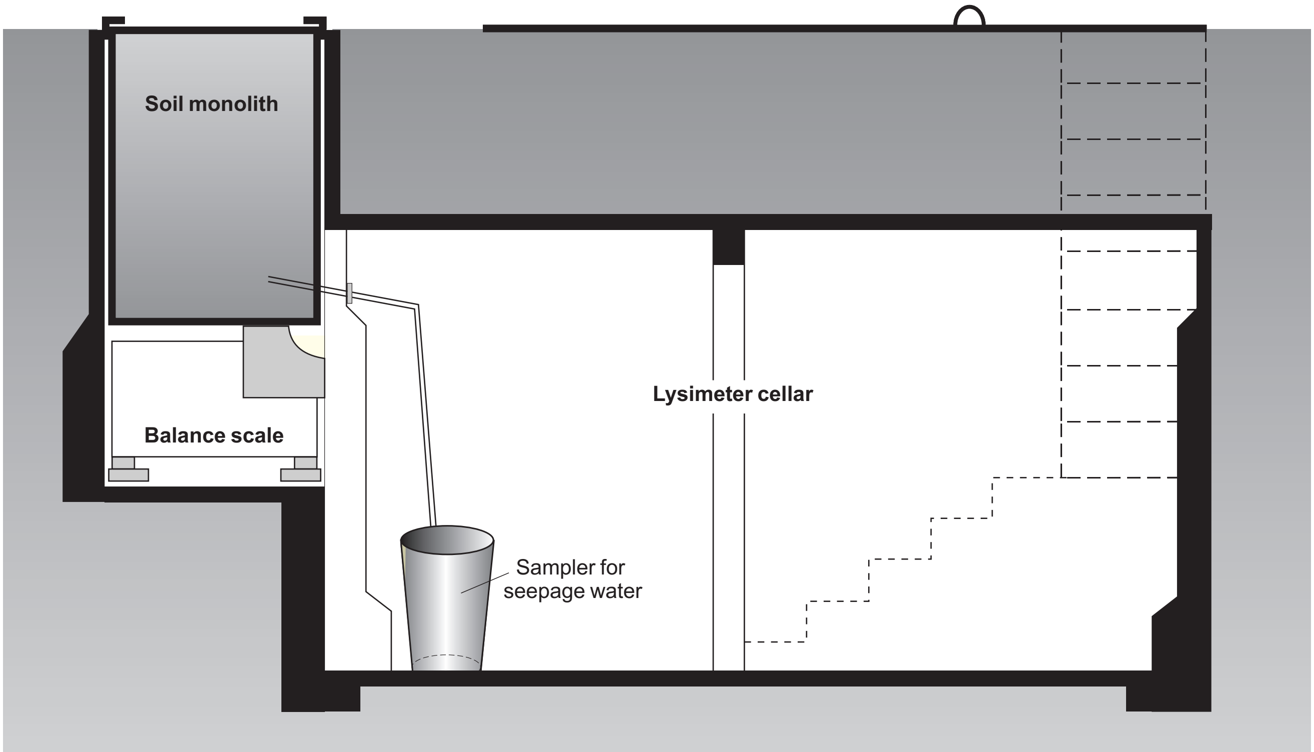


Figure 1:
Diagram of the Drachenkopf lysimeter station

Precipitation is measured with Hellmann rain gauges located 1 m above the ground and at ground level. Seepage is recorded at the seepage discharge point of the lysimeter tank. Soil moisture change is obtained from the difference in the lysimeter weight recorded using balance scales. These scales are accessed from a cellar corridor. The tanks, which themselves weight ca. 2 t, are weighed with an accuracy of within 10 g.

2.2 The large-scale lysimeter at Britz

Forest hydrology research into the effect of different tree species on evaporation and groundwater recharge prompted the construction of large-scale lysimeters at the research station at Britz, near Eberswalde, in 1972 (Müller, 1993).

After experiences gained from using lysimeters in the past, the large-scale lysimeters were installed at a depth of 5 m, necessary for forest lysimeters, having a surface area of 100 m^2 (10 x 10 m) (Figure 2). Nine large-scale lysimeters were set up, and, in 1974, planted with 0.3 ha experimental stands of the tree species Scots pine (3 lysimeters), European beech (2), European larch (2) and Douglas fir (2) at plant spacings corresponding to that applied for each species in forestry practice at the time (Figure 3). The areas surrounding the lysimeters were planted similarly. Thus, the large-scale lysimeters at Britz are unique in Europe in their scale since, although other lysimeters planted with trees have the required area, with depths of 3 m or 3.5 m, they are too shallow (Müller,1993).

The seepage water that collects above the lysimeter surface flows down a measuring shaft next to the lysimeter, and is measured mechanically by a water-meter and registered electrically. Soil moisture is measured with probes to a total depth of 5 m at 50 cm steps. Precipitation in the open, and the stand is recorded with Hellmann rain gauges.

The current forest conversion programme in Brandenburg, in keeping with ecological forest management goals, aims to convert as much of the current pure Scots pine stands as possible into mixed stands with diverse structures (MLUR, 2004). This forest conversion requires scientific supervision and funding; investigations of how sites with unfavourable forest growth and hydrological conditions can be altered by advance planting, and underplanting of European beech and sessile oak under Scots pine and European larch, and how these conditions can be improved through silvicultural measures are needed in particular. There are considerable gaps in knowledge about the effects of sessile oak on the landscape hydrology. To remedy this situation, individual lysimeter stands were modified in 2000 as follows:

- Larch underplanted with European beech,
- Scots pine underplanted with European beech

- Scots pine underplanted with sessile oak,
- New sessile oak plantings.

With the conversion of the lysimeter stands, and by close observation of oak, it will be possible to provide a better estimation of the long-term consequences of conversion for landscape hydrology in the north-eastern lowlands.

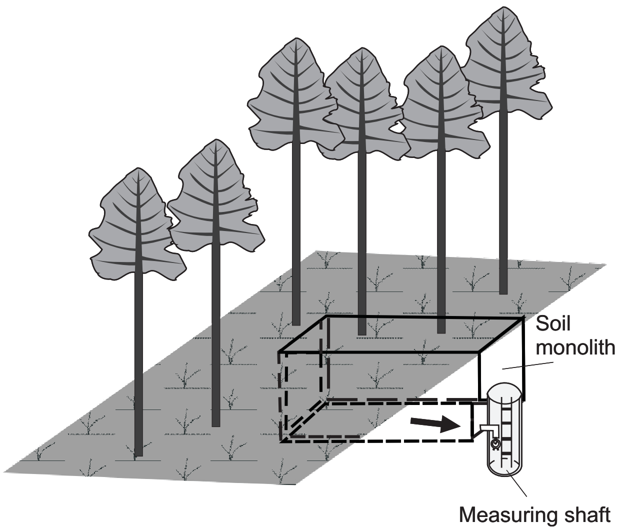


Figure 2:

Diagram of a large-scale lysimeter planted with trees

2.3 The weighable lysimeters

Total evaporation, determined with large-scale lysimeters, provides only a general understanding of the water budget in forest stands. The separation of total evaporation into its individual components crown canopy interception, transpiration from trees and evapotranspiration of soils and ground vegetation helps clarify the interaction between the individual components.

In Scots pine ecosystems in the northeastern German lowlands, the ground vegetation and the tree and shrub regeneration represent a substantial yet, so far, difficult to measure water consumer. Special measuring systems need to be used to ascertain the evapotranspiration of the undergrowth, and hence its specific water consumption separately from transpiration of trees in the stand. Consequently, in 1994, special weighing lysimeters (Figure 4) were designed to fulfil the following special requirements:

- Circular lysimeters with a surface area of 1 m^2,
- Lysimeter depths of 1.8 m so that the roots of the undergrowth do not reach the backwater that potentially could build up on the lysimeter floor,
- Soil monolith with an undisturbed, mature ground vegetation,

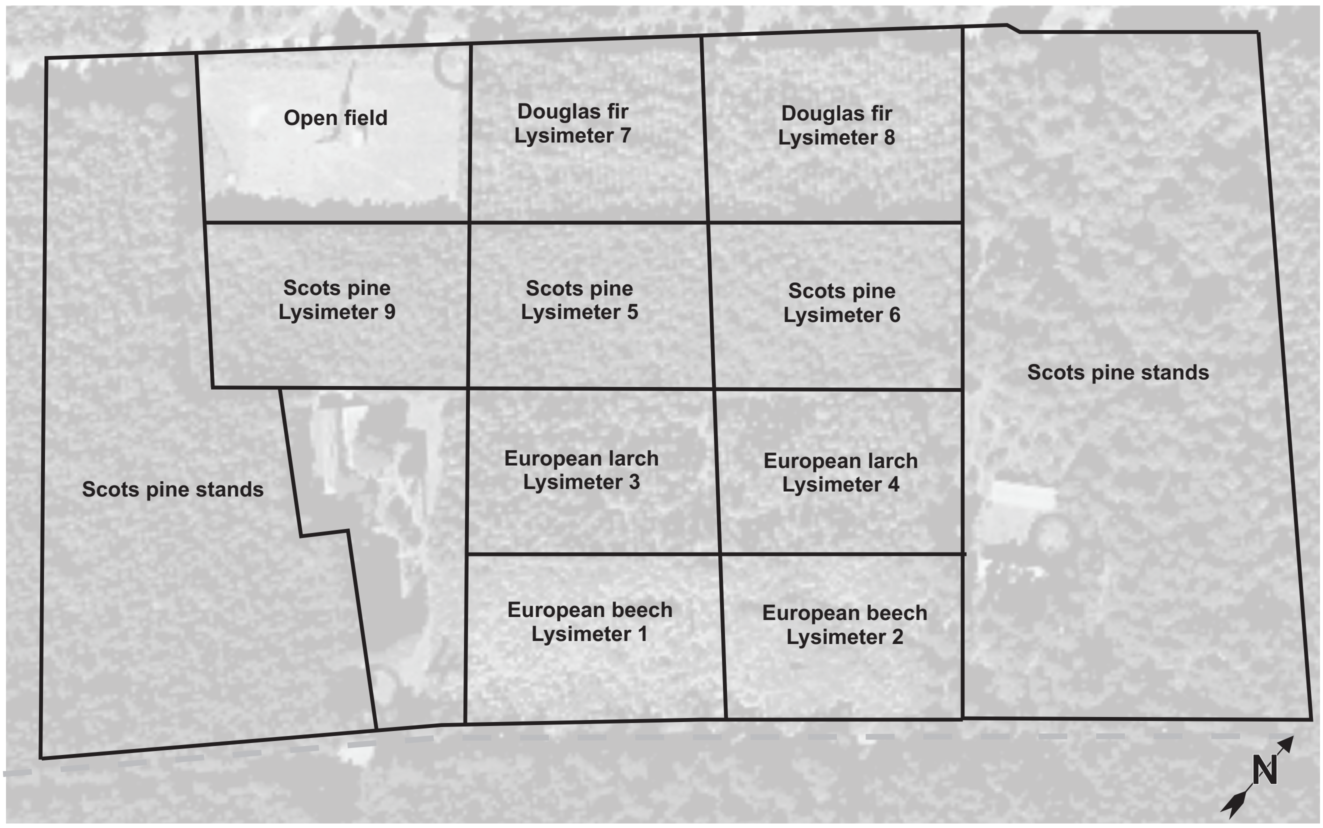


Figure 3:

Aerial photograph of the Britz Ecological Research Station showing the location of the large-scale lysimeters (in 1998)

- Minimal disturbance of the soil and vegetation cover surrounding the lysimeter, and thus maintenance of the homogeneity of the soil conditions and vegetation structures,
- Continual measurements of soil moisture changes and quantity of seepage water with high precision,
- Opportunities for flexible use of the lysimeter.

The new type of lysimeter developed contained an undisturbed soil monolith with sufficient size and weighability, for which the construction of a lysimeter cellar was not necessary. With it, the water budget could be balanced at low cost for different types of applications under open field conditions in the forest. Through the use of special weighing cells, the soil moisture change in the soil monolith and the amount of seepage water discharge could be recorded with an accuracy of 0.1 mm.

Firstly, the lysimeters were used to measure the water consumption of ground vegetation with different species compositions.

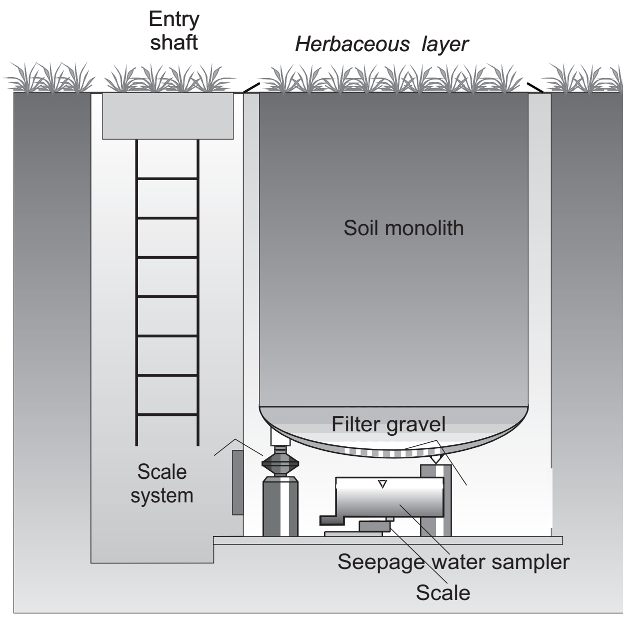


Figure 4:
Diagram of a weighable lysimeter

In 2000, individual lysimeters were extended and overhauled, and afterwards installed for ascertaining the water consumption of young European beech and sessile oak in Scots pine-European beech or Scots pine-sessile oak mixed stands. These investigations assisted explanations of the evaporation of Scots pine relative to European beech, and to the ground vegetation.

The current investigations should look into the influence of drought on the transpiration and young forest tree growth under changing climatic conditions (frequency of extreme summers) more intensively. The clarification of the influence of changing climatic conditions on the development of vegetation and, conversely, of vegetation on climatic conditions is of major environmental importance.

2.4 The weighable groundwater lysimeters

To date the lysimeters have been installed only on terrestrial sites well away from groundwater. In 2004, the installation of lysimeters was extended to sites close to the groundwater.

As enormous water storers, these near natural forest ecosystems are of extreme importance for the strained landscape water regimes in Germany's driest regions.

Consequently, with the assistance of weighable lysimeters, the water consumption of young black alder and common oak trees in an alder swamp are investigated. The aim of the investigation was to determine the transpiration and growth of common oak and black alder at different distances from the groundwater table.

2.5 The open field laboratory "Drylab"

Another recent application of lysimeter technology is being realised currently at the Institute of Forest Ecology and Forest Inventory at Eberswalde with the construction of an open field laboratory. This laboratory enables investigations of the effects of drought on the growth and vitality of young forest trees in the open under largely controlled conditions. Eight lysimeters with a surface area of 2 m² were installed in the open at ground level in isolation from the surrounding soil, and fitted with an automatic retractable roof to eliminate precipitation from the site (Figure 5). The lysimeters are filled with a standardised soil substrate and can be planted with up to 16 plants. Soil moisture sensors, together with equipment fitted for measuring soil water discharge and precipitation, enable accurate determinations of evapotranspiration as well as observations of soil moisture development in the soil column. One focus of the research is the investigation of fine root development using mini-rhizotrones. This is because few investigations of the response of fine roots to drought have been undertaken so far. Here, photographs are taken of the surrounding fine root layer with an endoscopic camera through four vertical glass tubes per column at small time differences, and then analysed by image processing. In this way, the high-resolution data for the turnover of fine roots and root growth are obtained.

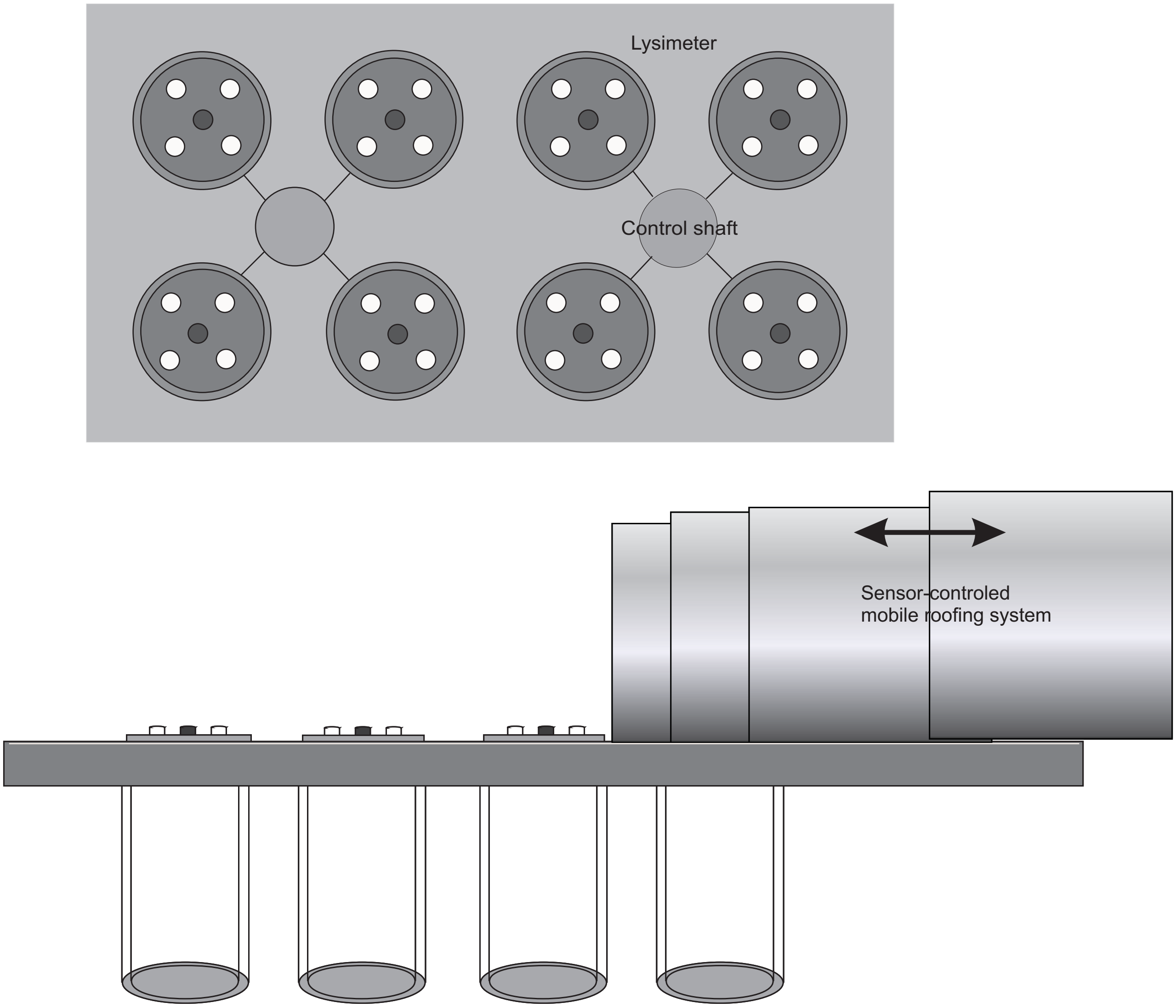


Figure 5:
Diagram of the open field laboratory “Drylab” showing the location of lysimeters and the retractable roof system

3 Results and discussion

The aim of the lysimeters at Drachenkopf was to provide the range of results required for subsequent investigations into the influence of landuse on landscape water catchment hydrology (Lützke, 1958, 1961; Müller, 2008).

One important finding is that, under comparable weather and soil conditions, plant species and the degree of vegetation cover influence the amount of, and temporal variation in seepage and evaporation. Under perennial grasses, three times the amount of water seeps into the depths than under the Scots pine stand (Figure 6). The features of the evaporation area in the forest ecosystem – height, surface area, distinct vertical stand structure in the tree, shrub and herbaceous layers, and the extent of forest area in the landscape - explains the higher evaporation in forests.

The investigations at the Britz large-scale lysimeter station showed that tree species have an important effect on seepage under forests.

The effect of differences in vegetation structure at different growth stages in a Scots pine forest, a European beech forest and a mature mixed stand with Scots pine and European beech on the amount of seepage and evaporation is shown in Figure 7.

In the Scots pine stand, total evaporation increases rapidly with growth whereas seepage declines. In the polewood stage, total evaporation is about 100 % so that seepage is largely absent. Scots pine growth culminates at this age, and thus the transpiration rates are high (about 60 % of the annual precipitation) and, as a consequence of the dense crown cover, interception losses are also high (about 40 %) (Müller, 2002, 2005).

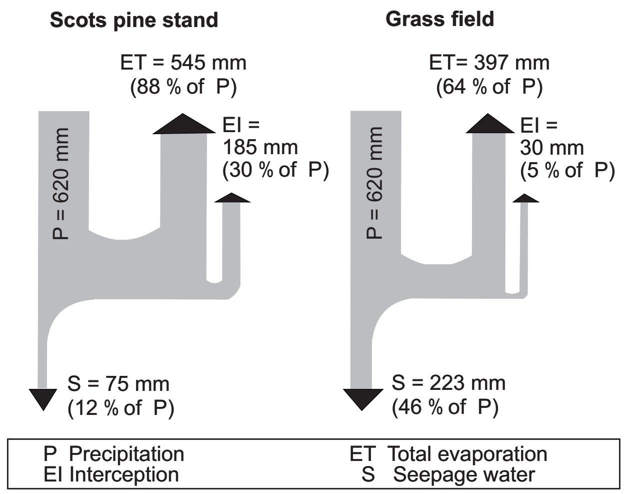


Figure 6:

Comparison of seepage and evaporation in a Scots pine stand and a grass field on sandy soil

The natural reduction in tree numbers and thinnings cause transpiration and interception to decline gradually, and the seepage percentage increases. However, the proportion of evapotranspiration from the ground vegetation increases relatively strongly due to the opening up of the canopy (Müller et al., 1998).

In the European beech stand, evaporation also increases quickly with stand growth, and, in the polewood stage, attains values of almost 80 % of the annual precipitation. This value remains relatively constant over a long period up to the saw-timber stage, so that steady seepage levels of over 20 % of the annual precipitation also are recorded. Transpiration increases slightly with stand growth, and interception declines as a result of the increasing stemflow (it reaches values of ca. 20 % of the annual open field precipitation). Due to the low-light regime in closed European beech stands (Emborg, 1998), the evaporation from the forest soil is of minor importance. Seepage is higher in European beech stands in all age phases than in Scots pine. Thus, for example, in mature European beech stands, 50 mm more precipitation seeps into the soil substrate than in mature Scots pine stands under comparable soil and weather conditions (Müller, 2002, 2005).

Under the lysimeter, planted with sessile oak in 1999, seepage amounted to 52 % of the average total precipitation in the period from 1999 to 2003 (637 mm). The evaporation of intercepted and transpired water in sessile oak regeneration is still low, and seepage correspondingly high. The percentage of seepage in 7-year old oak is comparable to that of European beech of the same age (Müller, 2002, 2005, 2007).

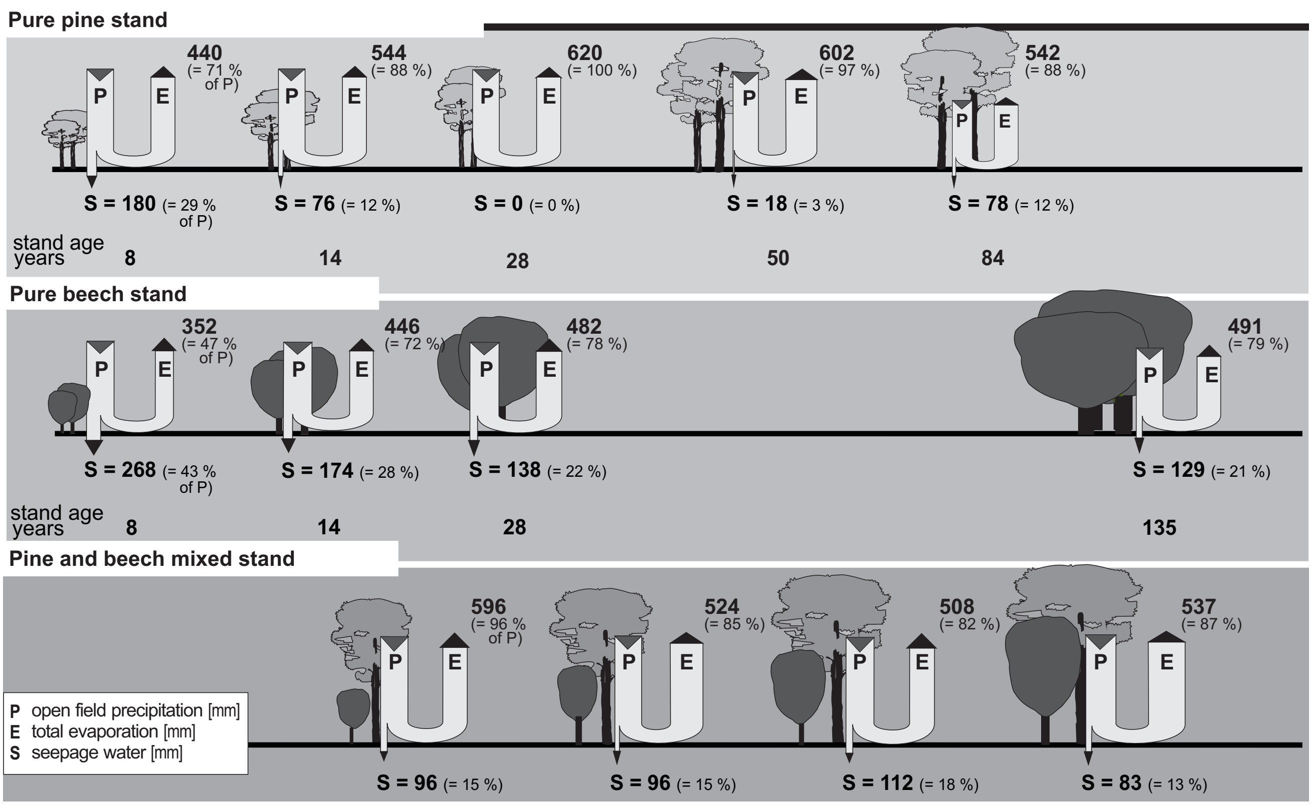


Figure 7:

Influence of vegetation structures of Scots pine and European beech at different growth stages on the water budget parameters, evaporation and seepage - (Finowtaler sandy brown earth, 620 mm annual precipitation)

Investigations in pine-beech mixed stands of different ages on sandy soil showed that the amount of seepage fell somewhere between that of the pure Scots pine and pure European beech stands depending on forestry operations performed, stocking density and the tree size of European beech (Müller, 2006, 2007). Measurements of seepage to 5 m depth in the 28-year old pure Scots pine stand growing on the large-scale lysimeter station at Britz, which was underplanted with European beech and sessile oak in 1999, already show improvements in the groundwater recharge as a result of the Scots pine thinning.

The **weighable lysimeters** were installed in Scots pine stands with a typical ground cover in the northeastern lowlands to determine the water consumption of these ground vegetation types. The typical ground cover consisted of wood small-reed (*Calamagrostis epigejos)*, wawy hair grass (*Deschampsia flexuosa),* wawy hair grass/raspberry *(Deschampsia flexuosa / Rubus idaeus)* and blueberry (*Vaccinium myrtillus)*.

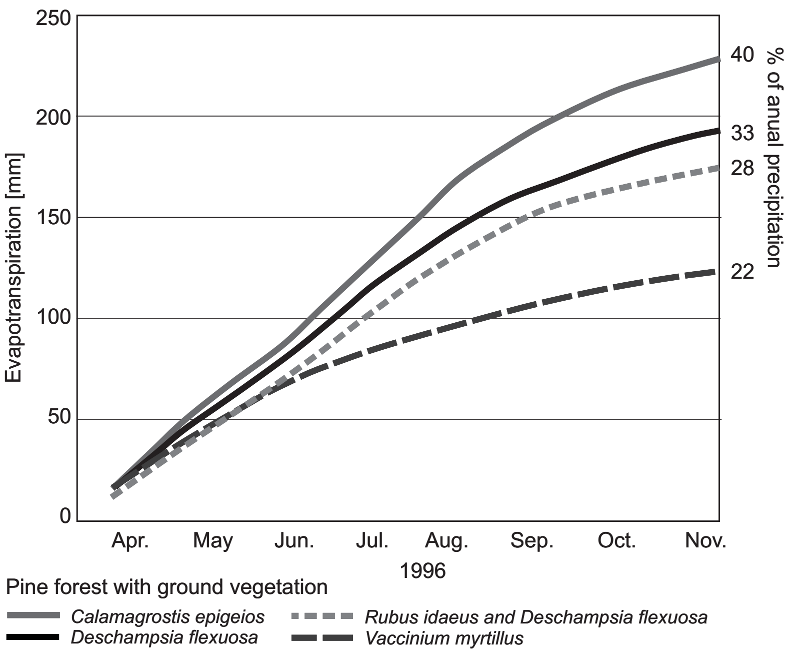
Investigations showed that evapotranspiration increased with increasing grass cover. The low shrub layer consumed less water. Thus, closed wood small-reed cover consumed more than one third, and the wavy hair grass almost 30 % of the annual precipitation of 620 mm. Where a low shrub layer was present, the evaporation from the wawy hair grass/raspberry layer, a little more than 25 %, and the blueberry/wawy hair grass layer, with almost 20 % of the annual precipitation, was sometimes distinctly lower than the pure grass cover (Figure 8). In addition to the evaporation from the ground vegetation layer, for which the annual sum varied, the seasonal development of evapotranspiration during the growing season is also ecologically meaningful.

In water limiting periods, the higher water consumption by grass cover leads to a reduction in the amount of plant available soil water, enhancing the water limitation for trees, and thereby impacting upon tree growth (Müller et al., 1998).

The composition and cover of the ground vegetation influence considerably the amount of water consumed by trees. The ground vegetation becomes a major consideration in the water budget in Scots pine forests (Müller et al., 1998; Müller and Seyfarth, 1999; Müller, 2002).

To explain the relationship between soil water removal, soils water availability, root distribution patterns and growth development of the overstorey and understorey in mixed stands with Scots pine and European beech, the evapotranspiration of both species need to be determined separately. The use of weighing lysimeters in European beech underplantings made separate determinations of transpiration from trees, and evaporation from forest soils possible (Figure 9). Thus, per lysimeter, the evapotranspiration of two European beech trees growing in an undisturbed soil monolith could be ascertained. In the overstorey, Scots pine transpiration was determined with Granier sensors.

In Figure 9, the relative changes in evaporation for Scots pine and European beech over time are presented



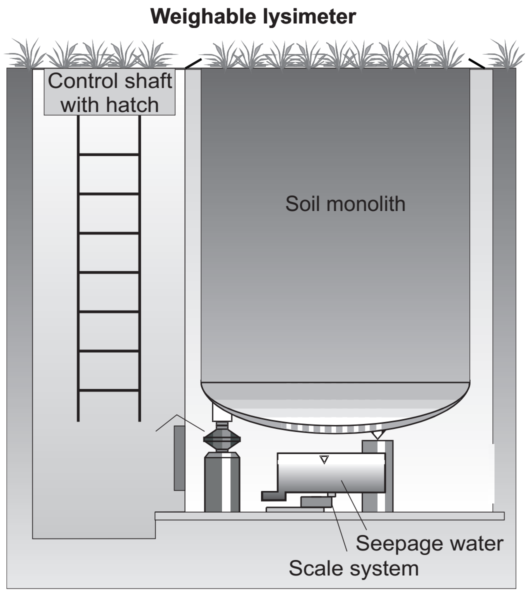


Figure 8:

Cumulative evaporation of different ground vegetation cover in Scots pine stands from March to October based on the average of the years 1996 to 1998

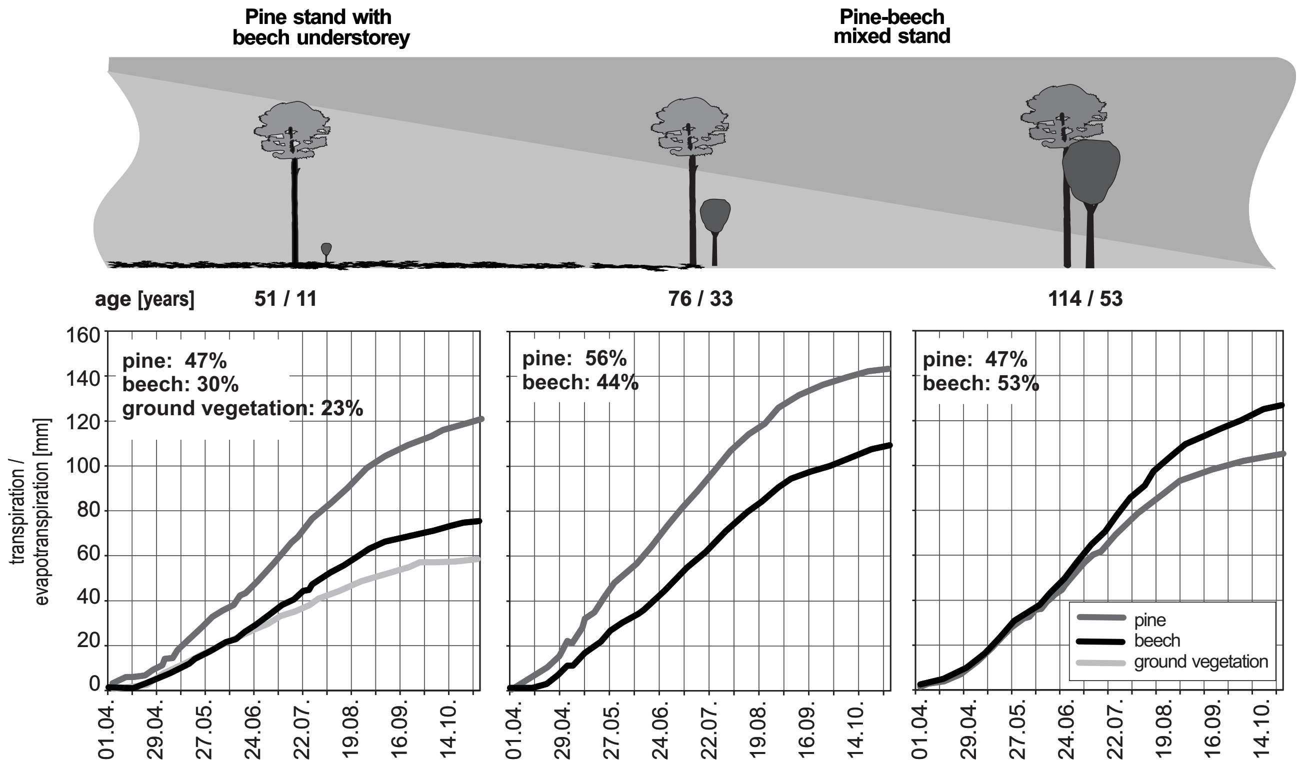


Figure 9:

Transpiration of European beech and Scots pine trees and evapotranspiration of the ground vegetation in the Scots pine-European beech mixed stand at different stand ages

separately. With increasing canopy closure, the proportion of evaporation of the ground vegetation declines. In the youngest stage, the ratio of Scots pine to European beech to ground vegetation is 47 % : 30 % : 23 %. As European beech develops, the evaporation percentage increases steadily, whereas that of the ground vegetation layer decreases or drops away entirely so that, in the next growth stage, the ratio was 56 % (Scots pine) to 44 % (European beech). With the upgrowth of European beech into the canopy layer of Scots pine, European beech transpiration in the oldest stand stage finally increased above that of Scots pine. The evaporation ratio of Scots pine to European beech then was found to be about 47 % : 53 % (Anders and Müller, 2006; Müller, 2006).

4 Conclusions from the research to date

Often a major problem of hydrological investigations in different types of ecosystems is the dissimilar conditions, or inability to control sufficiently the environmental conditions in the study sites. Thus, the effects of the parameters of interest may be blurred or false in the results. If one aims to determine the effect of the vegetation on hydrology in the unconsolidated rock substrate, then lysimeter measurements are appropriate for excluding conditions, which are not relevant. Assuming the lysimeters were constructed correctly and adequate in size, they can also be applied for forest ecosystems.

Only by considering the special features of the forest structure can one accurately evaluate the hydro-ecological effects.

Thus, with the assistance of large-scale lysimeters, the influence of tree species on seepage and evaporation in mature stands can be quantified. It shows that the crown canopy structure considerably influences the amount of seepage and the distribution of the precipitation in the stand as it affects the soil water availability.

Total evaporation provides only a general understanding of the water budget in forest stands. The separation of total evaporation into its individual components leads to more meaningful explanations of the interactions between the compartments. During the growing season, the water consumption of the individual vegetation layers is important in the assessment of possible occurrence of water stress.

The main advantage of lysimeter techniques is the opportunity to balance energy and nutrient flows at a high temporal resolution under carefully differentiated conditions. This makes the lysimeter increasingly more interesting for both scientific and practical applications in very different disciplines. Due to their innovative measurement techniques, e.g. weighing cells for determining moisture changes and seepage flows as well as soil moisture sensors and tensiometers for observing seepage water movement, lysimeters are an important instrument for the parameterisation of process models for modelling energy and nutrient cycling. This also applies to forest hydrology research. Lysimeters are indispensable in investigations of water consumption of small forest trees of different origin in the face of increasingly limiting water resources arising from climate change.

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