

# Use of Lysimeters to Assess Water Balance Components in Grassland and Atlantic Forest in Southern Brazil

Rafael Matias Feltrin · João Batista Dias de Paiva ·  
Eloiza Maria Cauduro Dias de Paiva ·  
Ralph Meissner · Holger Rupp · Heinz Borg

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**Abstract** This study aimed to quantify the water balance components at a grassland and a forest site representative of the Atlantic Forest biome in southern Brazil using drainage lysimeters. Since it was not possible to place mature trees on the forest lysimeter, it was planted with young trees and understory vegetation. Data from this lysimeter and computations with the water balance and the Penman-Monteith equation were then used to assess the values of the water balance components for the mature forest.

Total precipitation during the study period was 2308 mm. In the forest environment, 46% thereof was

intercepted by the canopy from where it later evaporated. Hence, much less rain reached the ground than under grassland. Runoff from both sites was <1% of precipitation and therefore not a significant factor in the water balance. Cumulative drainage amounted to 1136 mm from grassland; from the mature forest, it was estimated to be 389 mm. There were two reasons for this low value under forest: Interception prevented a lot of water from reaching the ground, and the actual evapotranspiration from the mature forest was much higher than from grassland (1231 mm compared to 1964 mm).

**Keywords** Water balance · Lysimeter · Precipitation · Drainage · Evapotranspiration · Atlantic Forest

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Eloiza Maria Cauduro Dias de Paiva died before publication of this work was completed.

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R. M. Feltrin (✉)  
Federal University of Pampa, Campus Caçapava do Sul, Av. Pedro Anunciação 111, Vila Batista, Caçapava do Sul, Rio Grande do Sul 96570-000, Brazil  
e-mail: agrofeltrin@gmail.com

J. B. D. de Paiva · E. M. C. D. de Paiva  
Department of Sanitary and Environmental Engineering, Center of Technology, Federal University of Santa Maria, Avenida Roraima 1000, Camobi, Santa Maria, Rio Grande do Sul 97105-900, Brazil

R. Meissner · H. Rupp  
Department of Soil Physics, Helmholtz Centre for Environmental Research – UFZ, Lysimeter Station, Falkenberg 55, 39615 Altmärkische Wische, Germany

H. Borg  
Faculty of Natural Sciences III, Martin-Luther-Universität Halle-Wittenberg, Julius-Kühn-Straße 23, 06112 Halle (Saale), Germany

## 1 Introduction

The degradation of natural resources in general and the increasing scarcity of drinking water in particular are problems that have generated great concern and demand special attention from scientists and governments. Brazil, being a large country, encompasses many different climates and many different ecosystems with unique features which are threatened by human activities. Tucci (2002) points out that due to the lack of monitoring, there is not enough knowledge of the behavior of the national eco-hydrological biomes.

Worldwide, there is a deficiency of data on the dynamics of hydrological processes and the water balance of different environments. According to Kramer and Holscher (2009), studies of the influence of biodiversity

on soil water dynamics have been conducted mainly in pastures, while little attention has been given to forests. Traditionally, forests are seen as very effective in stabilizing and maintaining the water balance of a region. They improve soil structure, which enhances infiltration, percolation, and storage of water, and thereby lessen direct runoff (Ávila 2011). However, despite the importance of forests in maintaining environmental stability, there are only few studies of their contribution to the water balance (Müller and Bolte 2009).

Vegetation cover has a significant influence on the hydrological cycle because it affects the movement and distribution of water in various compartments of the system, including outputs into the atmosphere and inputs into rivers and aquifers (Arcova et al. 2003; Cicco 2009). Fujieda et al. (1997) commented that maintaining the flow which sustains the streams and rivers is one of the most important hydrological characteristics of forests and underlines the role of the type of vegetation cover in the replenishment of water bodies.

Hydrological soil processes are strongly influenced by soil type, plant density, the plants' physiological behavior, and canopy structure and architecture (Almeida and Soares 2003). These authors also state that the leaf area index, which changes with season, is very important for evapotranspiration, photosynthesis, and the interception of light and rain. In line with this, Pezzopane et al. (2005) and Pinheiro (2007) showed that within a forest, the canopy structure affects the vertical stratification of the microclimate, e.g., the variation of temperature, humidity, and radiation.

Brutsaert (2005) reported that, although globally numerous studies have been conducted to quantify the components of the water balance, the available data are far from adequate. Furthermore, some of the methods used in these studies can be subjected to severe criticism. In the case of forests, Kramer and Holscher (2009) pointed out that, depending on the complexity of the situation and on the temporal and spatial scale, the measured parameters should include internal precipitation (throughfall), stem flow, soil water dynamics, and, ideally, evapotranspiration. If the latter is not measured directly, it should at least be estimated using an established method.

Lysimeters are an extremely important tool for the quantification and understanding of the components of the water balance (Goss and Ehlers 2009), because they allow a fairly detailed quantitative analysis of evapotranspiration and deep percolation and, if equipped accordingly, of soil water dynamics.

Meissner et al. (2010a) consider lysimetry to be the most important direct method for assessing soil water drainage. Lysimetry is certainly the most accurate tool to measure water and solute fluxes (Meissner et al. 2010b).

In developed countries, the use of lysimeters is common in various types of studies, but in Brazil, their use is still limited due to the high cost involved in their acquisition and installation. Currently, a tendency to increase research in this area can be observed in Brazil as highlighted by the studies of Faria et al. (2006), Carvalho et al. (2007), Santos et al. (2008), Feltrin (2009), and Campeche et al. (2011).

Unlike in many studies worldwide, almost all lysimeter studies in Brazil use disturbed soil cores. However, recently, Oliveira et al. (2010), Pinheiro et al. (2010), and Feltrin et al. (2011) carried out studies in southern Brazil using drainage lysimeters containing undisturbed soil monoliths. Although the filling and technical installation of this type of lysimeter present greater difficulties, this approach has the advantage of preserving the physical characteristics of the soil, thus ensuring that the conditions of water flow and solute transport are as close to natural conditions as possible (Meissner et al. 2007).

Although the use of lysimeters is widespread in the study of agricultural crops, its use in forest areas is still rare, because it is very difficult to place mature trees in a lysimeter vessel, and letting younger trees grow into mature ones takes a long time. Consequently, a survey conducted by Lanthaler (2004) on the number of lysimeters installed in Europe up to 2004 found that 117 institutions were operating 2930 lysimeters in 18 countries of which 78% were located in cropped areas, 21% in grassland, and only 1% in forests. Harsch et al. (2009) state that due to their scarcity, data generated from lysimeters under forest are particularly valuable.

In view of the growing intensification of land and water use and the associated conversion of forested areas to grass- or cropland in the region, this study investigates and compares precipitation, surface runoff, drainage, and evapotranspiration under the climatic conditions of the Atlantic Forest biome in southern Brazil. To accomplish this task, two drainage lysimeters were installed, one under grassland and one in a mature natural forest. It is the first study in Brazil to use a lysimeter in a forest environment and also one of the first to use undisturbed soil cores.

We, too, were faced with the problem that it is very hard to get mature trees into a lysimeter vessel. Furthermore, because the trees in a mature natural forest differ significantly in size and are from different species, one

would need a rather large vessel to hold a representative range of trees. Alternatively, one could use a number of smaller lysimeters, each with a different tree species and/or tree size. In light of this difficulty, we decided to initially install just one lysimeter under the mature forest cover and plant it with young trees and typical understory vegetation. To obtain approximate values for surface runoff, drainage, and evapotranspiration for the mature forest, we took the data from this lysimeter and extrapolated them to the mature forest, partly with the help of the water balance or the Penman-Monteith equation.

The aim of this study is threefold: First, to quantify various water balance parameters for grassland and forest understory. Second, to assess, if one can get reasonable values for a mature natural forest environment by extrapolating from the latter. Third, to check whether the methods used here work or how they must be improved. Here, we report on first results of this study covering the period from February 9, 2012 to March 31, 2013.

## 2 Material and Methods

### 2.1 Study Area

The study area (29° 37' 49.7" S, 53°48' 39.8" W, 205 masl) lies near the city of Santa Maria in the state of Rio Grande do Sul, Brazil. The area is characterized by marked ridge tops, valley slopes, and floodplains. The latter contain the streams which make up the local drainage system. These streams flow into the DNOS/CORSAN dam, which is largely responsible for the water supply of the city of Santa Maria. The region is part of the Guarani Aquifer system and belongs to the Atlantic Forest biome. Native forest is the main type of vegetation cover in mountainous areas. The flatter areas are dominated by grassland composed mainly of native grasses of the genus *Paspalum notatum*.

According to Köppen (1948), the climate is subtropical (Cfa), characterized by the occurrence of precipitation during all months of the year with no major quantitative difference between the wettest and driest month. The mean annual precipitation is 1780 mm, and there are on average 96 days with rain each year. The mean annual grass reference evapotranspiration (Allen et al. 1998) amounts to some 1300 mm. The yearly mean temperature is 18.8 °C with monthly averages ranging between 24.2 °C in the hottest month (January) and

13.9 °C in the coldest (June). The annual average relative humidity is 76.5%, and the total annual insolation is 2162 h.

The soils of the region are classified as entisols (Soil Survey Staff 1999) with a high spatial variability of soil properties depending on topography and vegetation. Further information on some of their properties will be given later.

### 2.2 Design and Installation of the Lysimeters

Two identical drainage lysimeters were built for this study. One was installed under grassland; the other, under forest. The locations where the lysimeters were installed were chosen for typical soil characteristics, ease of access, and safety of the equipment. The grassland soil is a sand, while the soil under forest is a loam. Textural details are given in Table 1.

The grassland lysimeter was installed between June 28 and 30, 2011, and the forest lysimeter between August 15 and 28 of the same year. The vegetation on the grassland lysimeter consists of the native grass *P. Notate*. On the forest lysimeter, it is composed of two young trees of the native species *Cupania vernalis cambess* with an approximate height of 150 cm and a canopy diameter of 60 cm at the time of the lysimeter installation. *Adiantum raddianum* C. Presl., a small fern species, covers the ground below the trees. Note that our forest lysimeter cannot truly represent the mature forest, because the trees on it are still small and shaded by the older, taller trees nearby. Hence, evapotranspiration is less, which results in higher soil moisture contents, which in turn affects drainage and, to a lesser extent, runoff. In the “Results and Discussion” section, we shall therefore extrapolate from the data obtained with this lysimeter to the mature forest situation, as already mentioned above.

The lysimeter vessels which contain the soil are 110-cm deep (Fig. 1) and have a circular cross-section with an internal diameter of 113 cm. This gives them a surface area of 1 m<sup>2</sup>. The vessels are made of carbon steel with a thickness of 4.75 mm (3/16") and are treated with an epoxy anticorrosive paint.

Both lysimeters contain an undisturbed 1-m-long soil monolith taken at the installation site. To obtain the monoliths, it was necessary to build a structure consisting of two carbon steel blades arranged as a guillotine for cutting and retrieving the soil profile without deforming its structure. Once a monolith was

**Table 1** Bulk density and particle size distribution at various depths of the soil in the grassland and forest lysimeter, respectively

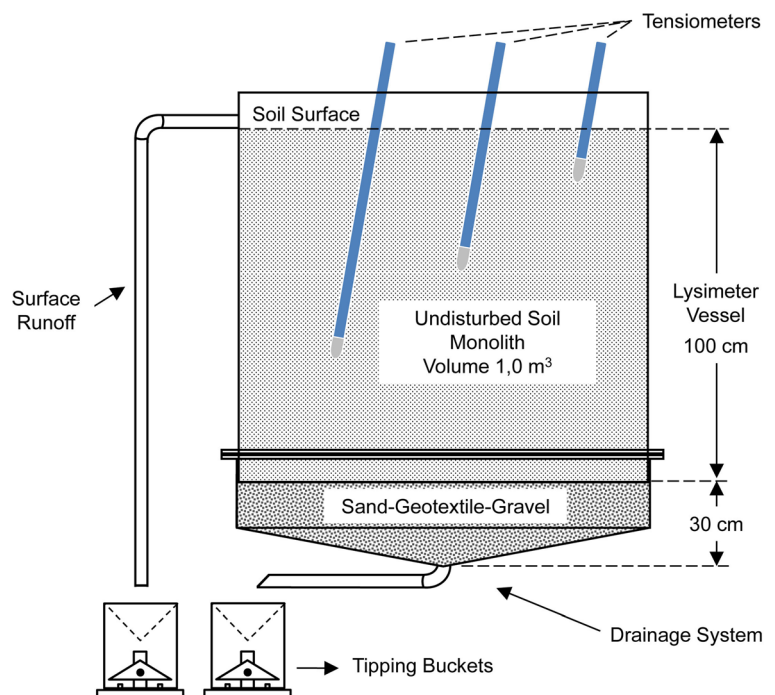
	Depth (cm)	Bulk density ( $\text{g cm}^{-3}$ )	Particle size distribution				Soil texture
			Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	
Forest	10	1.24	22.2	24.1	39.0	14.6	Loam
	20	1.30	20.1	26.3	42.1	11.6	Loam
	30	1.27	20.0	27.8	36.5	15.7	Loam
	50	1.37	20.9	25.8	37.5	15.8	Loam
	70	1.40	19.6	25.5	38.6	16.3	Loam
	90	1.21	24.0	22.3	37.5	16.2	Loam
Grassland	10	1.53	15.9	76.4	2.7	5.0	Sand
	20	1.51	15.8	74.3	4.8	5.1	Sand
	30	1.41	15.2	74.8	7.5	2.5	Sand
	50	1.39	13.8	74.8	6.4	5.1	Sand
	70	1.41	13.6	75.3	7.6	3.5	Sand
	90	1.48	13.6	74.9	7.9	3.6	Sand

retrieved, a 10-cm-thick layer of sand followed by a 10-cm-thick gravel layer was added below the actual soil profile to facilitate drainage from the lysimeter. A geotextile was placed between the sand and the gravel to prevent the sand being washed into the gravel. The sand-geotextile-gravel section was put into a separate vessel which is 10 cm lower at the center than at the

circumference (Fig. 1). As a result, the thickness of the sand plus gravel layer changes from 20 cm at the circumference to 30 cm at the center. This second vessel was screwed to the vessel containing the monolith via flanges.

Since the lysimeter bottom is 10 cm lower at the center than at the circumference, it has a conical shape

**Fig. 1** Sketch of the type of drainage lysimeter used in the study and of the device used for cutting and retrieving the soil monoliths in the lysimeters



which causes all drainage water to flow to the center. There is an opening with a diameter of 5 cm from where a tube of the same diameter carries the drainage water to a tipping bucket arrangement for quantification. Near the top of the lysimeter, level with the soil surface, there is an opening 5 cm in diameter from where surface runoff from the lysimeter is channeled via PVC tubes into another tipping bucket arrangement to measure it. Each tipping bucket arrangement is equipped with a microprocessor which automatically corrects for the amount of water bypassing the buckets while they are tipping. This amount depends on the flow rate.

At 10-, 30-, and 70-cm depth, electronic tensiometers with pressure transducers were installed in the lysimeters to monitor soil water tension. The tensiometers were inserted from the soil surface at an angle of inclination between 30 and 45°.

### 2.3 Meteorological Data

Meteorological data were recorded at 10-min intervals and aggregated for different periods as required (e.g., hourly, daily, or monthly).

The data were obtained from an automatic weather station 15 m from the grassland lysimeter. The variables measured were precipitation at 1.5-m height; atmospheric pressure, air temperature, and relative humidity at 1.8-m height; and wind speed and direction, incident solar radiation (global radiation), and solar radiation reflected by the surface (here grass) at 2.0-m height. Richter (1995) demonstrated that the precipitation registered by a rain gauge of the type used here is on average 10% below the precipitation that actually fell. This arises from a disturbance of the wind field around the gauge due to its isolated position at some height above the soil surface. Hence, our recorded amounts were multiplied by a factor of 1.1.

In addition, some meteorological data were collected near the lysimeter inside the forest, too, namely, air temperature, precipitation below the canopy, relative humidity, and incident solar radiation, all at 1.5 m high. A significant disturbance of the wind field around the rain gauge below the canopy is unlikely. Hence, here, the amounts actually recorded were used.

### 2.4 Soil Moisture Retention Curves

At the extraction sites of the lysimeter cores, three undisturbed soil samples per depth were collected 10,

20, 30, 50, 70, and 90 cm below the surface to determine the soil moisture retention curves. Additional soil samples were taken at these depths to determine the texture with the Bouyoucos hydrometer method (Bouyoucos 1962) and bulk density, again with three replications.

Eight tensions were used to delineate the retention curves (Fig. 2). The data for 0.1-, 1-, 6-, 10-, 33-, and 100-kPa tensions were collected using pressure plates in a Richards apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands), while for 500- and 1500-kPa tensions, a WP4 dewpoint potentiometer (Decagon Devices, Pullman, Washington, USA) was used. Note that with the WP4, one cannot select a tension, but only a water content for which the corresponding soil moisture tension is then determined. The water contents for 500- and 1500-kPa tensions were interpolated from the data obtained with the apparatus.

For each of the two lysimeter sites, the retention data from the three replicates for each depth were averaged. Afterwards, the van Genuchten (1980) equation:

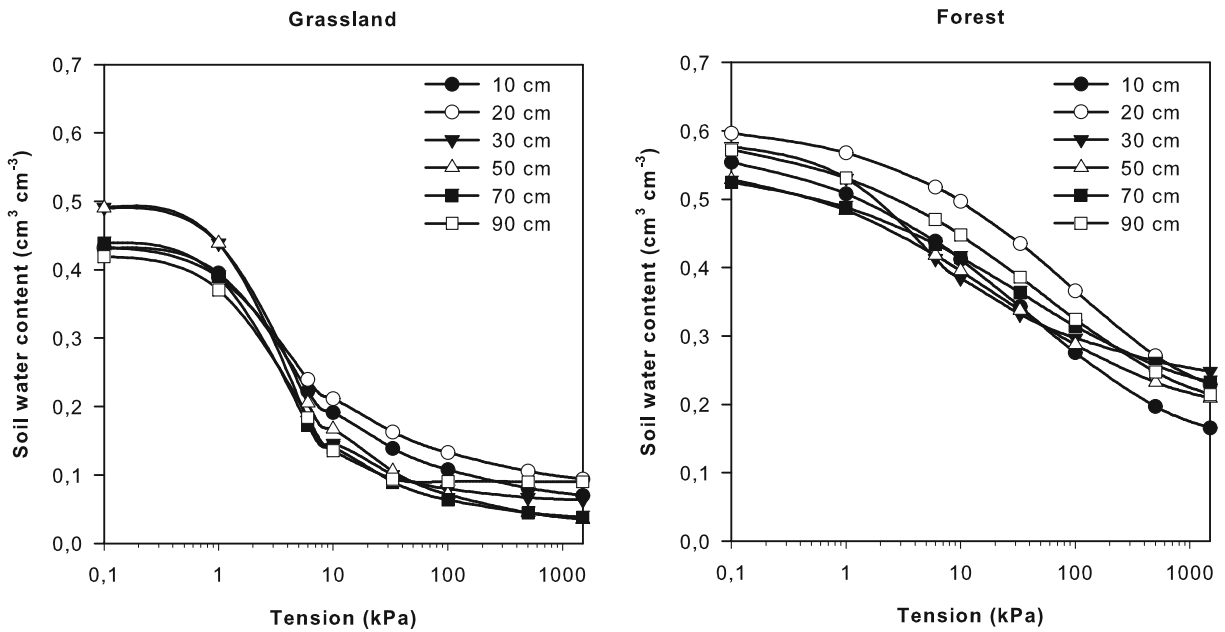
$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha \times \psi_m)^n]^m} \quad (1)$$

with  $\theta$  = soil water content,  $\theta_r$  = residual water content,  $\theta_s$  = saturated water content,  $\psi_m$  = soil moisture tension, and  $\alpha$ ,  $m$ , and  $n$  = empirical parameters with  $m = 1 - 1/n$  was fitted to the averaged data for each depth and site, using the software SWRC (Soil Water Retention Curve), version 3.0 beta (Dourado Neto et al. 2001) to obtain  $\alpha$ ,  $m$ , and  $n$  (Table 2). Note that all water contents stated in this paper are volumetric values.

In the lysimeters, soil moisture tension was monitored with tensiometers at three different depths (10, 30, and 70 cm). The observed tensions were then transformed into volumetric soil water contents with the fitted equations. The values thus obtained ( $\theta_i$ ) were assumed to be the mean soil moisture content for the 0–20-, 20–50-, and 50–100-cm depth interval ( $\Delta z_i$ ), respectively. Lastly, the total amount of water stored in the profile (WS) was computed as:

$$WS = \sum_{i=1}^3 (\theta \times \Delta z_i) \quad (2)$$

The change in soil water storage ( $\Delta WS$ ) over a given period was determined as the difference in WS at the beginning ( $WS_0$ ) and the end ( $WS_f$ ) of the period as:



**Fig. 2** Soil moisture retention curves for various depths. The symbols indicate the measured data, the *lines* were computed with the van Genuchten (1980) equation using the parameter values in Table 2

$$\Delta WS = WS_f - WS_o \tag{3}$$

$$ET_a = P - (SR + D + \Delta WS) \tag{4}$$

### 2.5 Evapotranspiration

Actual evapotranspiration ( $ET_a$ ) was obtained by applying the water balance equation to each lysimeter in the form:

with  $P$  = precipitation,  $SR$  = surface runoff, and  $D$  = drainage.

Potential evapotranspiration ( $ET_p$ ) was computed with the Penman-Monteith equation (Allen et al. 1998)

**Table 2** Values of the fitting parameters in the equation of van Genuchten (1980) obtained with the SWRC software (version 3.0 beta)

	Depth (cm)	$\theta_r$	$\theta_s$	$\alpha$	$n$	$m$
Grassland	10	0.05	0.431	1.2766	9.403	0.0414
	20	0.07	0.433	1.4319	8.695	0.0407
	30	0.06	0.491	1.2121	11.957	0.0539
	50	0.02	0.490	1.2837	11.718	0.0389
	70	0.03	0.439	1.2770	10.538	0.0489
	90	0.09	0.422	0.1497	1.284	2.0160
Forest	10	0.14	0.584	0.0018	0.4366	3.0633
	20	0.20	0.612	0.0004	0.4708	4.5750
	30	0.21	0.578	1.1614	1.8607	0.1632
	50	0.18	0.557	0.0218	0.4689	1.4097
	70	0.21	0.550	0.0028	0.4272	2.5795
	90	0.19	0.602	0.0003	0.4056	5.1923



$$ET_p = \frac{\Delta \times (R_n - G) + \rho_a \times c_p \times \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \times \left(1 + \frac{r_c}{r_a}\right)} \quad (5)$$

with  $\Delta$  = slope of the vapor pressure-temperature curve,  $R_n$  = net radiation,  $G$  = heat flux density into the soil,  $\rho_a c_p$  = volumetric specific heat of air,  $e_s$  = saturation vapor pressure at air temperature,  $e_a$  = ambient vapor pressure,  $r_a$  = aerodynamic resistance to vapor transport,  $r_c$  = canopy resistance to vapor transport, and  $\gamma$  = psychrometer constant.  $ET_p$  was combined with the degree of forest cover to compute the  $ET_a$  from the mature forest under the assumption that it did not experience any water stress. The degree of forest cover was assessed from ten photographs taken vertically upwards in the vicinity of the lysimeter.

### 3 Results and Discussion

#### 3.1 Precipitation

The cumulative precipitation during the 14-month study period was 2308 mm (Table 3). All of it fell as rain. The highest monthly precipitation (388 mm) was recorded in December 2012, the lowest (39 mm) in June 2012. Precipitation was below the historical average for the region in 7 months, and above it in 7 months, too. Overall, the amount was 6.6% above the long-term mean.

The main difference between forest and grassland with respect to precipitation is that in a forest environment, a lot of it is intercepted by the canopy and does not reach the soil surface, or at least not directly. Part of the intercepted precipitation evaporates from the canopy, another part drips from the canopy to the ground, and a third part moves to the soil surface as stem flow. In this study, only 54% (1239 mm) of the precipitation reached the rain gauge below forest canopy, while 46% (1069 mm) were intercepted by the canopy and later evaporated from it (Table 3).

Internal precipitation is highly variable due to the existence of preferred pathways, which in this context are openings in the tree canopy, stem flow, and drip points, which can channel rainwater to (or away from) certain points below the canopy. Sari (2012) therefore suggests that 20 rain gauges should be employed to

quantify internal precipitation, if the vegetation is uniform. For dense, non-uniform vegetation, she recommends a higher number of gauges (e.g., 40). In our study, only one rain gauge was installed inside the forest. Hence, one may question if the 1239 mm of internal precipitation (i.e., 46% interception) we recorded are representative. Andrade Deon (2015) sampled 100 spots to quantify interception in the forest surrounding our understory lysimeter and found an average value of 46.6% for an 8-month study period. This is practically the same as the 46% we obtained with our single gauge and means, although fortuitous, that our value is representative. We should add that in the study of Andrade Deon (2015), interception at the various spots ranged from 25 to 62% over her study period, a point we shall return to later.

It should be noted that there are interception losses under grass vegetation, too. However, for *P. notatum*, the grass looked at in our study, they cannot be measured. Judging from data for rye and wheat (Schroedter 1985) which are grasses, they probably amount to 10 to 20% of the above-canopy precipitation, which is much less than the interception by the forest.

In summary, this means that under forest, less precipitation reaches the soil surface than under grass. Hence, there is likely to be less surface runoff and less soil water recharge. The latter leaves less scope for drainage from the soil profile, too. However, this will only be so, if the soil moisture contents, which are strongly influenced by evapotranspiration, and the soil hydraulic characteristics are the same under grassland and forest. These aspects shall be discussed in the following.

#### 3.2 Runoff

Between February 9, 2012 and March 31, 2013, 54 precipitation events were recorded, some of them spanning several days. During this period, total runoff from the grassland lysimeter was 7.2 mm, while that from forest lysimeter was 8.2 mm. These amounts are very similar and also small compared to the total precipitation during this time. However, recall that only 1239 mm of rain reached the forest floor compared to 1962 mm for grassland (2308 mm minus perhaps 15% interception) so that the runoff from the forest lysimeter translates to 0.66% of the precipitation. The corresponding figure for the grassland lysimeter is just 0.37%.

**Table 3** Monthly above-canopy (incident) precipitation and interception by and precipitation below the forest canopy (internal precipitation). For comparison, the long-term means for the above-canopy precipitation are given, too

Year	Month	Incident precipitation (mm)	Canopy interception (mm)	Internal precipitation (mm)	Climate normals (1961–1990) (mm)
2012	February	152	81	71	143
2012	March	90	37	53	167
2012	April	122	47	75	148
2012	May	211	143	68	142
2012	June	39	26	13	158
2012	July	111	31	80	163
2012	August	56	25	31	151
2012	September	222	96	126	169
2012	October	337	101	236	160
2012	November	82	38	44	145
2012	December	388	181	207	147
2013	January	102	50	52	160
2013	February	173	98	75	143
2013	March	222	115	107	167
Total (mm)		2308	1069	1239	2166

In grassland, only 18 of the 54 precipitation events generated runoff, while in the forest, 47 events did. At first sight, this is surprising, because less rain reached the forest floor. Runoff occurs if the precipitation rate exceeds the infiltration capacity of a soil. In our study, the soils are quite different under the two land uses, namely, sand under grassland and loam under forest. Sand has a much higher infiltration capacity than loam. This explains why in our case, there were more runoff events under forest, even though the amount of rain reaching the ground was just 63% of that under grassland.

The total amount of runoff was similar for the grassland and the forest lysimeter, even though there were fewer runoff events under grassland. The roughly equal amount is mostly due to runoff from grassland on 6 days with high precipitation intensities. On these days, the higher infiltration capacity of the sand under grassland was partly offset by the much higher precipitation amount reaching the ground compared to forest. To illustrate this, let us look at May 29, 2012. On that day, 177.2 mm of rain fell, of which 150.6 mm presumably reached the soil at the grassland lysimeter. This led to 3.5 mm of runoff. At the same time, 52.6 mm of rain was recorded below the mature forest canopy near the forest lysimeter which resulted in 2.6 mm of runoff. So, because of its high infiltration capacity, the sand under grassland was able to take in 147.1 mm of rain. Due to

its lower infiltration capacity, the loam in the forest lysimeter absorbed only 50 mm of rain. Concurrently, the 98.0 mm of extra rain received by the grassland lysimeter led to 0.9 mm of extra runoff.

The total amount of runoff from the mature forest is likely to be a bit less than the amount from the forest lysimeter. In the mature forest, evapotranspiration is higher so that the soil moisture content is lower. The lower the soil moisture content, the higher the infiltration capacity of a soil and the less runoff occurs. The precise amount of surface runoff under mature forest is not important here, because at <1% of the precipitation, it is not a significant factor in the water balance of the grassland or the forest in our study.

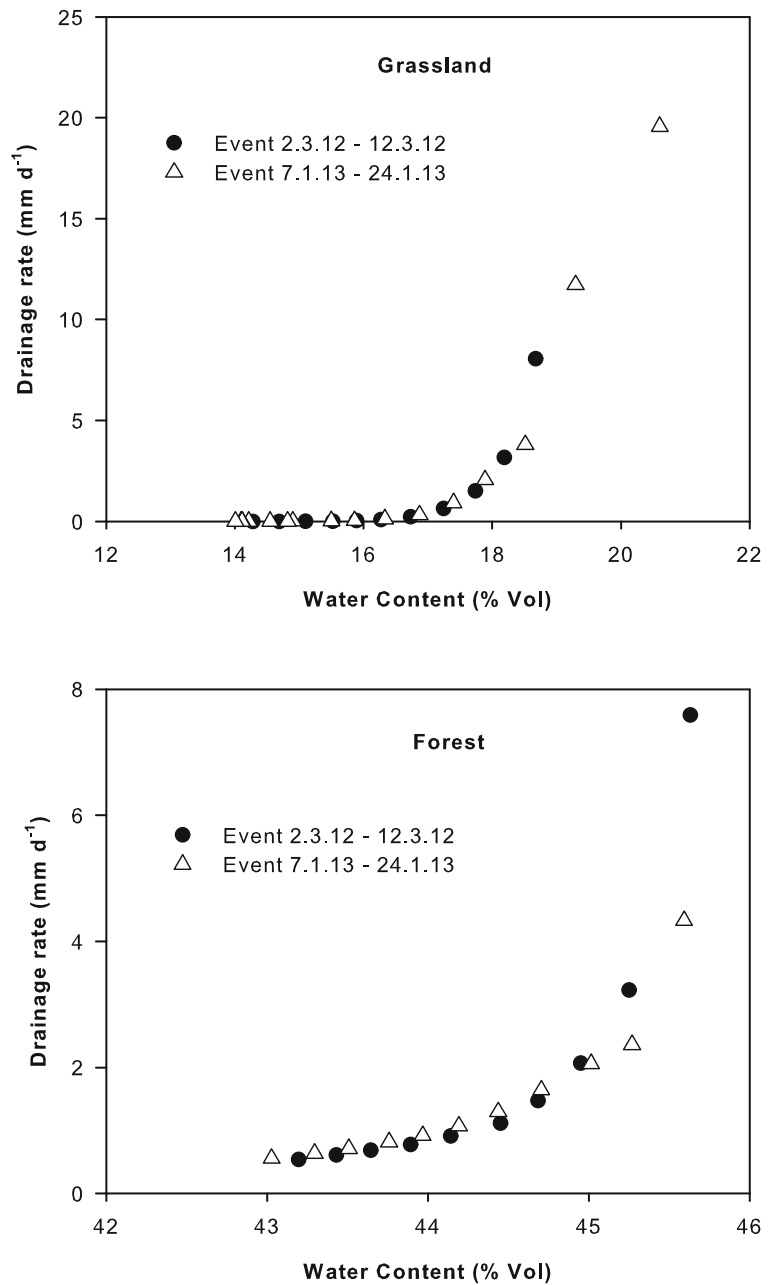
### 3.3 Drainage

When the soil moisture content is high (or in the extreme case at saturation), water drains out of a soil at a high rate. As water is lost and, consequently, the soil moisture content decreases, the drainage rate decreases, too. This is exemplified in Fig. 3 for two typical drainage events under grassland and forest, respectively.

This pattern occurs, because drainage is largely determined by the hydraulic conductivity of a soil which declines with soil moisture content. In sands, this decline is very rapid so that drainage appears to stop after a



**Fig. 3** Depiction of the relationship between soil water content and drainage rate for two typical drainage events under grassland and forest, respectively



few days. It does not actually stop, but becomes so low that it is hardly noticeable in practice (Veihmeyer and Hendrickson 1931; Gardner 1960; Hillel 1998). In loams, the decline in hydraulic conductivity with soil moisture content takes place more gradually so that drainage can still be appreciable after a few weeks (Israelsen 1927; Hillel 1998). Also, in sands, the hydraulic conductivity at water contents between roughly half and full saturation is very high. Hence, water can

drain out of a profile so fast that in the field, such high water contents hardly occur and only briefly, unless there is a perching layer near the soil surface or the ground water table is close to the surface. Neither is the case in our study area. In loams, the hydraulic conductivity and, thus, the drainage rate at water contents between half and full saturation are much lower so that such water contents appear more frequently and persist much longer.

As one would expect from these statements, we observed water contents above 25% in the sandy soil under grassland not very often and only for short periods, and drainage became immeasurable at water contents below 14.5% (Fig. 3, top). In contrast, we found water contents up to 50% in the loamy soil under forest. They rarely fell below 43% (Fig. 3, bottom) and only on three occasions below 40% at which point there was still some drainage (<0.1 mm/day). In fact, measurable drainage from the forest lysimeter never stopped.

In hydrologic studies, the term field capacity is often used to define the soil moisture content below which water no longer drains out of a soil profile. Above field capacity, water drains away rather quickly. Since the introduction of this term by Veihmeyer and Hendrickson (1931), it has been known that drainage does not totally stop at field capacity, but that it merely becomes negligible (Gardner 1960). The decision when drainage becomes negligible is subjective (Hillel 1998). If we assume in this paper that negligible refers to a drainage rate < 0.1 mm/day, then our drainage data suggest a field capacity (averaged over the profile) of 16.0% for the sand under grassland and of 42.3% for the loam under forest.

Figure 4 shows the drainage from the grassland and the forest lysimeter over the course of our study. Due to a failure in the tipping bucket mechanism used for monitoring drainage, there were some gaps in the recorded data. We filled them in by interpolation with the help of the water balance equation.

Each observed drainage event started with a marked increase in soil moisture content after a substantial rainfall. The soil moisture content, and with it the drainage rate, then declined with time until the next substantial rainfall. Four periods were observed in the grassland lysimeter in which the drainage flow ceased completely. Under forest, the drainage flow was rather low in these periods, but did not stop. Following the statements at the beginning of this chapter, this difference can again be attributed to the different soil types in the two environments: sand under grassland and loam under forest.

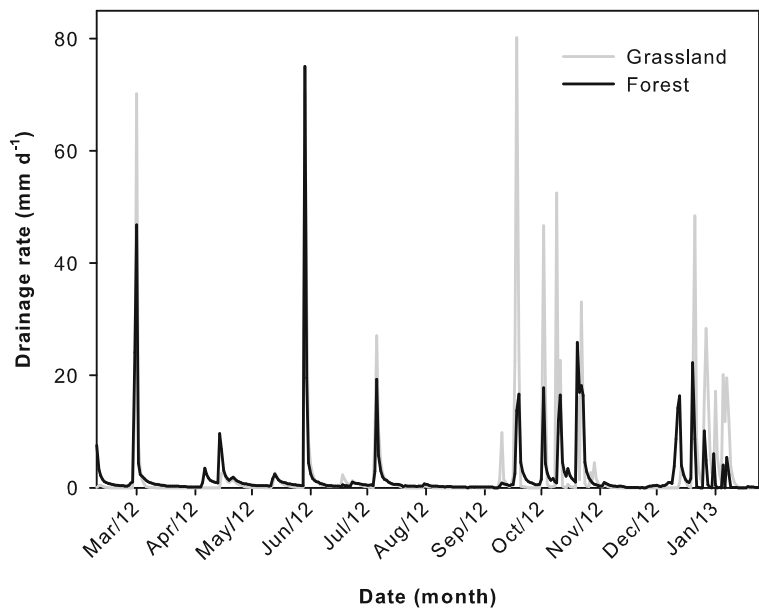
Cumulative drainage during the study period was 1136 mm from the grassland and 777 mm from the forest lysimeter. During this period, cumulative precipitation was 2308 mm (or 1962 mm, if 15% interception by the grass canopy is taken into account) on grassland and 1239 under the forest canopy. Hence, in the grassland lysimeter, 58% of the precipitation which reached the soil left the profile as drainage, but 63% in the forest lysimeter.

The differences in drainage between the two lysimeters arise from the following: Due to interception by the tree canopy, a lot less rain reaches the forest lysimeter. Consequently, it does not receive as much water which may end up as drainage. The tree canopy also shields the vegetation on the forest lysimeter from radiation and wind so that  $ET_a$  is lower than from the grassland lysimeter. Because  $ET_a$  is lower, less water is extracted from the soil profile, which means the soil water content remains closer to field capacity. The amount of water which can be stored during the next precipitation event depends on the difference between the moisture content brought about by  $ET_a$  and field capacity. Less extraction translates into less free water storage capacity and, thus, potentially into more drainage. The fact that the forest floor received 723 mm less rain but had only 359 mm less drainage than the grassland lysimeter suggests that the lower free storage capacity had a bigger influence on the observed drainage pattern than the lower amount of rain.

The question now remains, how much drainage there was under the mature forest. Rearranging the water balance equation (Eq. 4) for drainage one gets:  $D = P - SR - ET_a - \Delta WS = 2308 - 5 - 1964 + 50 \text{ mm} = 389 \text{ mm}$ . For precipitation ( $P$ ), the total amount recorded above the grassland was used, because this is also the amount that impinged on the forest canopy from where the intercepted precipitation later evaporates. Surface runoff ( $SR$ ) was set slightly lower than the value measured by the forest lysimeter (see “Runoff” section). As will be shown in the next chapter,  $ET_a$  from the mature forest (trees plus understory) was likely to be 1964 mm during the study period. The change in stored water from the beginning to the end of the study period was recorded to be 50 mm. The result is a total amount of drainage of 389 mm. This is 388 mm less than the 777 mm recorded by the forest lysimeter which just carries young trees and typical understory vegetation.

At first thought, one may have expected even less drainage from the mature forest, because it consumes a lot more water than the understory alone (1964 to 476 mm, see next chapter) so that the soil would be much drier on average. As a result, it could store more rain and less would drain away. However, much of the water consumed by the mature trees does not come out of the soil, but from water intercepted by the canopy (1069 mm, see below).

**Fig. 4** Time course of the drainage rates from grassland and forest



### 3.4 Evapotranspiration

Figure 5 shows the time course of soil water tensions at three depths in the grassland lysimeter. During the study period reported on here, the tension at 70-cm depth always remained around 6 to 8 kPa with very little variation. At 30-cm depth, the tension varied much more. From February to April 2012, the late summer month in the region, it fluctuated between about 5 and 65 kPa. In the cooler month thereafter, it fluctuated much less and mostly stayed around 6 kPa until the onset of the summer in November. At that time, the fluctuation increased again. The tensions ranged from near 2 to 60 kPa. The soil moisture tensions at 10-cm depth showed the same picture, but the maximum values (46 kPa) were lower. All measured tensions are low, which means that the plants suffered no water stress during the study period. The recorded “baseline” tension of 6 kPa represents the soil moisture tension at field capacity in this lysimeter.

The water contents under grassland derived from the tension data via the retention curves in Fig. 2 are shown in Fig. 6. As follows from the measured tensions, they changed very little at 70-cm depth and were mostly between 15 and 19%. At 30 cm, they fluctuated between about 9 and 25% from February to April and then less until 2012 November (mostly 16 to 25%). Thereafter, the variation increased again (10 to 33%). At 10-cm depth, the variation was larger (15 to 40%), again with a somewhat higher variation in the warmer periods.

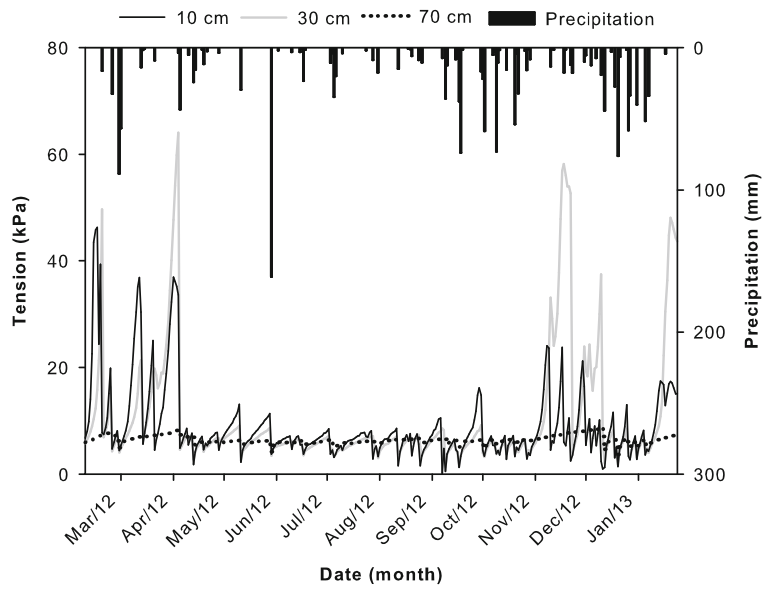
The water tension and content data indicate that the soil water dynamics, i.e., water extraction by plants and soil water recharge by rain, were most pronounced near the surface, decreased with depth, and hardly affected the profile below  $\geq 70$ -cm depth. This is a consequence of the frequent rains typical for the study region, which soon replenish water extracted from the upper soil profile so that there is no need for plants to obtain water from greater depths.

Figure 7 depicts the tension data for the forest lysimeter. Here, too, the soil moisture tension at 70-cm depth hardly changed. It remained around 3 kPa during the whole period. There was a bit more variation at 30-cm depths with values ranging from 3 to 8 kPa. The 10-cm depths exhibited the most fluctuation (0 to 25 kPa). All measured tensions are again low, which means that the plants on the forest lysimeter did not suffer water stress either. The baseline tension, i.e., the soil moisture tension at field capacity in the forest lysimeter, is 3 kPa.

The corresponding water contents are shown in Fig. 8. They hardly varied at 70-cm depth, because the tensions hardly varied, and hovered around 45%. At 30 cm, they fluctuated mostly between 40 and 45%. At 10 cm, the picture was similar, but the variation was a bit larger (40 to 50%). At all three depth, there was no pronounced difference in the variation between the warmer and the cooler periods.

The variations in soil moisture (i.e., the soil water dynamics) in the forest lysimeter are much smaller than

**Fig. 5** Soil water tensions at three depths in the grassland lysimeter



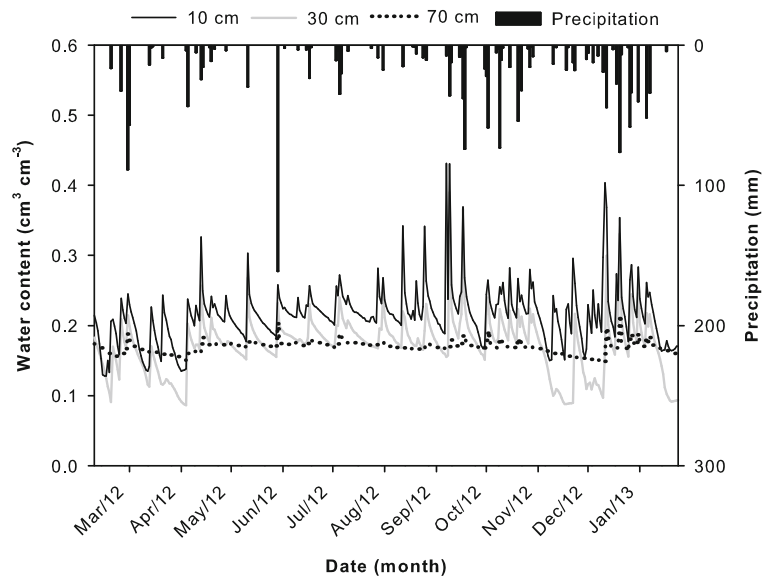
those in the grassland one. There are two reasons for this. First, evapotranspiration from the forest lysimeter is less because the vegetation on it is shielded from radiation and wind by the canopy of the mature trees. Second, a substantial amount of the precipitation is intercepted by the tree canopy from where it then evaporates into the atmosphere. Hence, less water reaches the ground and infiltrates into the soil and less water is removed from the soil by evapotranspiration.

The different baseline tensions arise from the different soil textures in the two environments (sand under grassland and loam under forest).

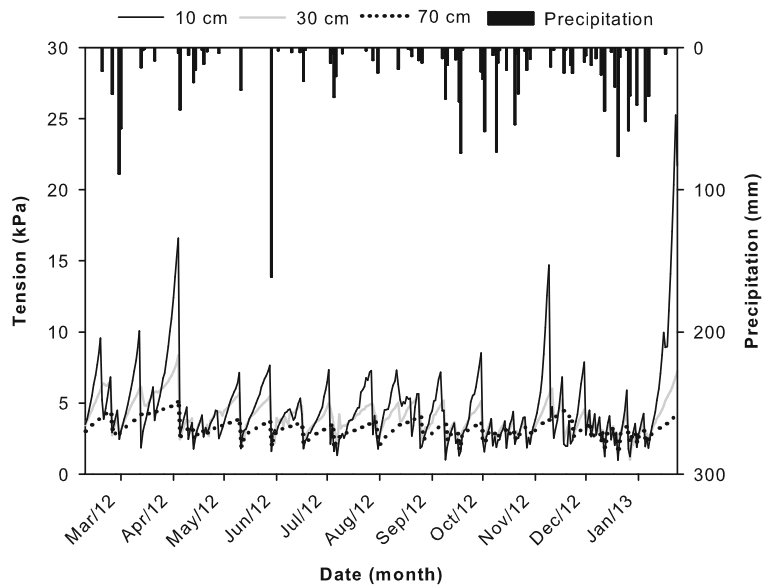
From February 9, 2012 to March 31, 2013, the total  $ET_a$  observed was 1231 mm from the grassland and 956 mm from the forest lysimeter.

Now the question remains, how much evapotranspiration there was from the mature forest (trees plus understorey). The soil moisture tensions in the grassland

**Fig. 6** Soil water contents at three depths in the grassland lysimeter



**Fig. 7** Soil water tensions at three depths in the forest lysimeter



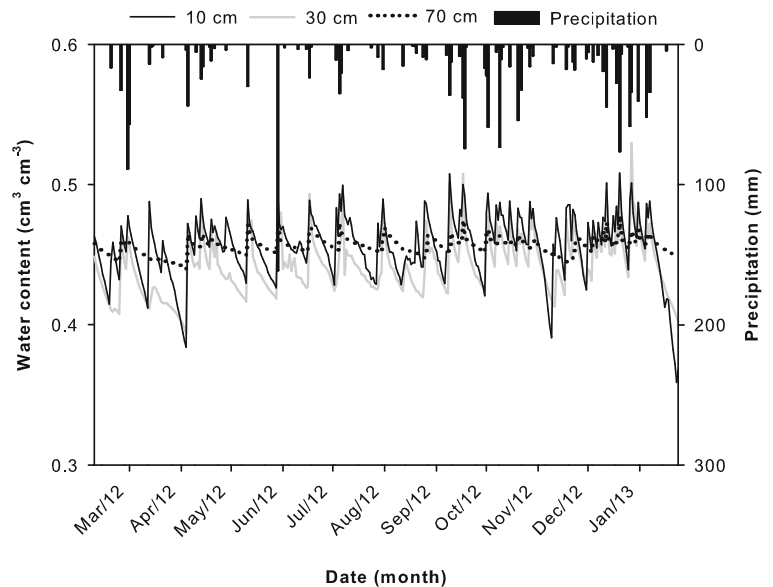
and forest lysimeter were well below 100 kPa during the whole study period. At such low tensions, plants do not suffer water stress. The mature forest trees, having deeper roots than grass, young trees, or the understory vegetation, are thus even less likely to have experienced water stress. Consequently, the mature forest almost certainly consumed water at the potential rate ( $ET_p$ ).

Computations with the Penman-Monteith equation (Eq. 5) based on our meteorological data yielded an  $ET_p$  of 1378 mm for a mature forest with full ground

cover. However, in our study area, ground cover by the canopy was only 87% so that  $ET_p$  from the tree canopy amounted to  $0.87 \times 1378 \text{ mm} = 1199 \text{ mm}$ .

There were 1069 mm of intercepted rain which evaporated from the canopy. Since this water did not have to pass through the stomata of the tree leaves,  $r_c = 0$  in Eq. 5. Computing  $ET_p$  with  $r_c = 0$  revealed that intercepted water evaporates 1.37 times faster than water which passes through the stomata. This means the intercepted 1069 mm were equivalent to 1069 mm/

**Fig. 8** Soil water contents at three depths in the forest lysimeter



$1.37 = 780$  mm of water transpired through the leaves. Hence, the amount of water removed from the soil by evapotranspiration is  $1199 - 780$  mm = 419 mm.

There was evapotranspiration by the understory, too. The vegetation on the forest lysimeter consumed 952 mm of water. However, the lysimeter had about twice the vegetation cover of its surroundings so that  $ET_a$  from the actual forest understory can be taken as about half of that from our forest lysimeter, i.e., 476 mm. Total evapotranspiration from the forest as a whole was therefore likely to be  $1069 + 419 + 476$  mm = 1964 mm. This is a lot more than from grassland (1231 mm).

#### 4 Discussion

We shall now look at how well our methods worked and where they must be improved. The amount of precipitation impinging on the grass and the forest canopy was determined with a tipping bucket rain gauge placed 1.5 m above the ground surface near the grassland lysimeter. This is the standard height in Brazil. For the observation period, it registered 2098 mm of precipitation. With this amount the water balance on the grassland site did not add up:  $P - SR - D - ET_a = \Delta WS = 2098 - 7 - 1136 - 1231$  mm = -276 mm. The observed net change in soil water storage over the study period was just -50 mm.

This discrepancy was probably due to the fact that a rain gauge placed at the aforementioned height underestimates the true precipitation by about 10%, because the gauge alters the wind conditions around it (Richter 1995; Hoffmann et al. 2016). When we increased the registered precipitation by 10% the grassland water balance worked out:  $P - SR - D - ET_a = \Delta WS = 2308 - 7 - 1136 - 1231$  mm = -66 mm. This is an acceptable deviation from the observed  $\Delta WS$ . Nevertheless, the 10% correction is based on studies in Germany and needs to be confirmed for Brazilian conditions.

According to Hoffmann et al. (2016), small Hellmann rain gauges placed directly on the soil surface provide more accurate precipitation measurements. Summed over several months, the amount of precipitation recorded with these gauges was comparable to that recorded by high precision weighing lysimeters. The deviation was only around 1.5%. We shall consider this finding in the continuation of our study.

Precipitation under the forest canopy was measured in the same way as outside the forest, i.e., 1.5 m above the ground. Because there is much less wind below the canopy, the amount of precipitation caught by the gauge is hardly affected by wind and therefore close to the amount which actually fell on this spot. However, if one looks at the water balance of the forest lysimeter one gets:

$P - SR - D - ET_a = \Delta WS = 1239 - 8 - 777 - 956$  mm = -502 mm. This says that from the beginning to the end of the study period, the net change in soil water storage was -502 mm. However, the observed net change was only -50 mm. There is no reason to suspect any serious error in our observed values for  $P$ ,  $SR$ ,  $D$ , and  $ET_a$ . However, as pointed out in the introduction, below canopy precipitation is highly variable. Therefore, it is plausible that the amount of rain which impinged on the forest lysimeter was much higher than what we measured with the gauge a few meters away. If it was 450 mm higher than at the gauge (1689 mm instead of 1239 mm), the water balance would add up, i.e.,  $\Delta WS = -50$  mm. This implies that only 27% of the incident precipitation of 2308 mm would have been intercepted by the canopy above the lysimeter. This is a low value, but still within the range observed by Andrade Deon (2015). In the continuation of this study, we shall place a rain gauge right next to or on the forest lysimeter to verify this low interception and further rain gauges elsewhere below the canopy to obtain more reliable data for interception.

There was very little runoff from either the grassland or the forest site. The instrumentation worked well. No changes have to be made here.

Drainage was substantial at both sites. Again, the instrumentation worked well, apart from some periods of malfunction. Here, too, no changes are necessary.

The determination of  $ET_a$  warrants more attention in the future. We obtained it by looking at the water content changes in the lysimeters. These we determined indirectly from soil moisture tensions which we then converted to soil moisture contents with the help of soil moisture retention curves determined in the laboratory. Retention curves are prone to errors which in turn can introduce errors to derived the soil moisture contents. Hence, it would be better in the future to determine soil moisture contents directly with TDR-probes.

In addition, tensiometers or TDR-probes are spaced at distinct depths, and the first instrument is typically placed some distance below the soil surface. This leads to a time delay in the reaction of the instruments to



precipitation and evapotranspiration, because a wetting or drying front must first reach the instruments before any precipitation or evapotranspiration is registered (Otto 2012). As a result, daily  $ET_a$  values obtained with these instruments may differ substantially from the actual values. This was clearly visible when we compared daily  $ET_a$  values from the tension data with  $ET_a$  values calculated with the Penman-Monteith equation. While the overall agreement was reasonable, individual values often deviated markedly. The discrepancies became smaller as the reporting period increased (e.g., to a week).

The biggest problem with our study, however, is that we did not directly measure values for the water balance components of the mature forest, apart from above and below canopy precipitation, the latter with the aforementioned weakness. Surface runoff is not really a problem, because it is very small. Hence, an estimate based on data from the understory is sufficient. However, for drainage and  $ET_a$ , a lack of measured data is more serious. We believe that our estimates are reasonable. Nevertheless, in the long run, they must be confirmed with measured data. A lysimeter with mature forest vegetation on it would be best, but this is technically very difficult to achieve. The best alternative is to equip a soil profile (or better several) under mature forest with tensiometers and TDR-probes at various depths to monitor changes in soil moisture content ( $\Delta WS$ ). In connection with the tension data and data on the hydraulic conductivity of the soil, one can then estimate how much of  $\Delta WS$  is due to evapotranspiration and how much due to drainage.

## 5 Conclusions

The exact determination of soil water balance parameters is the precondition for calculating the transport of pollutants to water resources. Water balance studies under natural conditions are quite rare. We carried out such a study under the conditions of the Atlantic Forest biome in southern Brazil using a drainage lysimeter at a grassland site and one at a forest site.

We were able to establish that the forest canopy intercepted a large portion of the incident precipitation so that much less rain reaches the ground than under grassland. The intercepted precipitation later evaporated from the canopy.

At <1% of the precipitation, runoff was not a significant factor in the water balance of the grassland or the forest in this environment.

Under grassland drainage amounted to about half of the incident precipitation, but under mature forest only to 17% thereof. There were two reasons for the latter: Interception kept 46% the precipitation from reaching the ground, and the actual evapotranspiration from the mature forest was much higher than from the grassland nearby.

In the continuation of this study a few things need to be improved: More rain gauges should be installed below the forest canopy to get more reliable interception data. Also, TDR-probes should be added to the lysimeters, because they yield more direct and therefore more reliable soil moisture content data than tensiometer values. The latter must first be converted to moisture contents with the help of soil moisture retention curves which are often erroneous. Furthermore, more attention should be paid to the determination of actual evapotranspiration from the mature forest. A promising approach is to equip several soil profiles in the forest with TDR-probes at various depth intervals.

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