Partitioning of evaporation fluxes in summer and winter using stable isotope approach

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ABSTRACT
Irrigation is the largest user of fresh water in the world. Unfortunately a large part of irrigation is unsustainable and inefficiently causing water scarcity with sometimes terrible effects on the water cycle, ecology, economy and food production. The key in determining the efficiency of irrigation is to investigate how much irrigation water is indeed used by crops for transpiration. Only this part of the total evaporation is used by crops to produce biomass and can be seen as productive evaporation. To separate evaporation into the productive (transpiration) and non-productive (interception and soil evaporation) terms we use stable isotopes ^{2}H and ^{18}O. This research investigates the changes of isotopic composition of stable isotopes ^{2}H and ^{18}O in the soil over the year in a lysimeter setup in the Netherlands. When the water balance is combined with isotopic values, an isotope mass balance can be made. This is used to separate evaporation fluxes and makes it possible to determine the transpiration flux of vegetation. During a six month period (November 2010 to June 2011) values of stable isotopes ^{2}H and ^{18}O in a lysimeter covered with grass were monitored. Furthermore, during a two month period (May and June 2011) a second lysimeter without vegetation was monitored to find out what the effect is of vegetation on isotope composition. When comparing the lysimeter with and without grass cover, it was found that transpiration plays no role in the non-covered lysimeter. In the latter, higher enrichment of soil water was observed and the isotope regression line had a lower slope. Isotope composition changes during the year. In winter (November to February) soil evaporation and isotopic enrichment were low. In summer (April to June) soil evaporation and isotopic enrichment were high. This research shows that it is possible to separate evaporation into soil evaporation and transpiration. During the cold period (December to February) the amount of transpiration was relatively high (75.0 % - 90.5 %) , since only limited soil evaporation could take place. When less water was available during warm periods (April and May), the share of transpiration in the total evaporation term decreased (47.3% - 53.4 %).

Keywords: Transpiration, evaporation, isotope mass balance

1. Introduction

In today's world most fresh water is used for agricultural means. For ages mankind is trying to invent more efficient ways of applying water to crops. In other words, minimizing water use and maximizing crop yields. Applied irrigation water can, simplified, be separated in two terms. Water is either used for productive or non-productive evaporation. Productive evaporation can be seen as water used by vegetation in order to produce biomass. Non-productive evaporation contains the fluxes that are not used by plants, i.e. interception and soil evaporation. Since productive evaporation is necessary for crop growth, most water savings can be obtained by decreasing non-productive evaporation. Therefore, it is important to understand how vegetation influences water fluxes and which processes are taking place. By doing this water fluxes that are not used by plants can be minimized (Wenninger et al., 2010) and hence water can be saved. Stable isotopes can be used to get an insight in evaporation fluxes.

Soil evaporation causes enrichment of the stable isotopes deuterium (^{2}H) and oxygen-18 (^{18}O) (Zimmermann et al.. 1967). In a soil sample, the stable isotope composition will therefore change due to soil evaporation, in contrast to transpiration, which does not cause enrichment of stable isotopes. Former studies by, for example, Williams et al. (2004) and Shichun et al., (2010) have shown that it is possible to partition evaporation fluxes, using the water balance, isotope mass balance or numerical models.

Until now performed studies where theoretical, or dealt with data series of a limited length (Sutanto et al., 2011). This study focuses on the partitioning of evaporation fluxes during a longer time series in different seasons. The objective of this

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research is two sided. Firstly, it is aimed to show the variation of partitioned transpiration and soil evaporation throughout the year. Secondly, the effect of vegetation on isotopic enrichment, and thus on transpiration and soil evaporation will be investigated. In this paper, the effect of interception will not be taken into account, because lies not within the scope of this research.

To gain insight in the seasonal variation of evaporation fluxes, a lysimeter covered with grass was installed and monitored. During the period from November 2010 to May 2011 water samples were taken and meteorological measurements were done in order to close the water balance and isotope mass balance within the lysimeter.

To investigate what the influence of vegetation on isotopic enrichment is, a second lysimeter without a vegetated cover was installed. In May and June 2011, water samples were taken from both lysimeters in order to make a comparison.

Using the isotopic values and combining them with the measured fluxes of the water balance, the total actual evaporation was partitioned into soil evaporation and transpiration. In this paper the results of evaporation flux separation are presented for the the period of November 2010 to May 2011. Furthermore the differences in isotopic composition between soil with and without vegetation are shown.

2. Methodology

Measurement Set-up

All measurement have been carried out with two lysimeters which were installed in the Botanical Garden of Delft University of Technology, the Netherlands. One lysimeter was constantly covered with grass, from which the grass roots reached a depth of approximately 10 cm. A second lysimeter was placed at a distance of approximately 1.5 m from the covered one and consisted of bare soil only. Both lysimeters were made from PVC pipes with an internal diameter of 20 cm and a length of 40 cm. Five soil moisture sensors (5TE ECH2O probes) and five Rhizon soil moisture samplers were installed with a center-to-center distance of 6.67 cm. To sample precipitation water, a manual rain gauge was placed on a distance of 1.5 m from both lysimeters to catch rainfall. After each sampling event, the manual rain gauge was emptied. Sampling events took place at irregular basis, as can be seen in Table 1. The manual rain gauge is not closed on top, so evaporation could take place. Therefore it could have been possible for the rain water to get enriched. However, during summer time the sampling frequency was increased, to limit the effect of enrichment of the precipitation water. From the grass-covered lysimeter water samples were taken from November 9th 2010 to June 25th and meteorological data was logged from November 9th to May 24th. The lysimeter with bare soil was installed later and samplers were taking from May 17th 2011 to June 25th 2011. Exact sampling dates per month can be found in Table 1.

Water samples from the soil were taken using 5 Rhizon soil water samplers, 1 Rhizon sampler was used to sample the percolation water and 1 Rhizon sampler was used to sample the groundwater. Precipitation was sampled directly from the manual rain gauge. An illustration of the measurement setup can be seen in Fig. 1.

Table 1. Sampling dates per month

	Sampling dates per month	
	Vegetated Lysimeter	Bare soil lysimeter
November	9, 12, 16, 19, 23, 26	
December	12	
January	4, 14, 20, 25	
February	3, 8, 15, 24, 25	
March	1, 7, 10, 18, 23, 29	
April	13, 26, 29	
May	11, 17, 20, 27, 28, 31	17, 20, 24, 27, 28, 31
June	7, 8, 9, 14, 15, 17, 20, 23, 25	7, 8, 9, 14, 15, 17, 20, 23, 25

Meteorological measurements

To be able to compare the results from the analysis with the climatological circumstances a HOBO Onset weather station was installed. This weather station measured temperature [Θ], wind speed at 2 m above ground level [LT^{-1}], incoming solar radiation [MT^{-3}], relative humidity [-] and precipitation [LT^{-1}], in order to calculate Penman-Monteith evaporation. All climatological variables were measured with an interval of 1 minute. The HOBO Onset weather station's tipping bucket was placed 2 meters above ground level. Since the Botanical Garden is irrigated on a daily basis, two extra tipping buckets (Decagon Devices ECRN-50 Rain Gauge) was placed (one next to each lysimeter) to measure the amount of precipitation (including irrigation water) on the water sample.

To close the water balance, a weighing device was installed underneath both lysimeters. Herewith it is possible to measure the percolation at the same interval. Both the HOBO Onset weather station as the percolation meter measured with a 1 minute interval.

Soil water monitoring and sampling

Water samples were taken to perform the isotope analysis. During every sampling event, five samples

where taken from the lysimeter, with a center-to-center distance of 6.67 cm. Extracting water was done using Rhizon water samplers. To extract water a vacuum was applied using a syringe. At the same depths as the water samplers, five 5TE ECH2O (Decagon Devices) sensors were installed as well. Every sensor measures the volumetric water content [-] and soil temperature [Θ]. The measurement interval is equal to the meteorological measurements, i.e. 1 minute.

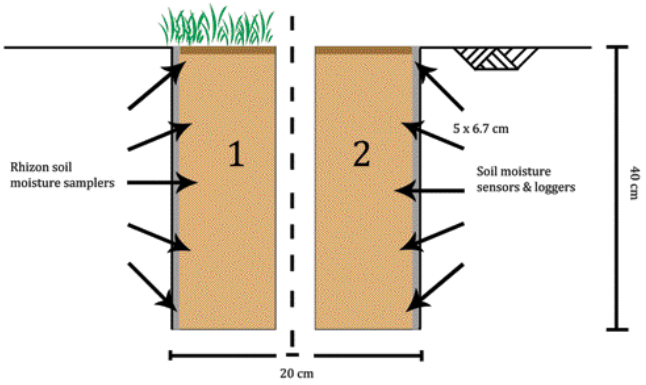

Fig. 1 Schematic drawing of the lysimeter

Isotope analysis

All water samples were analyzed at UNESCO-IHE using LGR liquid water isotope analyzer (LWIA-24d). The analyzer measured stable isotopes ^{2}H and ^{18}O in liquid water samples in a sample volume of maximum $10\eta l$. The accuracy of the analysis is $0.6^{0}/_{00}$ for ^{2}H and $0.2^{0}/_{00}$ for ^{18}O. Results are reported in δ values, which is the deviation from the Vienna Standard Mean Ocean Water (VSMOW) in per mil ($^{o}/_{oo}$).

Partitioning of evaporation fluxes

To separate total evaporation into transpiration and soil evaporation, we combine the water balance with isotope measurements. Using a simple mass balance as presented in Eq. 1 the actual total evaporation can be determined. As mentioned before.

$$\frac{\mathrm{d}S}{\mathrm{d}t} = P - P_e - E_{tot} \qquad [1]$$

$\mathrm{d}S/\mathrm{d}t$ is the storage change in the measurement sample, P is precipitation [LT^{-1}], P_e percolation [LT^{-1}] and E_{tot} the total evaporation [LT^{-1}]. After the last term is determined an isotope mass balance will be used to partition the evaporation in soil evaporation and transpiration. The total actual evaporation from Eq. 1 can be described as

$$E_{tot} = E_s + E_t + E_i \qquad [2]$$

With soil evaporation E_s [LT^{-1}], transpiration E_t [LT^{-1}] and interception E_i [LT^{-1}]. Interception is not taken into account and is equal to 0. We assume that water taken out by plant roots for transpiration is not affected by isotope fractionation until the water is leaving the plant through the stomata (Ehleringer and Dawson, 1992; Kendall and McDonnel, 1998; Tang & Feng, 2001; Riley et al., 2002; Williams et al., 2004; Balazs et al., 2006; Gat, 2010). Evaporated water from the soil is affected by isotope fractionation. Eq. 3 – 7 show the isotope mass balance that will be used.

$$m_i + m_r = m_v + m_f + m_t + m_z \qquad [3]$$

$$x_i\delta_i + x_r\delta_r = x_v\delta_v + x_f\delta_f + x_t\delta_t + x_z\delta_z \qquad [4]$$

In which m represents the mass of water of each component [M], δ represents the $\delta^{18}O$ value of each component [$^{0}/_{00}$ VSMOW] and x is the fraction of the water amount in a component related to the total water amount of the investigated system [-].

All subscripts represent a component within the system. i is the initial soil water, f is the final soil water, r is the precipitation, v the evaporation, t the transpiration and z the percolation.

The isotopic composition of transpired and deep percolated water are not affected by isotopic fractionation. These two terms can be combined as the non-fractionation term x_{nf} see Eq. 5.. The isotopic content of these terms is equal to the average δ value of the soil water over the time interval (δ_i and δ_f) (Robertson&Gazis, 2006), see Eq. 6 – 7.

$$x_{nf} = x_t + x_z \qquad [5]$$

$$\delta_{nf} = \delta_t = \delta_z \qquad [6]$$

$$\delta_t = \delta_z = \frac{(\delta_i + \delta_f)}{2} \qquad [7]$$

If the isotopic value of the transpiration water (δ_t) is assumed as a mixture of initial soil water (δ_i) and precipitation water (δ_r), the unknown fraction of the evaporated water (x_v) and transpiration water (x_t) can be calculated as:

$$x_v = \frac{x_i \delta_i + x_r \delta_f - (x_t + x_z)\delta_z}{\delta_v} \qquad [8]$$

and

$$x_t = x_r + x_i - x_v - x_f - x_z \qquad [9]$$

3. Results

Isotope composition in winter and summer

In Fig. 2 a – h the composition of stable isotope ^{2}H is showed from November 2011 to February 2011. November to February is accounted as winter, March as spring and April to June as summer. At every sampling date water samples were taken at five different depths. In Fig. 2 a-h the isotope value is plotted against the depth. Furthermore, the isotope values for both rain and percolation are plotted in the graphs as well.

It can be seen in Fig. 2 a – h that the composition strongly varies per month. In the winter months (i.e. November to February) the isotope values in the deeper layer (z = -20 to -35 cm) remain quite constant. In the top part of the soil the water has rather high values. Evaporation is low during this period of the year, which prevent the sample to get enriched. What is remarkable is the enrichment at a depth of 20 cm. Especially in December to February, highly enriched values occur around this depth.

In the summer months (i.e. April to June) evaporation is higher. From the isotope values this can be seen, since water in the upper soil layers is enriched. This process takes mainly place in the upper part of the soil, although in May and June it can be seen that water is getting enriched in lower layers as well.

Besides evaporation, precipitation has a significant influence on the isotope composition. After a rainfall event the isotope values in especially the top layer is heading towards the precipitation's value, in case of a rainfall event. This phenomenon was observed the best in November, January, February, April and June.

In Fig. 3 a the precipitation and temperature over the measured period are shown from November 6th 2010 to May 11th 2011. In Fig. 3 b - g the ^{2}H and ^{18}O values of precipitation, percolation and in the soil in are plotted against time and depth. Isotope samples were taken from the precipitation, the percolation and five points over the depth, which are interpolated to get a clear graphical image. Similarly as in Fig. 2 a – h varying values can be seen over time. In November to mid-February high isotopic values can be found around 20 cm depth, indicated with A. At the top layer, the isotopic values are low during winter and high during summer, indicated with B. Furthermore it can be seen that the isotopic values of precipitation changes as well. In the winter isotopic values are lower in contrary to summer in which the isotopic values are higher.

In Fig. 3 h the soil moisture content are plotted against time. At 5 sampling points the soil moisture content was measured and to get a clear image these values are interpolated over the depth. At the top layer the soil moisture content is quite high until March, from April on the soil moisture content decreases (point B, z = -5 cm). Around 20 cm below ground level the soil moisture content is low compared to the top layer, until March. Starting in April, the soil moisture content decreases more and reaches a value similar to the values at the top layer.

Deuterium excess

From the isotope values the deuterium excess is calculated and plotted against time. Deuterium excess can be calculated using

$$d = \delta^2\mathrm{H} - 8 \cdot \delta^{18}\mathrm{O} \qquad [10]$$

Were d is deuterium excess. The result is showed in Fig. 3 i. According to the Global Meteorologic Water Line as described by Craig (1961) , for average water in the world the deuterium excess is 10. When soil evaporation plays an important role in the soil, more enrichment will take place, leading to a lower slope of a drawn regression line. Therefore, the deuterium excess will be lower. Remarkable is that the spot around 20 cm depth in the first 100 days (A), and the spot around day 180 at the upper layer (B), can be found again in Fig. 3 e.

Bare soil versus vegetated soil

In Fig. 4 a – d the isotope values of the five sampling points at the measuring dates in May and June are plotted against depth. It can be seen that there is a difference between isotope composition in vegetated lysimeter and in bare soil lysimeter.

According to theory water should get more enriched in an environment where soil evaporation is a more important process than transpiration. As explained, soil evaporation causes stable isotope enrichment. Transpiration does not cause enrichment.

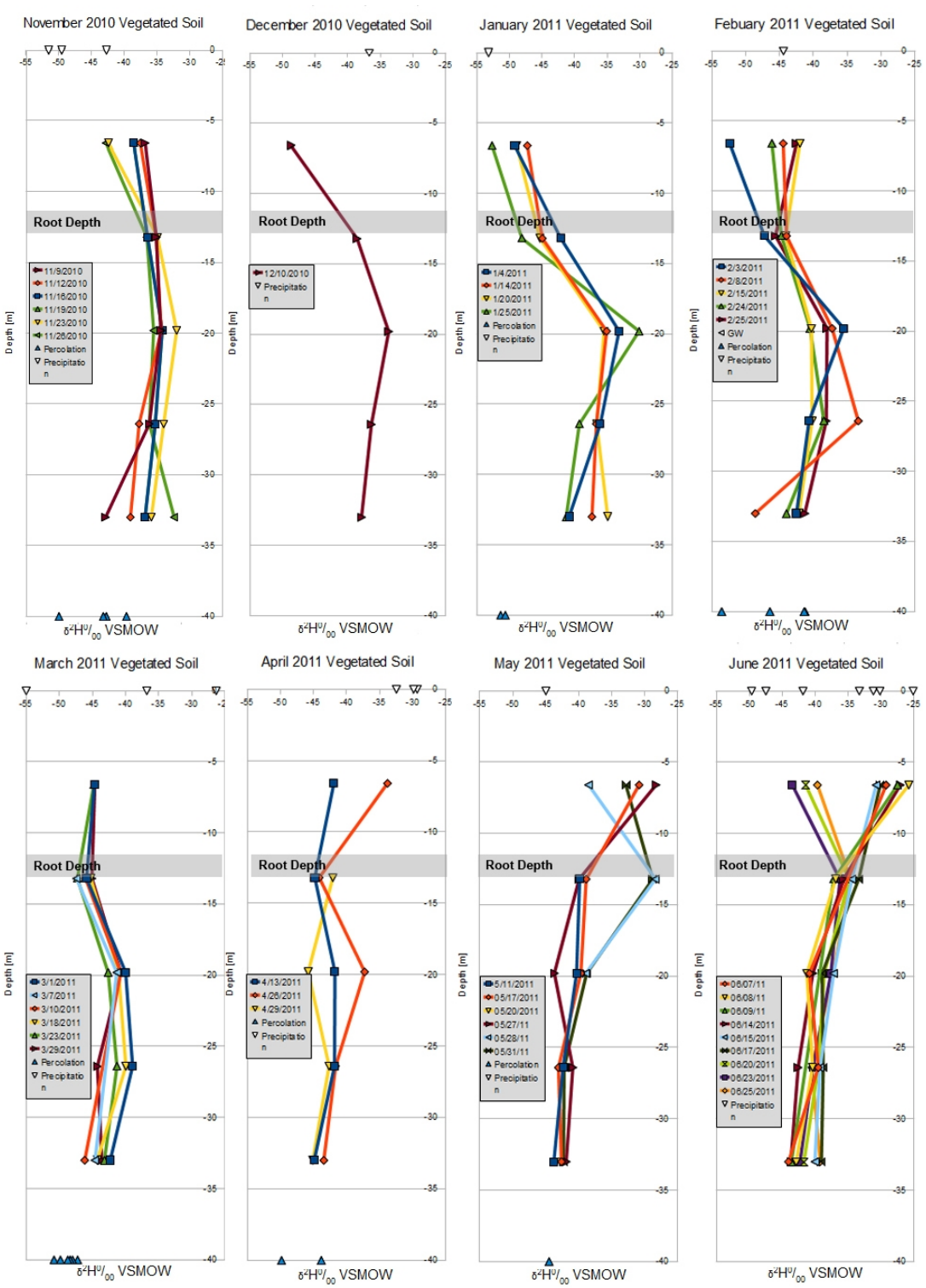

Fig. 2 Isotope profile of ^{2}H in November (a); December (b); January (c); February (d); March (e); April (f); May (g) and June (h)

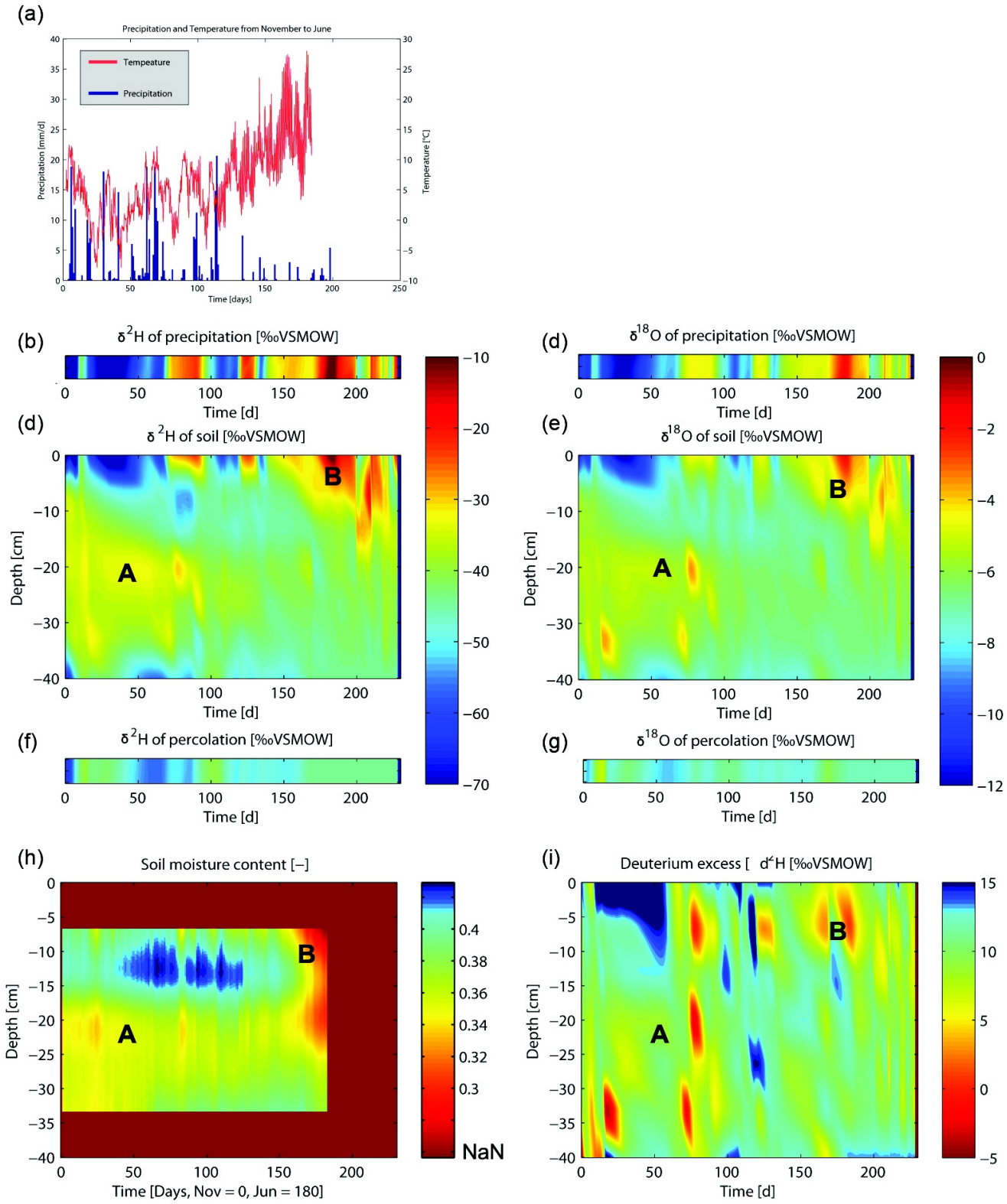

Fig. 3 Precipitation and temperature over time (a), Deuterium values of precipitation (b), soil sample in time (c) and percolation (d), Oxygen-18 values of precipitation (e), soil sample in time (f) and percolation (g), Soil moisture over time (h) and Deuterium excess over time (I). Day 1 is November 9, 2011, day 225 is June 22, 2011

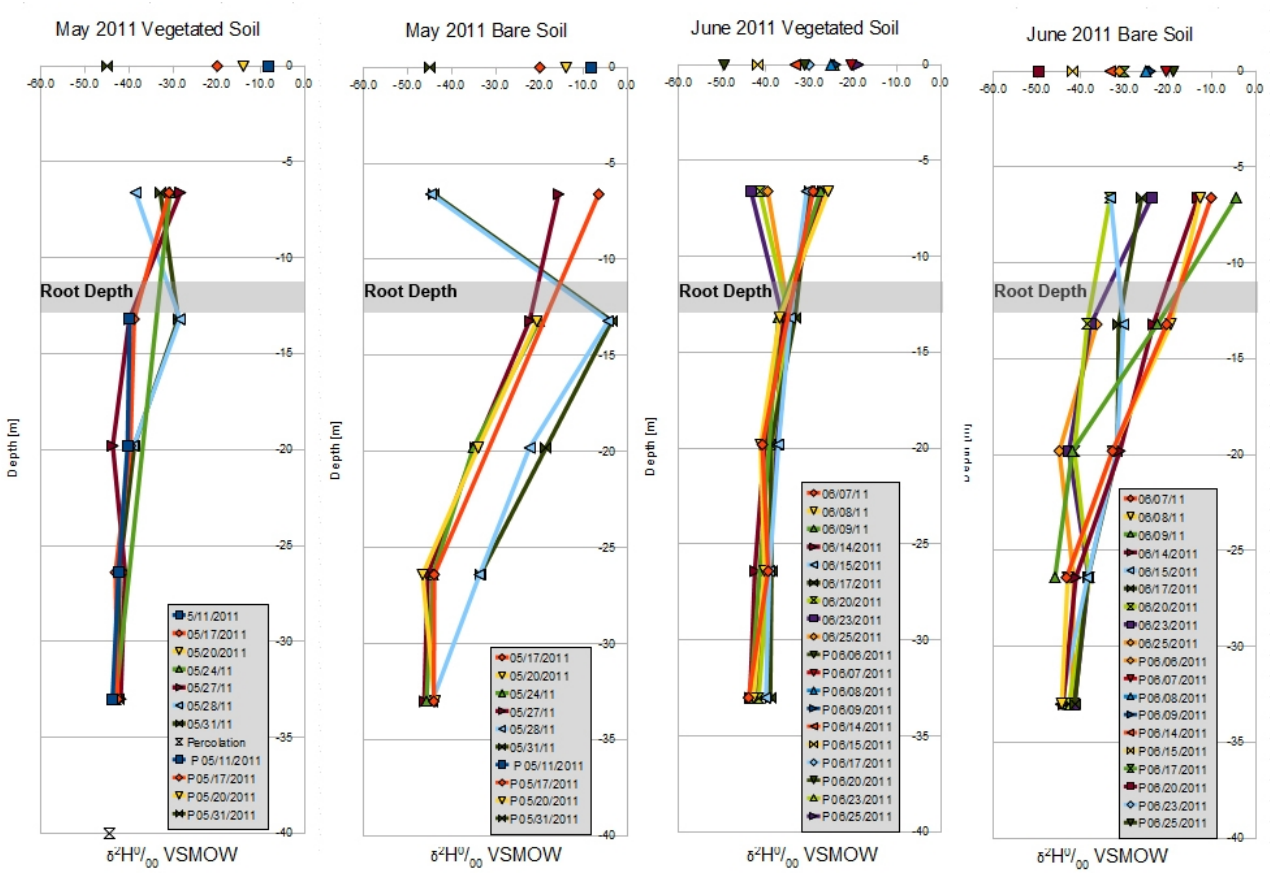

Fig. 4 Isotope profile of vegetated soil in May (a) and bare soil in May (b), vegetated soil in June (c) and bare soil in June (d)

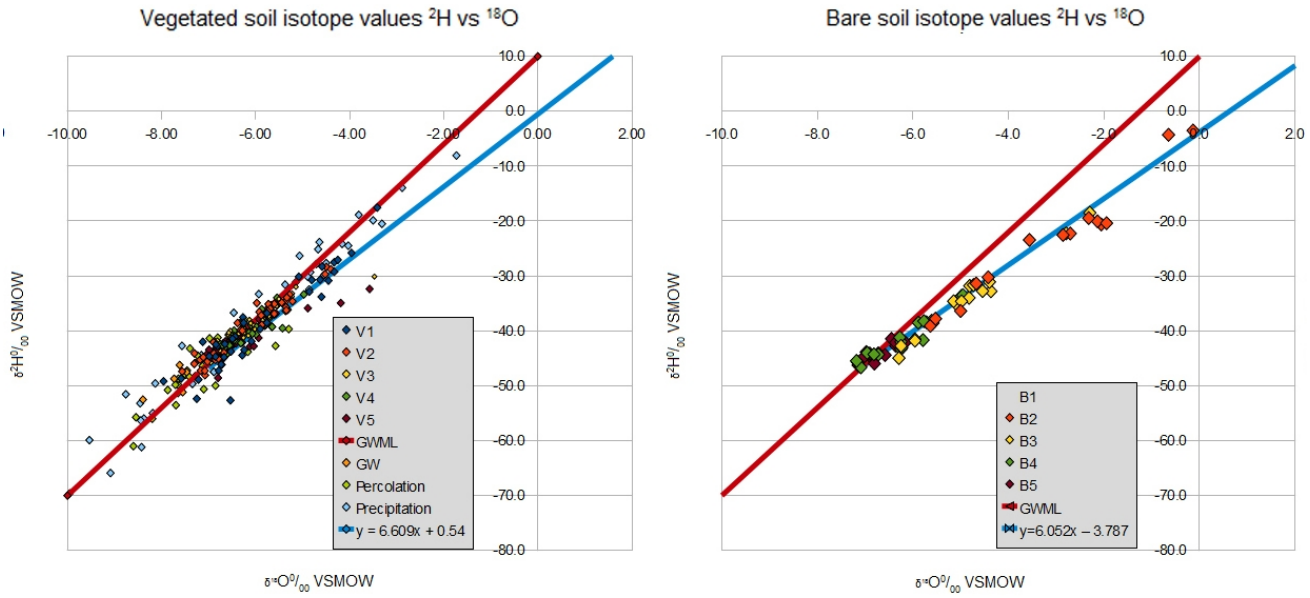

Fig.5 Vegetated soil isotope values (a) and bare soil isotope values (b), V 1 – 5 corresponds with sampling points (1 is closest to ground surface, 5 is the deepest) of vegetated lysimeter, B 1 – 5 corresponds with the bare soil lysimeter sampling points

Table 2. Calculated and measured fluxes per month of the vegetated lysimeter, precipitation P [LT^{-1}], percolation P_e [LT^{-1}], potential evaporation E_p [LT^{-1}], soil evaporation E_s [LT^{-1}], actual evaporation E_{act} [LT^{-1}], transpiration T [LT^{-1}], measured change in storage dS/dt [LT^{-1}], residual flux [LT^{-1}] and average monthly temperature T_{av} [Θ]

	dS/dt Measured	P	P_e	E_p	E_{act}	T		E_s		Residual Flux	T_{av}
	[mm/month]	[mm/month]	[mm/month]	[mm/month]	[mm/month]	[mm/month]	% of E_{act}	[mm/month]	% of E_{act}	[mm/month]	[°C]
November*	-3.9	67.8	7.5	4.2	3.2	2.1	67%	1.0	33%	59.4	4.8
December	1.5	50.2	20.0	4.1	1.5	1.1	75%	0.4	25%	27.2	0.2
January	-3.6	88.4	144.4	5.2	1.5	1.4	90%	0.1	10%	-54.0	4.3
February	1.8	72.8	142.5	10.0	1.4	1.2	86%	0.2	14%	-72.9	5.1
March	0.4	15.0	78.1	30.6	2.3	1.7	74%	0.6	26%	-65.8	6.9
April	-21.7	8.2	2.2	60.1	25.3	12.0	47%	13.3	53%	2.4	13.5
May**	-8.5	12.6	0.0	40.9	17.2	9.2	53%	8.0	47%	3.9	14.2

* 11 – 30 November
** 1 – 24 May

In the vegetated lysimeter transpiration has a higher share in the evaporation flux, which means that there should be less enrichment. In the graphs it is showed that water in bare soil lysimeter is indeed more enriched. Not only in the upper layer of the soil, but over the entire depth the values are higher than in the vegetated lysimeter.

Furthermore it can be seen that after a rain event, the bare soil lysimeter adjusts itself sooner to the precipitation's isotope value than the vegetated lysimeter.

In Fig. 5 a – b the isotope values for ^{2}H are plotted against the value for ^{18}O for both the bare and vegetated lysimeter. To make a valid comparison, the regression line for the vegetated lysimeter is drawn through the values of May and June only. Consequently the same sampling days are used for the vegetated and bare soil. In both figures the Global Meteoric Water Line has been plotted as well. The line shows the average ratio between deuterium and oxygen-18 in natural water. When isotope values are plotted together with the Global Meteoric Water Line, it can be seen to which extend water has been enriched. In other words, the lower the slope, the more the water samples are enriched.

For both measurement setups a regression line throughout all points was made in order to determine the fractionation. The following regression lines could be found:

Vegetated Soil:

$$\delta H^2 = 6.05 \cdot \delta O^{18} - 3.8$$
$$R = 0.96$$

Bare Soil:

$$\delta H^2 = 6.61 \cdot \delta O^{18} + 0.54$$
$$R = 0.94$$

Water balance and partitioning of evaporation fluxes

In Table 2 soil evaporation, transpiration, precipitation, percolation and soil storage change are shown per month. It can be seen that the amount of total evaporation is about the same from November to March. The amount of precipitation is very low in March, April and May, compared to December to February. Furthermore, almost no percolation was measured in April and May. However, in January to March very high amounts of percolation were measured.

The total evaporation was determined using a simple water balance as presented in Eq. 1. For every day the potential and actual evaporation were calculated. Is was assumed that the actual evaporation (E_{act}) could not be higher than the potential evaporation (E_p). E_p was therefore used as a upper boundary for E_{act}. During many days the calculated E_{act} was higher that E_p. Therefore the water balance was not closed. In Table 1 the calculated residual flux is shown. In November and December there was a positive residual flux and in January to March a negative residual flux was found.

During abstraction of water for the isotope analysis, it was observed that in April and May sometimes large quantities of water were abstracted. This term has not been taken into account in the water balance and could be a source of error and disturbance.

Partitioning of evaporation fluxes was done using the isotope mass balance as presented in Eq. 3 – 9. Table 2 shows the results for the period from November to May. It can be seen that the percentage of transpiration decreases in time. In April and May the share of transpiration in the total evaporation is lower than in November to March.

4. Discussion

Around 20 cm depth high isotopic values could be found during November to February (point A in Fig. 3 d, e, h & i). It shows that evaporation has an effect until 20 cm depth. The maximum isotope value is called the drying front. This process can be caused by kinetic effects of diffusion (Kendall and McDonnel, 1998; Clark and Fritz, 1997; Sutanto et al, 2011). The shape of the isotope profile from surface to 20 cm depth is caused by vapor diffusion. From 20 cm depth to 40 cm depth the profile is caused by downward diffusion of isotopes. Furthermore, a quite low soil moisture content and deuterium excess was measured. This indicates soil evaporation. Besides soil evaporation during that period, the high values can also be the result of enriched water that infiltrated from the upper layer to the lower layers.

When the isotopic values from Fig. 3 b - g are compared to the soil moisture from Fig. 3 h, it can be seen that there is a relation between isotopic value of soil water and the soil moisture content. Especially in the first 100 days it can be seen that the soil moisture content and isotopic values show familiar patterns. Probably the decrease in soil moisture is caused by evaporation, resulting in enrichment in these very soil layers. Hence the water remaining get heavier. Furthermore the graphs are comparable around May, day 180. Temperature is rising, causing more soil evaporation. This can be seen in Fig. 3 d & e, where enrichment is taking place (point A). A similar image is shown in Fig. 3 h, where a low soil moisture content is the result of soil evaporation. However, it is not only soil evaporation that causes a decrease in soil moisture content. Although transpiration can not accounted for isotopic enrichment, it is a source of water use and does cause a decrease of soil moisture content. Nevertheless, it seems likely that at a moment when soil moisture content is decreasing, water is evaporating and the remaining soil water is getting enriched.

Isotopic values correspond with the precipitation's isotopic values. There are two explanations for the increase of isotopic values at the lop layer. Firstly, it can be because of the enrichment caused by high temperatures during summer and thus a higher soil evaporation flux. Secondly, the isotopic values of precipitation change during the year and thus influence the isotopic value of the top layer.

In Fig. 3 i it can be seen that in periods and locations where soil evaporation was taking place, concluding from isotope enrichment and low soil moisture contents, the deuterium excess was indeed lower than average. This was expected from theory, which states that a low deuterium excess value should indicate soil evaporation.

From theory it was expected that in the bare soil sample more water would evaporate from soil evaporation and would thus be more enriched. This can indeed be seen in Fig. 5 a & b, were the slope of the isotopic values for bare soil is lower than the slope of the isotopic values of vegetated soil. From this it can be concluded that more soil evaporation takes place in the bare soil sample in contrary to the vegetated soil sample, where transpiration has a greater share in the total evaporation.

In a soil sample it is expected that the water in the upper layers will evaporate sooner than the water in lower layers. In the upper layer water is close to ground level and it takes therefore less energy to have it evaporated. Also, no water is necessary for transpiration. Keeping in mind the isotope composition, it can be expected that also within a soil sample there exists a difference in enrichment over the depth. The graphs indeed show that this difference of enrichment exists between the several soil layers. In the top layer the water is more enriched, which point at higher soil evaporation in the upper layers. This can be seen in both the bare soil and vegetated soil graphs. However, the in vegetated lysimeter high isotopic values were found around 20 cm depth. This is explained by kinetic effects of diffusion.

In Table 2 the results of the evaporation fluxes partitioning was shown. An interesting point is the fact that the during most months the water balance was not closed. In November, December, March and May a positive residual flux was found. For November and December this might be caused by snowfall. Snowfall was measured as precipitation by the tipping bucket, but might not have infiltrated in the soil. In January to April a negative residual flux was found. This could partly be due to melted snowfall from previous months that infiltrated. However, in March and April this is not considered plausible. Another explanation could be irrigation water from the Botanical Garden. Despite the placement of the rain gauge next to the lysimeter, there might be a possibility that irrigation water was applied onto the lysimeter without being gauged as rainfall. In April and May a positive residual flux was found. This can be explained by the fact that a larger quantity of water was abstracted, which lead to an extra (ungauged) outgoing flux in the water balance. Furthermore, interception was not taken into account, which in many cases can be a substantial term in the water balance. The water balance as assumed might not have been appropriate since large errors were found.

In Table 2 it can be seen that in April and May the share of transpiration was lower than in November to March. This can be explained by the fact that in April and May the temperature was higher than in the previous months, causing more soil evaporation. What is remarkable as well is that the total amount of evaporation in April and May is comparable to the amount in November to January. A probable explanation is that during April and May less water was available to evaporate and/or transpire, which is backed by the very low amounts of precipitation in April and May. Furthermore, the registered amount of percolation was very high in January to March. This resulted in a low amount of water left in the soil to be used for evaporation. Because of snow fall in the winter, it is possible that high percolation rates were caused by melting snow. Unfortunately the snow cover on the lysimeters was not measured. High amounts of percolation can also be caused by malfunctioning equipment. Percolation rates measured do not seem likely for the size of used lysimeter.

An aspect that needs further attention is investigating how water can be abstracted without influencing the soil sample. In this study it is assumed that the amount of water abstracted would not have a significant influence on the soil moisture and/or isotopic composition. Though, by applying a syringe to create a vacuum, it is likely that the soil sample will be disturbed, especially during longer periods of abstraction. This was observed by large quantities of water were sometimes abstracted by the syringe.

Another critical error can be the absence of registration of how much water was abstraction during every sampling event. The consequence is that the water balance can not exactly be determined. If an amount of water is abstracted another loss term should be added to the water balance. This was not done in this research, but would be advisable in further research. In addition to that, a point of improvement would be to have a controlled abstraction method. In this research the amount abstraction was quite arbitrary. A result is that during some sampling events more water was taken out than necessary, leading to unnecessary disturbance of the soil. Another solution in order to decrease the impact of water abstraction is to enlarge the sampling area. If the lysimeter would be significantly larger, the relative amount of water taken out is smaller, creating a smaller disturbance in the soil.

5. Conclusions and recommendations

Isotope composition changes over the months. In months with relative little soil evaporation (November to February) fractionation cannot take place, causing isotope values to stay quite low. In the warmer months (April to June) soil evaporation increases. Regarding isotope values, especially in the upper layers, this can clearly be seen. Soil water becomes enriched and isotope values increases. A clear relation can be seen in the precipitation isotope values and the isotope composition over time. After a rain event it could be observed that the isotope values in the soil are strongly influenced by the precipitation.

Besides a relation between precipitation and isotope composition, a strong link can be made between soil moisture content and stable isotope values. A decrease in soil moisture content can indicate soil evaporation, causing isotopic enrichment. Water indeed became heavier in this case, as could be observed in Fig. 3 b – i.

The deuterium excess was calculated for the measured period, to act as an indicator for soil evaporation. In the case of soil evaporation and thus isotopic enrichment of water, the deuterium excess was indeed lower.

Concluding it can be said that soil evaporation leads to a lower soil moisture content, more enrichment of stable isotopes in soil water and a higher value for the deuterium excess.

When comparing soil with and without vegetation, differences can clearly be seen. In the isotopic values this could be seen, since the bare soil experienced higher enrichment of soil water. Secondly the regression line of the bare soil has a lower slope, indicating more soil evaporation.

With the used theory and equations it was possible to separate the evaporation flux into soil evaporation and transpiration. This showed that when little water is available during warm periods, the share of transpiration in the total evaporation term decreases. The validity of these results can however not be expressed, because we noticed some problems with taking soil water samples. The influence of water abstraction was not studied, which is recommended to do in further research.

The water balance could not be closed, causing an error in the separation of evaporation fluxes. In this research a simple water balance model was used, which only describes the measurements and did not contain any predictive aspects. Furthermore, interception and water abstraction for isotope analysis was not included in the water balance. For accurate results it is recommended to include these terms in the water balance.

Further research is recommended with a more complex model, taking into account the interaction

within the soil sample. In this water balance model the soil was seen as a whole, while it might be better to divide the soil into multiple layers.

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