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RESEARCH ARTICLE

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Seasonal evaporation cycle in oxbow lakes formed along the Tisza River in Hungary for flood control

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Abstract

As a result of water regulation, dykes (i.e., embankments against floods) were constructed along the Tisza River and meanders were cut to control the floods in the region. These cut-off meanders resulted in oxbow lakes that are important locations for nature conservation. We collected water samples over 5 years in 7 campaigns to measure the δ^{18}O (‰) and δ^{2}H (‰) ratios in 45 oxbow lakes from the Upper Tisza Region (NE-Hungary). We applied Random Forest Regression involving climatic data to reveal the connection with the stable isotopes. We determined that isotope ratios changed as a function of time, due to evaporation and a varying water supply (precipitation and groundwater). The average difference in the isotopic ratios for the river and oxbows increased from spring to winter, but decreased between the oxbows on both sides of the dyke. We found that isotope ratios were determined by the maximum monthly temperature in the case of oxbows in the active floodplain, whereas in case of oxbows on the reclaimed side, this was also influenced by the maximum monthly temperature, and the cumulative evaporation. As direct measurement of evaporation is difficult to evaluate, stable isotope measurements provided an effective quantitative alternative to estimate evaporation. Measuring the seasonality of the δ^{18}O and δ^{2}H is important to interpret the results and these data are useful to water management experts to identify the lakes at risk of running dry.

KEYWORDS

CarpatClim, oxbow lake, random forest regression, stable isotope ratio, Tisza River

1 | INTRODUCTION

In the 21st century, water is a strategically important resource in all countries of the world (Hering et al., 2010). Rivers represent a crucial factor in the distribution of the population and any stress (either natural as climate change or anthropogenic) increases the risk of a social crisis (Vörösmarty, Green, Salisbury, & Lammers, 2000). Both the quantity and the quality can be exploited through irrigation (Cai, McKinney, & Rosegrant, 2003), which can endanger drinking water (Fick et al., 2009) or ecological state (Nilsson, Reidy, Dynesius, & Revanga, 2005). It is important to find the level at which this exploitation affects rivers only to a restricted extent, so as not to endanger their multifunctional role or to disturb the operation of their environment.

Hungary, in the middle of the Carpathian Basin, is well supplied with water, but as 96% of Hungary's surface water originates in surrounding countries, these water sources are affected by the environmental consciousness and water management practices in those countries (Barreto et al., 2017; Szűcs, Kompár, Palcsu, & Deák, 2015). The River Tisza is considered one of the most natural river valleys in Europe. The river is a significant factor in Eastern Hungary's natural landscape and, at the same time, it is exploited in several ways (e.g., for water management, irrigation, fishing, recreation, and cooling water). In addition to the river itself, oxbow lakes (both natural lakes and ones formed due to 19th–20th century flood-control projects) constitute significant natural and nature conservation resources and contribute to stabilizing ecological corridors. Oxbow lakes near the Tisza have received more attention, partly due to problems related to flooding, cyanide, and heavy metal contamination (Balogh et al., 2016; Donato et al., 2007; Nguyen et al., 2009; Tamás & Farsang, 2011), and partly due to their role in nature conservation, water management, and the preservation of landscapes (Guida, Swanson, Remo, & Kiss, 2015; Pálfai, 2001; Szabó, Vass, & Tóth, 2012).

The experience in other controlled floodplains around the world is similar to the Tisza, with flood control affecting many other aspects of the local environment (Dévai et al., 2001; Kerényi & Szabó, 2007; Négrel, Petelet-Giraud, Barbier, & Gautier, 2003; Ortmann-Ajkai, Lóczy, Gyenizse, & Pirkhoffer, 2014; Schindler et al., 2016). A change in the state of an oxbow lake can cause problems over a wider area; therefore, it is important to know the state, water balance, and the factors influencing the quality, and how the relative location affects the water supply. Oxbows can be in different states of natural succession (Dévai et al., 2001), which is a function of water supply (from precipitation and floods) and the aggradation of suspended sediments transported by floods, because oxbows in the floodplain are exposed to significant sediment accumulation (Korponai et al., 2010). For oxbows outside the dyke (i.e., where floods are not expected to occur), rainfall and underground seepage through permeable layers of paleo river channels are the only sources of water supply. The decreasing water table in this area can also lead to a reduction of water in oxbow lakes (Pálfai, 2001).

There are many methods used to examine the water balance of different lakes, but a great challenge is the exact identification and quantification of the input sources and the magnitude of evaporation as these environmental variables cannot be measured directly. We can only estimate these volumes, such as the volume of rainfall falling in the catchment, and it is difficult to estimate the size of the watershed in floodplains where even the smallest topographical barriers can change the runoff. It is also difficult to determine the evaporation rate from the water body (i.e., usually only temperature data is available but relative air humidity and wind speed are also important, thus, only potential evaporation can be calculated with relevant bias) and the level of subsurface input or output. One of the possibilities to quantify the state of water bodies is the analysis of ^{18}O and ^{2}H stable isotopes. These isotopes are tracers for the sources and movement of water, because they are essential constituents of water molecules (e.g., Coplen, 1993; UNESCO/IAEA, 2000). Examining δ^{18}O (‰) and δ^{2}H (‰) helps to establish the age and origin of waters and also the magnitude of evaporation, because δ^{18}O (‰) and δ^{2}H (‰) values alter proportionately (increasing or decreasing) in natural waters (UNESCO/IAEA, 2000). This is an exact and repeatable approach, and knowing the seasonal cycles, it is also appropriate for a long-term monitoring, including the assessment of the consequences of climate change on oxbows.

Oxbows usually are shallow lakes with about 1–3 m average depth and about 10–15 ha area in Hungary (Pálfai, 2001). Water balance determines the existence of these lakes, thus, a lag in the timing of floods can eliminate the shallowest ones, whereas for larger and deeper lakes, the water table can decrease significantly, which has a detrimental impact on water quality and living organisms. Future climate scenarios generally predict 3–4 °C increase in temperature for the Carpathian Basin, which would mean up to 8–9 °C for the summer period (Bartholy et al., 2009), which would endanger the existence of oxbows and change the managed ecosystems of the floodplains.

In Babka, Futó, and Szabó (2011), we began a stable isotope-based analysis of the oxbow lakes in the Upper Tisza Region, but this work was restricted to finding the potential sources of their water supply: had water supply from precipitation or the Tisza River; and there was subsurface infiltration. However, the seasonal cycle and regularity was not studied, although these are also important issues in the long-term lifespan of oxbow lakes. We measured the isotope composition (δ^{18}O (‰) and δ^{2}H (‰)) of water samples taken from the Tisza River and the neighbouring oxbow lakes. We focused on the changes of stable isotopes in the oxbow lakes in different seasons. We aimed (a) to test whether a seasonal pattern in evaporation can be identified; (b) to reveal the influencing climatic factors of the changes of stable isotopes; and (c) to show whether the evaporation can be predicted or quantified from the stable isotopes. This can provide better information about the water supply of the oxbow lakes and which can help in their preservation.

2 | MATERIALS AND METHODS

2.1 | Study area

The total length of the River Tisza is 966 km, of which 596 km is situated in Hungary. Its discharge ranges between 170 and 3,400 m^3/s (low and high flow conditions), and the annual average is 500–800 m^3/s (Barreto et al., 2017; Lászlóffy, 1982). Seasonal floods occur at the end of the winter and occasionally in the early summer. The 19th century river control projects had a remarkable impact on the river: around 100 meanders were cut to assure shipping and flood control. The length of the river decreased and the floods were able to run off more quickly. As a result, many artificial oxbow lakes formed, but formerly natural meanders are also present in the floodplain. As part of the regulation, ~3,000 km of defensive dykes were built (Lászlóffy, 1982), dividing the floodplain into an active floodplain and a reclaimed side (Figure 1). Oxbow lakes are located on both sides of these dykes; **F1** that is, on the active floodplain (between the dyke and the river) and on the reclaimed side (outside the dyke). Many of the cut-off meanders have already filled up and run dry. They have water in their shallow beds only after heavy rainfall and floods (Wittner et al., 2004).

Usually, there are two floods in the River Tisza: first, after the melting of the winter snow and second, at early summer due to heavy rainfalls. The river inundates the floodplain between the dykes, and fills and renews the water of the oxbow lakes located in the area (Szalai et al., 2005; Türk, Bertalan, Balázs, & Fehérné Baranyai, 2016). However, without additional water supply from precipitation or subsurface infiltration through the permeable layers of the old river beds, shallow lakes can run dry. Input sources of oxbows have not been previously studied in the case of the River Tisza, although an understanding of the water supply of the oxbow lakes is of vital importance to this area due to the ecological (habitats and ecological corridors), economic (fishing), and social (recreation) role of the lakes (Kerényi & Szabó, 2007; Ortmann-Ajkai et al., 2014). For this reason, we examined the stable isotopes of the oxbow lakes and the River Tisza.

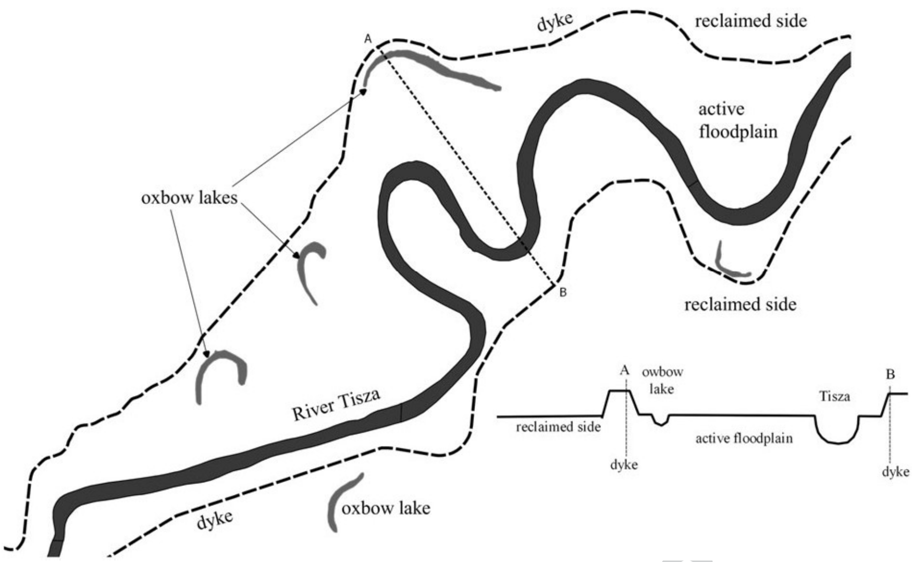

FIGURE 1 A floodplain and its regulated environment in case of River Tisza

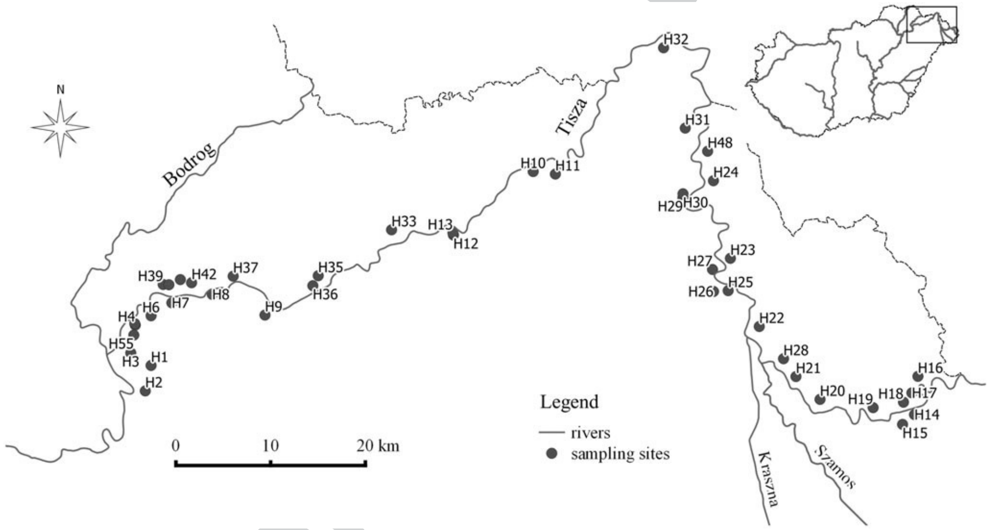

FIGURE 2 Location of the study area and the sampling points in the Upper Tisza region

The study area is located in the Upper Tisza Region (Figure 2) and there are more than 90 oxbow lakes between the Hungarian–Ukrainian frontier (Tiszabecs) and Tokaj city. Oxbow lakes of this region are situated both in the floodplain (around 80%) and reclaimed sides (less than 20%). The floodplain is a natural reserve and also a MAB, Man and Biosphere Program (2018) network core area.

2.2 | Collection of water samples

Our goal was to perform at least two sampling campaigns in the spring, summer, and autumn seasons during our investigations. Accordingly, samples were taken in October 2005, May 2006, August 2006, November 2009, March 2010, July 2010, and August 2010. On these occasions, surface water samples were taken from 45 oxbow lakes (12 from the reclaimed side, 33 from the floodplain) and from 7 different locations on the Upper Tisza River (Figure 2). All samples were collected 3 m from the shores of the water bodies from a depth of 0.2–0.3 m. We took one average sample (from three different places) from each oxbow because these are shallow lakes without stratification. We were not able to sample each oxbow lake in each sampling period, because of changing environmental conditions: after a dry period, shallow oxbow lakes ran dry.

2.3 | Stable isotope analyses

Isotope analytical examination was carried out on the samples. The stable isotope ratios (δ) were measured with a Thermo Finnigan DELTA^{plus}XP mass spectrometer in the Isotope Climatology and Environmental Research Centre (ICER) at the Institute for Nuclear Research, Hungarian Academy of Sciences. The δ^{18}O (‰) and δ^{2}H (‰) were measured; the uncertainty of the stable isotope results was $\delta\ ^{18}$O: ±0.2 ‰, δ^{2}H: ±3 ‰.

Stable oxygen and hydrogen isotopes behave conservatively in most low-temperature environments. The main processes in a catchment area that determine the oxygen and hydrogen isotopic compositions of water are the phase changes that influence the water above or near the ground surface (melting of the snow, evaporation, and condensation), and simple mixing at or below ground surface (e.g., Clark & Fritz, 1997; Cook & Herczeg, 2000; Fontes & Edmunds, 1989; Kortelainena & Karhu, 2004; Mazor, 1997; Négrel et al., 2003; UNESCO/IAEA, 2000). These changes are very small, but can be detected with a specialized mass spectrometer. They are presented as δ values in the unit of measurement of parts per thousand (‰) enrichments or depletions relative to a standard. The Vienna Standard Mean Ocean Water (VSMOW) is the internationally accepted standard in the case of O and H.

The ^{18}O and ^{2}H contents of meteoric waters are well correlated (Craig, 1961). The δ values of the precipitation are aligned along a Meteoric Water Line, whose global average is $\delta^{2}H = 8\ \delta^{18}O + 10‰$ and described by the Global Meteoric Water Line (GMWL). The Local Meteoric Water Line (LMWL) depends on regional water sources and also reflects seasonal conditions. The $\delta^{2}H$ and $\delta^{18}O$ values of evaporating lake water produce a line with a smaller slope than the LMWL (Turner, Wolfe, & Edwards, 2010; Vandenschrick et al., 2002). Yi, Brock, Falcone, Wolfe, and Edwards (2008) concluded that in the case of numerous shallow lakes in the Peace-Athabasca Delta wetland complex (northern Alberta, Canada), the melting of the snow, river water, and rainfall are the most important water supplies. These sources can be differentiated on the basis of the position of the isotope ratios along the LMWL and GMWL. LMWL refers to the local precipitation origin, but GMWL refers to waters originating from the River Tisza that has a much larger (more global) catchment area. The LMWL was calculated from isotope ratio-means of monthly precipitation in Debrecen between May 2005 and August 2010 (Vodila, Palcsu, Futó, & Szántó, 2011) and is valid for the Upper Tisza Region because of the short distance (around 100 km) between the two areas.

2.4 | Climatic data

The CarpatClim database uses different variables (monthly precipitation, PREC; total monthly maximum temperature, TMAX; monthly potential evapotranspiration, PET; Szalai et al., 2013) to quantify the relationship between the stable isotopes and the climatic factors. We analysed the monthly data and the cumulative values, that is, we summed 4 months of precipitation and evaporation values before the dates of each water sampling (labelling these variables as PREC_SUM, TMAX_SUM, and PET_SUM) to take into account the previous climatic conditions that can have influence at the given date. CarpatClim is a homogenized database and the observations of the meteorological stations were interpolated to a 10 km grid network (Szentimrey & Bihari, 2007). We matched the nodes of the grid with the oxbows with the nearest neighbour function of QGIS (QGIS, 2017).

2.5 | Statistical analysis

We applied hypothesis testing to show the significance of the differences in data from oxbows on the reclaimed side and on the active floodplain in the different seasons. According to the result of the Shapiro–Wilk test, we used the Spearman's rank correlation and the Kruskal–Wallis test combined with the Mann–Whitney test with Bonferroni correction, as the variables did not follow a normal distribution (Sokal & Rohlf, 1969). We also applied the two-way factorial ANOVA and the ANCOVA tests (Field, 2009) to take multiple factors into account in the models. ANOVA and ANCOVA have assumptions about normal distribution and variance homogeneity, and ANCOVA assumes the homogeneity of regression slopes. Therefore, we applied the robust ANOVA and nonparametric ANCOVA tests (Kabacoff, 2011).

We investigated the relationship between the climatic variables and the stable isotopes with correlation analysis (applying the Spearman's ρ considering the distributions) and Random Forest Regression (RFR; Liaw & Wiener, 2002) to find the most important influencing factor of the stable isotopes. We used half of the data as a training, and the other half as a testing dataset. The efficiency of the prediction was judged by the Pseudo R^2 calculated from the equations of the predicted and observed values. RFR is a robust technique and uses a large number of regression trees. Omission (i.e., loss) of a variable reflects its importance (Variable Importance Factor, VIF), and as the algorithm performs 500 trees with random sampling from the dataset, we can obtain a final function that is not sensitive to the preconditions (such as OLS regression). Thus, based on the VIF values, we were able to find the most relevant variables with the largest explained variance and also, the largest Pseudo R^2 values.

Data processing and statistical analyses were conducted with Microsoft Excel 2010, SPSS 22 (IBM Inc.) and R 3.4.3 (R Core Team, 2017) with the Rattle (Williams, 2011), sm (Bowman & Azzalini, 2014), and walrus (Love & Mair, 2017) packages.

3 | RESULTS

The $\delta^{18}O_{VSMOW}$ (‰) and $\delta^{2}H_{VSMOW}$ (‰) values had a correlation of 0.986 ($p < .001$); therefore, to avoid redundancy, only the $\delta^{18}O_{VSMOW}$ (‰) results were evaluated (Figure 3). F3

3.1 | Relevance of relative location of water bodies on $\delta^{18}O$

Less negative values were found on the floodplain than in the River Tisza; moreover, the isotope ratio values of the oxbow lakes on the reclaimed side were closer to zero compared with those from the floodplain (Figure 3). Accordingly, we can establish the evaporation state: waters originated in the melting snow and the precipitation coming with the River Tisza from the Carpathian Mountains had typically more negative δ values than the Hungarian precipitation samples; furthermore, their variance was smaller (mean ± standard deviation: $\delta^{18}O_{Tisza}$: −10.65 ± 0.6‰; $\delta^{18}O_{precipitation}$: −7.06 ± 1.0‰; Vodila et al., 2011). Therefore, the water samples from the River Tisza had more negative δ values and their standard deviation was also smaller than in the case of the oxbow lakes. Both $\delta^{18}O$ and $\delta^{2}H$ differed significantly in all the three sampling locations (Kruskal–Wallis H: 64.522, *df*: 2, $p < .001$; pairwise comparisons are in Table 1). T1

3.2 | Analysis of seasonal changes of $\delta^{18}O$

Sampling periods also had an effect on the isotope ratios (Figure 3); δ values were affected by the month when the sampling was

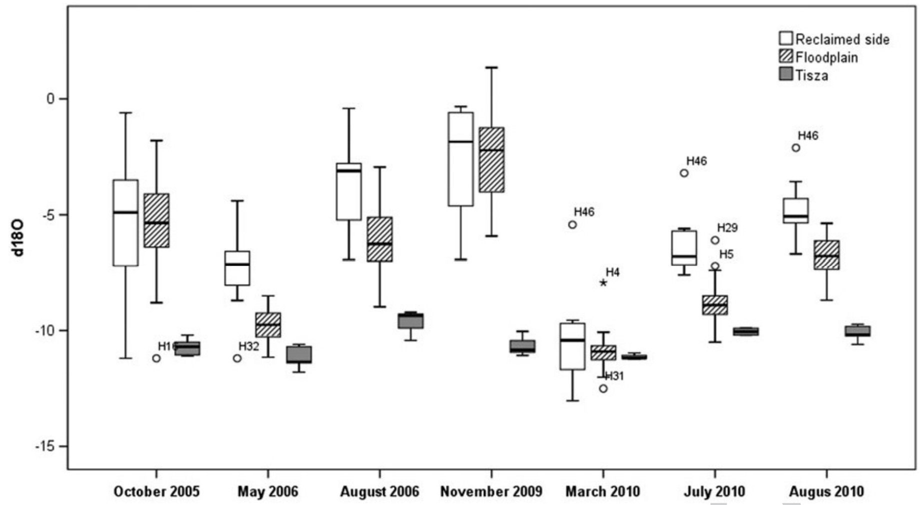

FIGURE 3 $\delta^{18}O_{VSMOW}$ (‰) according to location, by sampling periods

TABLE 1 Mean differences of the $\delta^{18}O$ (‰) between the samples collected from the oxbows of active floodplain, reclaimed side, and the river

	Reclaimed side	Floodplain	Tisza
Reclaimed side	-	1.486	4.744
Floodplain	<.001	-	3.258
Tisza	<.001	<.001	-

Note. Above diagonal: mean differences; below diagonal: significance based on the Bonferroni-corrected Mann–Whitney test.

conducted. There was a continuous positive shift in evaporation when considering the seasons of the sampling, independently of the years (Figure 3). The most negative values (i.e., less evaporated) were measured in March 2010 ($\delta^{18}O$: −10.76 ± 1.23 ‰) and May 2006 ($\delta^{18}O$: −9.36 ± 1.59 ‰). They were followed by the samples from July 2010 ($\delta^{18}O$: −8.18 ± 1.51 ‰), August 2010 ($\delta^{18}O$: −6.75 ± 1.80 ‰), and October 2005 ($\delta^{18}O$: −6.17 ± 2.85 ‰). Finally, August 2006 and November 2009 showed the highest evaporation effect ($\delta^{18}O$: −5.84 ± 2.22 ‰ and $\delta^{18}O$: −4.00 ± 3.78 ‰, respectively). Standard deviations of the sampling periods increased with the intensity of the evaporation: from the spring to autumn, the difference in the δ values increased between the River Tisza and the oxbow lakes, but the differences between the reclaimed side and the floodplain decreased over time (Figure 3); that is, the medians of the reclaimed side and the floodplain values were closer to each other as a result of evaporation in the later period of the year. Sampling in March 2010 was performed right after the melting of the snow; samplings in May 2006 and July 2010 were conducted after the flooding of the River Tisza. Standard deviations and 1.5 times interquartile ranges indicated a wider range as the intensity of the evaporation increased from the spring to the autumn. Regarding the seasons, we found significant differences between the $\delta^{18}O$ values for spring and summer ($p < .05$; $r = .67$), for spring and autumn ($p < .05$; $r = .77$), and for summer and autumn ($p < .05$; $r = .48$; Table 2).

We found that both the relative position of the oxbow lakes ($F(1, 227) = 17.704$; $p < .001$) and the season when the samples were taken ($F(2, 227) = 148.977$; $p < .001$), as well as their statistical interaction ($F(2, 227) = 4.209$; $p < .05$), had significant effect on $\delta^{18}O$ values with $R^2 = 0.57$. This indicated that the oxbow lakes' δ values showed a seasonal pattern and were influenced differently by their relative position (Figure 4). Post hoc test revealed that mean $\delta^{18}O$ values were similar in both sides of the dykes in the spring, the difference was 1.125 ‰ ($p = .283$), then the difference became significant (1.98; $p < .001$) in the summer, and finally, the delta values were similar again (difference:

TABLE 2 Mean differences of the $\delta^{18}O$ (‰) between the sampling seasons

	Spring	Summer	Autumn
Spring	-	−3.028	−4.709
Summer	<.001	-	−1,680
Autumn	<.001	<.001	-

Note. Upper diagonal: mean differences; lower diagonal: significance based on the Bonferroni-corrected Mann–Whitney test.

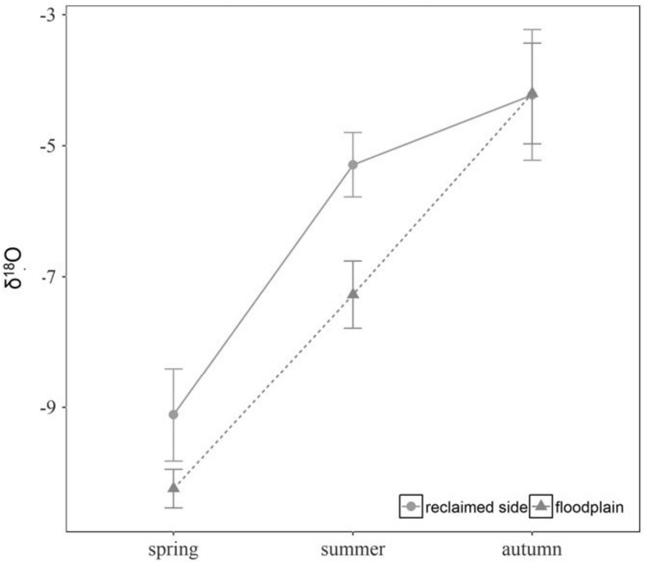

FIGURE 4 Interaction plot of $\delta^{18}O$ values by the seasons of the sampling campaigns and the relative location of the oxbow lakes (mean ± standard error)

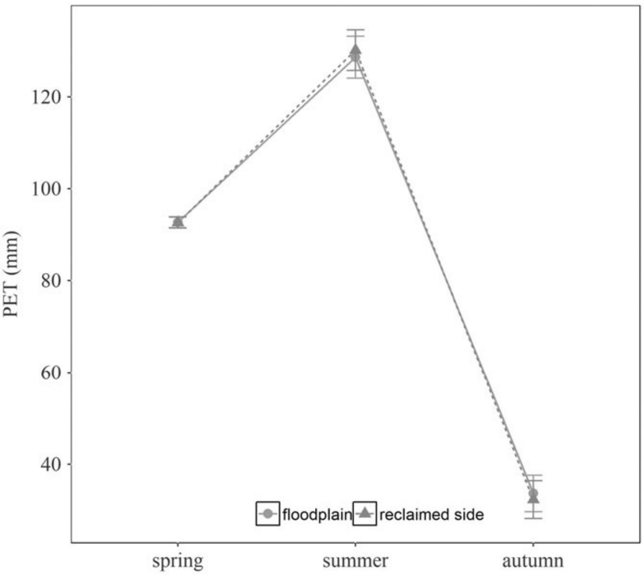

FIGURE 5 Intensity of potential evaporation (PET) in the function of seasons (mean ± standard error)

0.02; $p = 1.00$). We also plotted the PET values that showed that the potential evaporation can explain the changes in the lakes having the maximum in the summer and a decreased volume in the autumn (Figure 5). As PET was only an interpolated value over a 10 × 10 km region, the differences were minimal between the lakes in the floodplain and in the reclaimed side.

3.3 | Evaporation cycle of the oxbow lakes

Evaporation had an annual cycle in the region with peaks in the summer and winter minima (Figure 6). The range was between 0 mm to the maximum of 150 mm; there were fluctuations but a definite trend cannot be identified in this short period.

Plotting the isotope ratios of δ^2H and δ^{18}O helped to describe the evaporation process (Figure 7). In the case of the River Tisza, different sampling periods were not distinguished by months because the differences were not significant ($p > .05$) according to the Mann–Whitney test with a Bonferroni correction (considering a full factorial comparison of the sampling periods). Samples collected from the River Tisza were distributed around the GMWL, reflecting the fact that the river was filled with water from melted snow. Below this point, the LMWL crossed the GMWL, meaning that the local precipitation was very similar to the global precipitation. However, the δ values of the oxbow lakes formed a straight line in a narrow range with a smaller slope, crossing both the GMWL and the LMWL. This line is an indication of evaporation. Oxbows distributed along the GMWL (and the River Tisza) received their water supply from the River Tisza (March 2010, May 2006, July 2010 samplings) and were marked with the ellipse seen in Figure 7. Around the centre of the line formed by the oxbow samples, both local rain and evaporation affected the oxbows (August 2010 and 2006). The highest values (below the line of the LMWL) represented those oxbows in which evaporation was the most dominant (October 2005, November 2009). This shows that there was not enough precipitation to counterbalance the effect of evaporation, either on the floodplain or the reclaimed side.

Considering the differences between the oxbow lakes on the reclaimed side and the floodplain, more floodplain oxbow lakes can be observed around the GMWL (Figure 9), whereas from the oxbow lakes on the reclaimed side, only the March 2010 values were so negative as to occur close to the GMWL (Figure 8). The reason for this was not a flood, because in 2010, this occurred in May–June, but the sudden winter-end melting of the snow before the samples were taken. This meant the reclaimed side oxbow lakes had very negative values at this time. The oxbow lakes on the reclaimed side were affected by evaporation in every sampling period (except for the previously mentioned March 2010 sample), and among the samplings, there were not such large differences as in the case of the floodplain oxbow lakes, except for the November 2009 and March 2010 samplings (Figure 8).

Nevertheless, large differences can be found among the single sampling periods in the floodplain oxbow lakes (Figure 9). For example, in the case of oxbow lake H31, the δ values were 1.4 (δ^{18}O) and −15.7 (δ^2H) in November 2009; and −12.5 (δ^{18}O) and −90.3 (δ^2H) in March 2010. This oxbow lake produced the largest difference between two sampling periods. The effect of the evaporation appeared in the month-level study. Primarily, we can observe the regenerating effect of the River Tisza in spring, then the influence of the evaporation and the precipitation, and finally the overcoming evaporation.

Oxbows inside the floodplain close to the Tisza may have an underground connection with the river through the gravelled, permeable layers of the old river beds. This can be shown by the fact that the isotope composition of some oxbow lakes hardly changes over time as evaporation continues (Figure 10). These oxbow lakes can be found among those whose δ values hardly shifted in a positive direction compared with the negative δ values of the River Tisza.

3.4 | Stable isotopes and climatic variables

The largest relationship was a positive moderate correlation between the δ^{18}O values and the PET_SUM ($r = .62$). PREC, PET, and TMAX had a negative correlation with the δ^{18}O (with −0.51, −0.45, and − 0.41 r values, respectively). Cumulating PET and PREC was not reasonable, the correlations with δ^{18}O were lower than with the simple monthly data (−0.45 vs. −0.38 and −0.51 vs. −0.23, respectively).

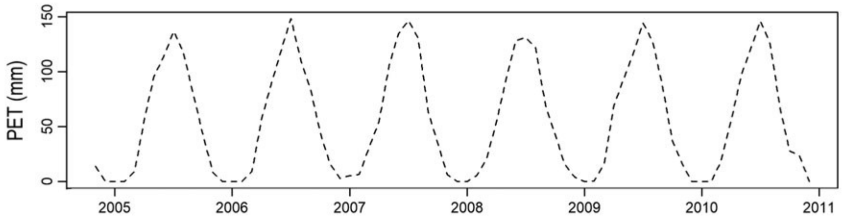

FIGURE 6 Time series of potential evaporation (PET) data in the studied period

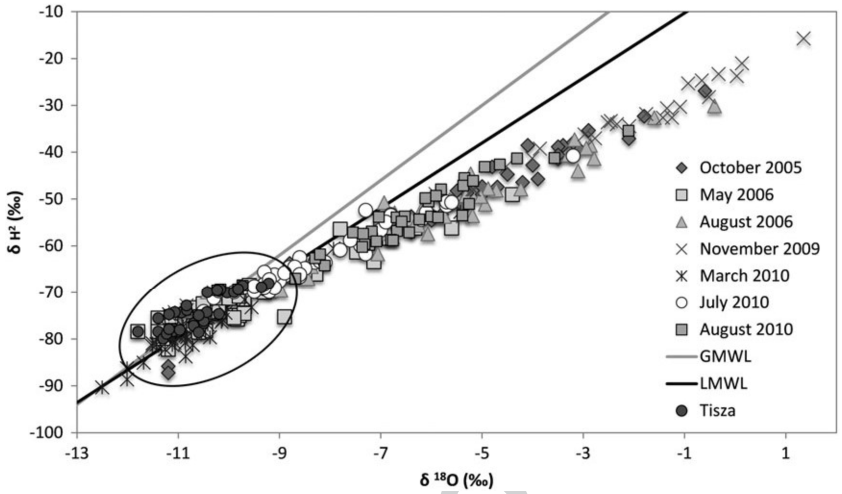

FIGURE 7 The δ^2H and δ^{18}O values of the samples (ellipse: oxbows with a water supply from the River Tisza). GMWL = Global Meteoric Water Line; LMWL = Local Meteoric Water Line

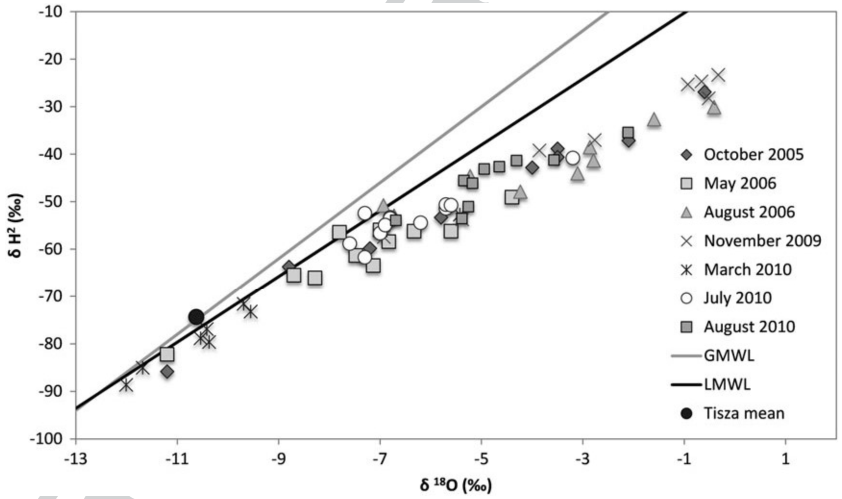

FIGURE 8 The δ^2H and δ^{18}O values of the reclaimed side samples. GMWL = Global Meteoric Water Line; LMWL = Local Meteoric Water Line

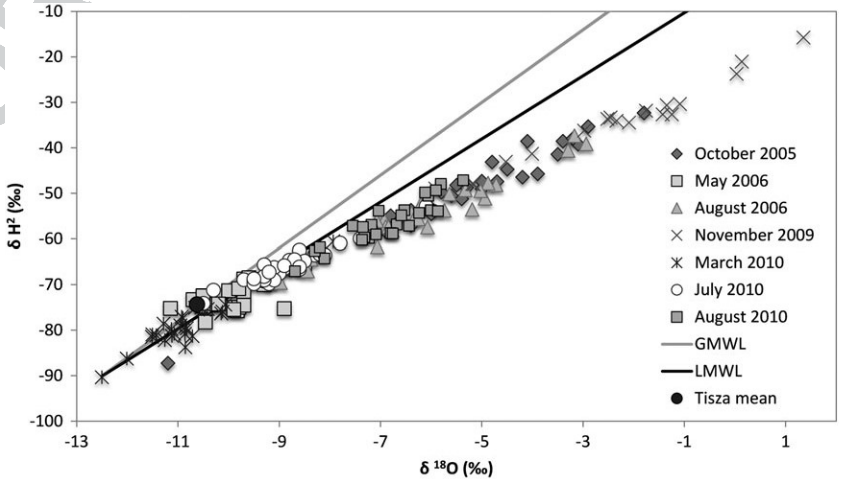

FIGURE 9 The δ^2H and δ^{18}O values of the floodplain samples. GMWL = Global Meteoric Water Line; LMWL = Local Meteoric Water Line

RFR revealed that the most important climatic variable to predict the δ^{18}O values was the PET_SUM; explained variance was 51.74, and the Pseudo R^2 was 0.56. Our next step was to examine the variables by the relative location of the oxbows. In the case of the oxbows of the active floodplain, the most important variable was TMAX (33.1% explained variance and 0.68 Pseudo R^2), whereas for the reclaimed side, we obtained the best result with the inclusion of two variables: PREC_SUM and TMAX (VIFs were 25.32 and 16.96, respectively), and the explained variance was 45.3%, the Pseudo R^2 = 0.40.

However, in the investigation of the climatic variables, δ^{18}O values and seasonality, PET was the most efficient predictor. Evaporation (PET) in the lakes also had significant effect on the δ^{18}O values as covariant ($F(3, 232) = 160.408$, $p < .001$) in an ANCOVA model where the season of the sample collection was the fixed factor (F(2,

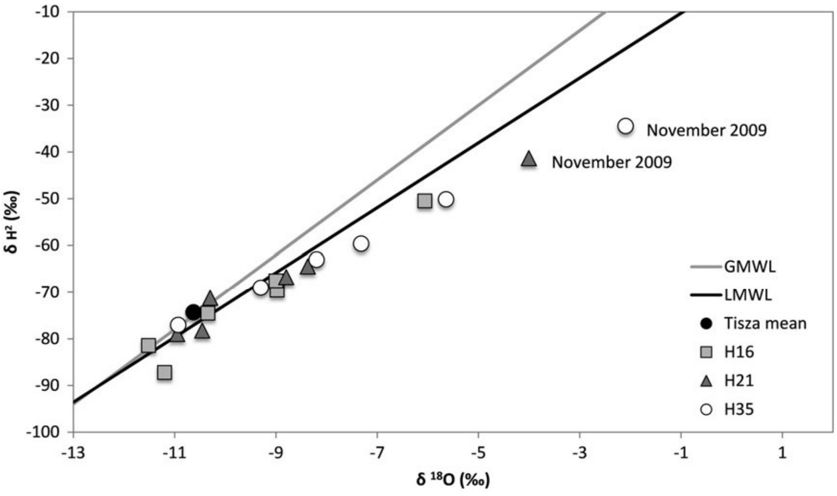

FIGURE 10 The δ values of some floodplain oxbow lakes showing the least change (the highest values derived from November 2009). GMWL = Global Meteoric Water Line; LMWL = Local Meteoric Water Line

232) = 168.013, $p < .001$). The model indicated the relevance of the season (partial $\eta^2 = 0.59$) related to the PET (partial $\eta^2 = 0.29$) with the R^2 of 0.67. Furthermore, there is a significant interaction between the season and the PET variables ($F(2, 227) = 4.79$, $p = .009$; Figure 11).

We calculated the potential evaporation using the stable isotopes with RFR model and found that best results can be achieved when both the δ ^{18}O and δ ^{2}H values were involved; PET can be calculated with the pseudo R^2 of 0.79 using the whole dataset (Figure 12). However, if we split the dataset into a train and a test partition (to develop the model and to apply it on independent data), it indicated a weaker result, with the Pseudo R^2 of 0.288.

4 | DISCUSSION

Examination of the δ^{18}O and δ^{2}H values can reveal the dynamics of water addition in the oxbow lakes. The difference in the isotope ratios between the River Tisza and the oxbow lakes increases from the spring to winter, but the difference between the reclaimed side and the floodplain decreases. Most of the floodplain oxbow lakes gradually approach the level of the reclaimed side oxbow lakes, due to evaporation. In spite of the fact that the oxbow lakes are shallow (1.1 m mean depth) with a relatively large water surface (11 ha on average), the amount of rain has no significant effect on evaporation tendencies from month to month, on either the floodplain or the reclaimed side, except when there are canals collecting the surface water and leading it to the lakes directly (H14, H32, and H38). Our results support the conclusion that the δ values of the oxbows in the active floodplain are determined by the TMAX, whereas in the reclaimed side, the causes are more complicated: beside the TMAX, the PREC_SUM and PET are also important.

In France, Négrel et al. (2003) came to a similar conclusion when analysing the isotope ratios of the River Loire, the River Allier, and a neighbouring body of standing water, finding that the δ^{18}O and δ^{2}H isotope ratios of the two rivers were more negative than those of the standing water. They examined the interaction between the

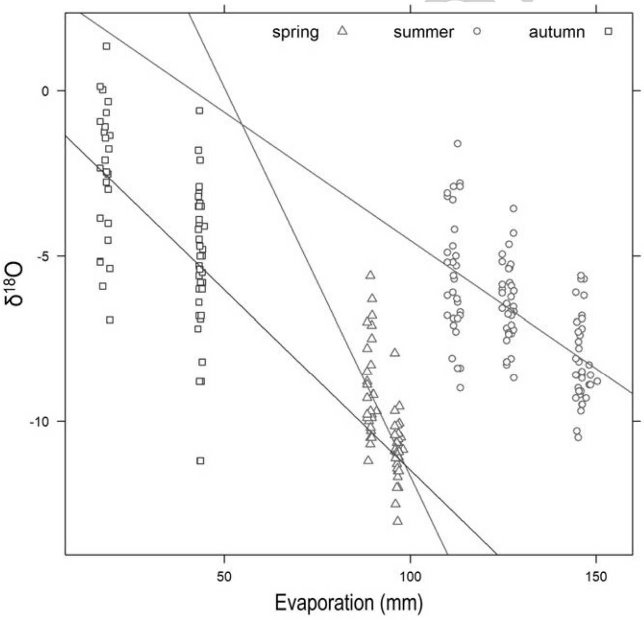

FIGURE 11 Plot of the relationship between evaporation and δ18O for each of three seasons of water sampling campaigns

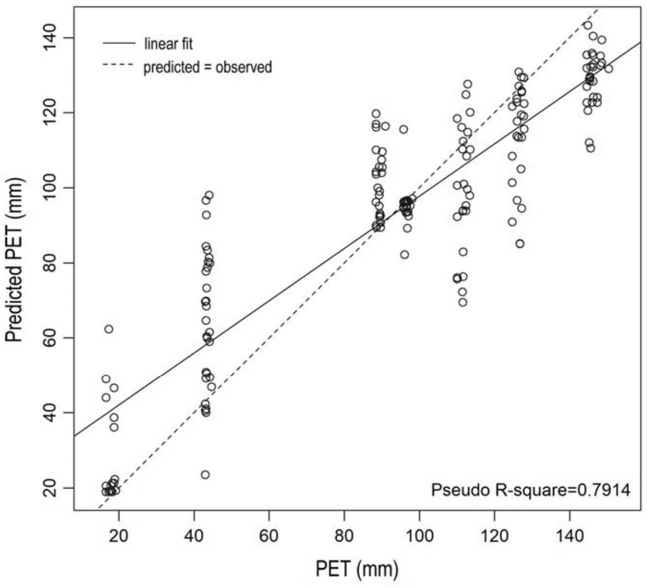

FIGURE 12 Evaluation of model performance where potential evaporation (PET) is predicted with δ ^{18}O and δ ^{2}H stable isotopes

surface and the groundwater, and proved the role of local precipitation in riverside water bodies on an alluvial plain, despite the close proximity of the River Loire and the River Allier. They also measured the most negative values from the rivers after the end of winter, as we also observed. Jonsson, Leng, Rosqvist, Seibert, and Arrowsmith (2009) found that the δ^{18}O values measured in rivers decreased after the spring melting of the snow in northern Sweden, and they also experienced measurable evaporation in the subarctic lakes, which corresponds with our results.

Yi et al. (2008) observed, similarly to our results, that the isotope ratios of the river they examined are within narrow bounds, and also that the isotope ratios of the standing waters flooded by the river are always similar to the ratios found in the river. However, Longinelli et al. (2008) found evidence that the isotope ratios of Lake Garda are affected neither by the River Sarca nor the typical heavy summer precipitation. Lake Garda is a deep lake with a large surface and its volume is about 50 km^3 (Piccolroaz, Toffolon, Sighel, & Bresciani, 2013), whereas the lakes we examined are shallow and only had volumes between 5×10^{-5}–2.5×10^{-4} km^3 (Pálfai, 2001). Although the precipitation and river surplus is small in the case of Lake Garda, Hungarian oxbows can exchange their entire body of water in a short period of time (Türk et al., 2016).

In Hungary, and generally in Central and Eastern Europe, where the climate is continental and rivers have two maximums (or floods) in a year (nivo-pluvial type river regime in Pardé's classification system; Leopold, Wolman, & Miller, 1995), the first maximum occurs in the spring when oxbow lakes' basins are filled up with melted snow and rainwater, and later, in the early summer, there is a second maximum (due to the intensive warming as wet oceanic air arrives in the inner regions of the continent, Lajter, Schnitchen, Dévai, & Nagy, 2009). However, maximums mean high water but do not always inundate the floodplains; thus, they do not ensure water supply for the oxbow lakes in every year. During our study, floods occurred only in April 2006 and in May 2010. After the precipitation maximums and floods, evaporation is the dominant process, later, the input is from precipitation; therefore, the water balance turns into deficit and smaller shallow lakes may run dry. This process is reflected in the stable isotope values, δ^{18}O and d^{2}H values has a seasonal cycle: in the spring values, they are the most negative, and during the year, these values increase, and finally, at the end of autumn, approach the zero (or even can be positive; Figure 3).

The relative position of the oxbow lakes determines the possible sources of water supply. Although the lakes on the reclaimed side never get water from the river directly, and their evaporation status was higher related to the ones in the active floodplain, the differences between their δ^{18}O values was not significant in the spring. Evaporation had a linear trend in the lakes of active floodplain from the spring to autumn, while the trend was more logarithmic in case the reclaimed side: there was an intensive period from the spring to summer and the pace became slower from the summer to autumn. Accordingly, the δ^{18}O values had significant differences in the summer, but the means became similar in the autumn.

The magnitude of evaporation depends on the environmental conditions; however, in this case, we were not able to prove this influence due to several reasons. Water bodies with large surface can be shallow, the correlation between depth and area of the lakes is only −0.14; thus, volume can be larger in the lakes having a smaller area. Depending on how much snow fell in the winter, and how fast the snow melted, how much rain fell in the spring, and whether the precipitation initiated a flood or not, the starting state of water bodies can be very different at the beginning of the year. The degree of evaporation is reflected in the stable isotope records of the lakes. Oxbow lakes are elongated and narrow water bodies and usually surrounded by forests, which project shadows on the water surface and ensuring cooler temperature and, therefore, decrease the rate of evaporation. Lake evaporation level also can be affected by the underground input sources.

Prediction model of the evaporation resulted an explained variance of 79%, which is promising; however, it is important to note that we had only potential evaporation data as dependent variable and the calculated evaporation is not equal to the actual evaporation of the given lakes. The model is appropriate to calculate the PET values from the stable isotopes but has weak performance (only 28.8%) on predicting. The seasonality of oxbow lakes' evaporation cycle can be hypothesized, but with the help of stable isotopes, we were able to quantify the details of this cycle. Stable isotopes can reflect the water sources of the lakes, which can help in the long-term nature conservation plans. Considering the connection between the TMAX and δ values, and the long-term predictions on the increasing temperature for the future, we have to expect that there will be a higher frequency of smaller or completely dry lakes due to evaporation. When oxbow lakes' water table decrease or run dry, there are detrimental consequences on the water quality, ecosystem, and economy: living organisms die and this can also result in reduced income from the fishing and recreation (Sendzimir, Magnuszewski, Balogh, & Vári, 2006; Vári & Ferencz, 2006). Furthermore, oxbow lakes are the organic elements of the habitat system and ecological corridors along the rivers: several protected bird species use this environment for nesting, and valuable plant species can find here an optimal refugium (Báldi, Moskát, & Zágon, 2000; Gőri, Aradi, Dévai, & Nagy, 2000; Stella et al., 2011). In case of the River Tisza, oxbow lakes were the most important refugia in revitalizing the river after the cyanide spill in 2000 (Nagy et al., 2001). If drought periods endanger the stability of the lakes, sensitive species disappear.

5 | CONCLUSIONS

Seven stable isotope examination campaigns were performed over 5 years, allowing us to explore systematically how the isotope ratios have changed in the River Tisza and the oxbow lakes during this time. Oxbow lake isotope ratio values show a positive shift over a year (from March to November). After the melting of the snow and flooding, the isotope ratios of the oxbows shifted in a more positive direction with evaporation. The Tisza, as well as the oxbow lakes on the floodplain and the reclaimed side, showed differences based on the stable isotope examination of the water samples. The isotope ratios of the River Tisza were sharply different from those of the oxbow lakes. The oxbow lakes on the reclaimed side differed significantly from those on the floodplain and the intensity of evaporation was higher from the spring to summer than from the summer to autumn, whereas in case of lakes in the floodplain, it followed a linear trend. The effect of climatic variables on the stable isotope values varied by the relative location of the oxbow lakes: TMAX had a significant effect on the floodplain oxbow lakes, unlike the reclaimed side where TMAX and monthly evaporation both influenced the isotopic signal observed. Stable isotopes can provide information on the risk of desiccation through the δ^{18}O and δ^{2}H measurement.

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