THESIS OF DOCTORAL (PhD) DISSERTATION

SZABINA SIMON

GEORGIKON CAMPUS

KESZTHELY

2023

HUNGARIAN UNIVERSITY OF AGRICULTURAL AND LIFE SCIENCES

EFFECT OF METEOROLOGICAL VARIABLES ON THE LITTER DECOMPOSITION IN THE BALATON CATCHMENT AREA

Szabina Simon

Keszthely

2023

Name of doctoral school: Festetics Doctoral School

Study field: Environmental sciences

Head of the doctoral school: Dr. habil. Angéla Anda, DSc

University professor, doctor of the Hungaryan Academy of Sciences

MATE, Georgikon Campus, Institute of Agronomy, Department of Agronomy

Doctoral supervisor: Dr. habil. Angéla Anda, DSc

University professor, doctor of the Hungaryan Academy of Sciences

MATE, Georgikon Campus, Institute of Agronomy, Department of Agronomy

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Approval by the Head of the Doctoral School

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Approval of the Supervisor

1. Background and objectives

Among the knowledge related to the connections between biodiversity and ecosystem functions, the area related to plant productivity is the most widely discussed. Other basic processes, such as decomposition, are relatively less researched (TILMAN et al. 2014), this is especially true for the investigation of litter decomposition in the aquatic environment (HÄTTENSCHWILER et al. 2005, GESSNER et al. 2010).

In addition to the chemical properties of litter and biotic factors, abiotic factors also play a key role in the process of litter decomposition (GARCÍA-PALACIOS et al. 2013, GARCÍA-PALACIOS et al. 2016). Among the many external factors that can influence litter decomposition, temperature has attracted more attention (FERREIRA & CANHOTO 2015, FERREIRA et al. 2015, FOLLSTAD SHAH et al. 2017). The assessment of the relationship between temperature and litter decomposition still receives a lot of attention nowadays in terrestrial (FIERER et al. 2005, PRESCOTT 2010) and aquatic ecosystems (FERREIRA & CANHOTO 2015).

According to climate change projections, by 2100 the average atmosphere temperature will increase by 1.5–4.6 °C compared to pre-industrial levels (IPCC 2021, HAWKINS et al. 2017). In aquatic ecosystems, temperature is a particularly important physical property, and an increase in air temperature (T_a) predictably leads to an increase in water temperature (T_w) (KAUSHAL et al. 2010, MOLINERO et al. 2016).

Between 1750 and 2011, atmospheric carbon dioxide (CO_2) increased by about 40%, from 280 ppm to 391 ppm, and is expected to reach 936 ppm by the end of the 21st century (IPCC 2021). Global warming and an increase in atmospheric CO_2 are likely to affect the metabolism of microorganisms (BROWN et al. 2004), which may ultimately affect ecosystem processes.

One of the processes affected by increased CO_2 and air temperature is the decomposition of litter in water. Plant material that has fallen into water is the main source of energy and carbon for numerous bodies of water (WALLACE et al. 1997). Due to the increased atmospheric CO2, plants accumulate different metabolites (e.g. starch and various sugars) in the leaves (STILING & CORNELISSEN 2007). These metabolites are often characteristic of plant species that produce rapidly decomposing litter (KINNEY et al. 1997).

- One of the main goals of the study is to learn about the effect of Tw and various meteorological elements on the decomposition. Aim of study was to predict the rate of degradation based on meteorological elements.

- Among the meteorological variables included in the study, T_w occupied a central role in our analysis. In previous studies, as the meteorological variables were measured, the observations usually referred to long time intervals (annual and monthly averages). Very few studies have used daily averages of meteorological variables. In this study, the collection of meteorological data was used at a resolution of 10 minutes.

- Related to the above, our aim was to determine the decomposition coefficient extended by the temperature term

(k_T). Furthermore, the temperature sensitivity coefficient (Q_{10}) was determined. We also aimed to include the very rarely used global radiation (R_n) and meteorological variables that affect the microclimate.

- To better understand the decomposition process, we also aimed to the leaching dynamics investigate. Ammonium (NH_4-N) and phosphate (PO_4-P) were examined in the leaching dynamics investigation. Considering the winter observation period, the monitoring of the organizations performing litter decomposition was not the subject of our investigation.

- We analysed the local effects of climate change in a microcosm experiment (in climate chamber). The microcosm experiment was set up based on the parameters measured in the "decomposition experiments", as well as the expected changes. The higher temperatures (T_a and T_w) were considered with the values predicted for the winter period of the Hungarian downscaled model of the RegCM (+2 °C warming). Unlike before, our goal was to determine the amount of CO_2 released during underwater decomposition, under current and expected rising temperature conditions.

2. Materials and methods

2.1 Study sites

We set up our "in situ" investigation at the following locations: Kis-Balaton Ingói bay (KB), River Zala (Z), Balaton Keszthely Bay (B), Lake Hévíz (HT) and 3 different temperature points of the Hévíz effluent (HL) (HL1, HL2, HL3). The HL points were selected in such a way that T_w decreases along a temperature gradient. The further away HT is from HL, the lower the T_w: HL1 sampling point: 400 m from HT, HL2 sampling point: 1562 m from HT, HL3: 4280 m from HT.

2.2 Investigation of meteorological variables and water physical and chemical parameters

In the case of the Keszthely bay, the meteorological variables (T_a, T_{max}, T_{min}, PR, relative humidity-RH, windy-u, R_n) were recorded by the climate station type QLC-50 (Vaisala, Helsinki, Finland) located at the Agrometeorological Research Station (N 46°73'5.686", E 17 °23'8.615”). The climate station is part of the observation network of the National Meteorological Service. The meteorological data measured on the KB (Almás island, N 46°65'7.383" E 17°19'4.199") were recorded by the station located in the experimental area of the West Transdanubian Water Directorate. The data measured at HT were provided to us by the Lake Hévíz Monitoring Station (N 46°78'6.268", E 17°19'3.656").

In the water bodies during the experimental period, T_w was measured in situ with a HOBO UA-002-64 data logger,

and pH and conductivity (EC) were measured during sampling with Adwa AD111 and AD310 instruments.

A Lovibond MultiDirect (type 0913462) spectrophotometer was used to determine NH_4-N, PO_4-P and SO_4-S in water samples. The determination of the chemical oxygen demand (KOI_p) in the water samples was carried out based on MSZ 448-20 (1990). We also determined the biochemical oxygen demand (BOI_5) based on the European standard MSZ EN 1899-1 (2000). The total organic carbon content (TOC) was determined based on the MSZ EN 1484 (1998) standard.

2.2 Investigation of litter decomposition and leaching dynamics

The following plants and plant parts were included in the experiment: reed, *Phragmites australis* (leaf–NL, stem–NSZ, rhizome–NR); goldenrod, *Solidago canadensis* (leaf–AVL, stem–AVSZ); cattail, *Typha angustifolia* (leaf–GYL, stem–GYSZ); swamp cypress, *Taxodium distichum* (MC); willow, *Salix* (F); poplar, *Populus* (NY); and a mixture of willow and poplar (50-50%) (K). We examined the rate of decomposition of these plants and plant parts between December 9, 2019 and March 16, 2020, using the litterbag technic (BÄRLOCHER et al., 2020).

During our calculations, we used a decomposition coefficient normalized by temperature (k_T).

When investigating the relationship between the decomposition coefficient and the temperature, we used Q_{10} values, which show how the coefficient of the decomposition process changes when the temperature is increased by 10 °C.

In our study, we examined the rate of leaching of NH_4-N and PO_4-P during the immersion of plants and plant parts in water based on the percolation method of POMOGYI (1983). The concentration of NH_4-N and PO_4-P in the water was tested with a Lovibond MultiDirect (type 0913462) spectrophotometer.

2.3 Examination of total organic carbon (TC), nitrogen (TN) and phosphorus (TP) content of plants

The TC and TN content examination were performed based on the MSZ EN ISO 16634-2:2016 standard with an Elementar vario MACRO CUBE element analyzer.

In the case of TP, the examination was carried out based on the MSZ 448-18 (2009) standard. The destruction was carried out in a ONE TOUCH TECHNOLOGY MARS 6 microwave machine, and the TP content of the plant parts was determined spectrophotometrically at 410 nm.

2.4 Determination of CO_2 emissions in a climate chamber (microcosm experiment)

Using the data measured at KB, we controlled the temperature in the Angelantoni Industrie Ekochl 700 type climate chamber. 1 g of plant material, 10 g of mud and 100 ml of water were placed in a 300 ml flask. Flasks containing 10 g of mud and 100 ml of water were also used as controls, thus excluding the plant effect. A Testo 535 type CO_2 measuring instrument was used for the CO_2 measurements. We repeated the 98-day experiment by raising the temperature in the climate chamber by 2 °C, thereby predicting the impact of global climate change on the study area by 2100 (IPCC, 2021, 2014; EASTERLING, 2007;

PONGRÁCZ et al., 2014). At the end of the experiment, the pH and EC were measured in water samples, and the NH_4-N and PO_4-P content in the water was determined using the previously described methods. Furthermore, the TC content of each plant part was determined with an elemental analyzer at the beginning and end of the experiment.

2.5 Statistical analysis

The normal distribution of the data was tested using the Shapiro-Wilk test (SPSS 17.0; IBM Corp., New York, USA). The data used showed a normal distribution, so we were able to perform Pearson correlation, two-way analysis of variance (ANOVA) and linear regression tests. The comparison of decomposition, dissolution and CO_2 emission of plant parts within and between locations was performed using Student's t-test (significance level 5%, $p<0.05$).

3. Results and discussion

Compared to the average of 1981–2010, we detected a higher air temperature of 3 °C ($p<0.001$) during the experimental period. With the exception of one month (B, March), the mean monthly temperature of all sites was 0.6–6.2 °C warmer than the long-term average.

During the experimental period, B had the most balanced average daily T_w (T_w=3.6–8.4 °C) due to the large water mass. KB (T_w=-1.1–10.7 °C) and Z (0.0–13.0 °C) showed greater variability in T_w. Compared to HT with the highest average T_w (24 °C), HL1 was lower by 1.3 °C, HL2 by 5.0 °C, and HL3 by 10.3 °C.

The variability of T_w measured on KB, Z and B on the two windy and warm days exceeded those observed on calm days. Among the three locations, we measured the highest average u at B, which was 17.9% higher than the other locations.

At the sampling points, the pH of the water was in the range of 7.37-8.88, which can be considered optimal in terms of decomposition.

BOI_5, KOI_p and TOC differed at each sampling point; the warm thermal waters are well separated from the other locations with their lower values. Z had the highest value for all three variables. Although there were no differences in NH_4-N between the sampling sites, the variable still moved in a larger range on Z. The reason for this is that Z functions as a sediment transporter on the water catchment. In the case

of PO_4-P, the natural waters (B, KB, Z) are also clearly separated from the thermal waters (HT and HL1–3).

The weight loss during litter decomposition was the greatest for all plants and plant parts at the locations with the highest water temperature (HL1, HT). The smallest mass loss was detected at the location with the coldest water temperature (KB).

The plant parts of macrophytes standing in water behaved similarly regardless of the location: the leaves decomposed faster than the stem, and the rhizome decomposed faster in all of them. We found that the plants standing on the shore decomposed faster than those standing in the water, AVL the fastest, MC and AVSZ the slowest.

Contrary to previous studies, in which the rate of decomposition in mixed litters was faster than the value measured separately for each species, this was not confirmed in our results. Although the individual decomposition of F and NY took place as described in the following studies, the decomposition rate of the mixture of the two litters was the average of the results obtained for the two litter separately. With this, we could not prove the accelerating effect of mixing on litter decomposition.

The effect of plant parts, plants and study sites, as well as their cross-effects, were also significant. This means that the litter decomposition at different speeds in the different sampling sites, showing significant differences from each other as well.

Initial TC was similar for all plant parts (426.9-465.2 mg^{-g}). At the end of the experiment, the TC in HT was the

highest in all plant parts and exceeded the increases seen in the other study sites. A greater TN increase was found at the HT and HL1–3. The same occurred in the case of TP, although there were some exceptions (KB-NL, GYSZ, AVSZ, MC; HL2-GYL).

The evolution of the k_T follows the trend observed in the analysis of the litter mass loss, and the effect of the study sites is also clear (HL1<HT<HL2<HL3<B<Z<KB). The Q_{10} values were the lowest for KB (1.6-2.1), while the highest for HT and HL1-3 (1.7-2.5).

With the exception of GYSZ, plant parts of aquatic macrophytes produced the highest NH_4-N values during the leaching dynamics investigation. Based on the two-way ANOVA, the study sites, plant parts and their interaction are also significantly different. The leaching of PO_4-P in the case of NR was exceptionally high at all study sites. In the case of PO_4-P, the release value in the leaves of the examined species exceeded the release from the stems. Based on the ANOVA analysis for NH_4-N and PO_4-P leaching, the study site, the plant parts and the cross-effect also showed a significant effect.

Similar to what was experienced in the "litter decomposition" experiment, the TC remaining after leaching increased almost everywhere, most prominently at HT. On the other hand, the TN left after leaching (with the exception of HL3-NSZ, HL2-3 GYSZ) decreased compared to the initial value, mainly on HT and HL1-3. Furthermore, in the case of the leaching dynamics experiment, surprisingly lower values appeared compared to the "in situ" measurements. The latter tendency also appeared in the case of TP, although there

were some exceptions (KB-NL, GYSZ, AVSZ, MC; HL2-GYL).

In the microcosm study, the CO_2 emissions of flasks containing plant material were significantly higher compared to the treatment containing only water and mud (control). A temperature increase of +2 °C (depending on the species and plant parts) resulted in 14.01-35.23 % higher CO_2 emissions. For both the "normal" and +2 °C elevated temperatures, the ANOVA confirmed a significant difference for both plant species and plant parts.

In the climate chamber and in the leaching dynamics experiment (in "in situ" investigation), the pH, EC, NH_4-N and PO_4-P values of the water samples did not differ significantly between the plant parts.

CO_2 emissions of plant parts at elevated T_w were consistent with reduced TC content for all plant parts.

4. Conclusion

Based on our results, the warming of the climate seems to be confirmed in the areas of the Carpathian Basin B and its catchment, as we detected a 3 °C higher Ta compared to the 1981–2010 normal during the experimental period.

Since our study sites were located within a small area (~50 km^2) in terms of the spatial distribution of R_n and spanned a relatively short period of time in the winter, the Rn values were similar at all sites (80.3–81 W m^{-2}). However, this does not mean that the role of R_n in the decomposition process is negligible. Because this energy forms the basis for the vital functioning of the organisms involved in the implementation of the decomposition process. This is confirmed by the fact that R_n was the most dominant of the meteorological elements based on the correlation and regression analysis.

In the multivariate linear regression equations (except for NSZ), constant variables were R_n and T_w, regardless of the study site and the examined plant part. Based on this, the rate of decomposition of individual plant parts can only be determined (predicted) on the basis of meteorological data. It follows from this that the available energy is the most relevant factor for the decomposition of litter in the studied areas.

The study sites of the investigation gave us the opportunity to analyse the decomposition processes in several water bodies with different T_w in a single year. In contrast, previous publications were only able to produce different

temperatures in microcosm experiments or by involving several study years at the same time.

Based on our results, we were also able to verify the already known fact that the effects of individual meteorological elements can only be separated "ex cathedra". The presence of the u had a decisive influence on the development of T_w, the probable cause of which could have been the inclusion of smaller water bodies in the area.

There was a difference between the lowest pH of HT and its effluent, and the higher pH values of B and KB and Z. However, the pH difference between the individual study sites was not large enough to fundamentally affect the decomposition process.

Based on the correlation analysis, the most dominant variables among the indicators of organic pollution of water bodies were TOC and KOI_p, which could have an influence on the litter decomposition.

It can be concluded that along the decreasing temperature gradient found naturally on our study sites (HT–KB), the rate of litter decomposition also decreases. The most intense decomposition was observed near the HT, which mass loss values decrease towards the KB, in the case of the same plant species.

An elevated value of TC at HT may indicate increased microorganism activity due to the high and constant temperature available (the biofilm was “unwashable”). HL1 generally had the highest TN values, and KB had the smallest (HT–HL1 highest T_w, KB lowest T_w), which temperature

dependence is probably closely related to the presence of microorganisms.

Based on our results, we found that the T_w-based k_T values are more accurate than the widely used exponential decay coefficient that ignores T_w. The Q_{10} values also show the different role played by study sites and plant parts in the decomposition process.

PO_4-P leaching from NR was exceptionally high at all study sites. The value of leached PO_4-P in the leaves of the studied plants exceeded the value of leaching from the stems. The reason for this is probably that the phosphorus content in the stems is already lower, and it is also present in a form that is difficult to break down.

After the leaching dynamics study, the outstanding value of the final TC was observed on the HT. This is probably due to the fact that the microorganisms already start to colonize on the litter when the before falling, and the biofilm cannot be removed from the later.

Based on the results we obtained, it can be concluded that the rate of litter decomposition (mass loss) and the cumulative leaching (NH_4-N, PO_4-P) follow a polynomial relationship.

Despite the fact that the decomposition processes place under water, we have made it possible to measure the CO_2 emissions into the atmosphere of the litter decomposition under water with the method we have used. Based on the ANOVA, the significant cross-effect indicated that the gas emission was not the same in each treatment.

The pH, EC, NH_4-N and PO_4-P values of the water samples in the microcosmos experiment and in the leaching dynamics study did not differ significantly, from which the conclusion can be drawn that the field conditions were simulated in the climate chamber.

CO_2 emissions from treatments containing plant parts at elevated T_w were consistent with reduced TC content for all plant parts. This finding could be a consequence of the fact that the higher T_w increased one of the products of decomposition, the CO_2 emission, which caused a lower residual TC content.

5. New scientific results

1. Based on the multivariable linear regression equations, the decomposition rate of the individual plant parts can be determined (predicted) using the daily average of the meteorological variables. Among the 8 variables included in the study, R_n and T_w were present in the equations regardless of the location and the examined plant part (except the NSZ). Based on this, among the meteorological variables, the available energy (represented by R_n and T_w) is the most relevant factor for decomposition.

2. The sites of the investigation, a unique thermal lake unique in Central Europe, the shallow B, and the associated water bodies, which provided the opportunity to analyse the decomposition in several water bodies with different T_w in a single year. It can be concluded that along the decreasing temperature gradient found naturally on our study sites (HT–KB), the speed of litter decomposition also decreases.

3. At the end of the experiment, the TC content was the highest in the HT with the warmest T_w. This may mean that there was increased microorganism activity due to the high and constant temperature available (the biofilm was "unwashable").

4. Based on the results we obtained, it can be concluded that the rate of litter decomposition (mass loss) and the cumulative leaching (NH_4-N, PO_4-P) follow a linear relationship.

5. In the microcosmos study (climate chamber investigation), the CO_2 emissions of samples containing plant

material were significantly higher compared to the treatment containing only water and mud. Despite the fact that the decomposition takes place under water, we have made it possible to measure the CO_2 emissions of the underwater litter decomposition into the atmosphere with the simple method we have used. A temperature rise of +2 °C resulted in 14.01–35.23 % higher CO_2 emissions, depending on the plant species.

6. The pH, EC, NH_4-N and PO_4-P values of the water samples in the microcosmos experiment and in the leaching dynamics study did not differ significantly, from which the conclusion can be drawn that the field conditions were simulated in the climate chamber.

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6. Publications related to the topic of the dissertation

Peer-reviewed technical article in foreign languages:

Simon, Sz., Simon-Gáspár, B., Anda, A. (2023): Carbon dioxide emission and its impacting factor from goldenrod (*Solidago canadensis*) and bulrush (*Typha angustifolia*) decomposition during the winter period. Ecohydrology & Hydrobiology. m3Gdc 1-9. https://doi.org/10.1016/j.ecohyd.2023.01.002 **Q1 IF: 2.957**

Anda, A., **Simon, Sz.**, Simon-Gáspár, B. (2023): Impacts of wintertime meteorological variables on decomposition *of Phragmites australis* and *Solidago canadensis* in the Balaton System. Theoretical and Applied Climatology. 151 (1-2) 1963-1979. https://doi.org/10.1007/s00704-023-04370-y **Q2 IF: 3.410**

Simon, Sz., Simon-Gáspár, B., Soós, G., Anda, A. (2021): Preliminary Study on Water Bodies' Effects on the Decomposition Rate of Goldenrod Litter. Atmosphere. 12 1394. https://doi.org/10.3390/atmos12111394 **Q2 IF: 3.110**

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Simon, B., **Simon, Sz.**, Kucserka, T., Anda, A. (2019): A nád (*Phragmites australis*) lebontási ütemének vizsgálata a Kis-Balaton Ingói-berkében. Hidrológiai Közlöny 99 (3) 61-64 p.

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