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The Effects of Soil Drying Out and Rewetting on Nitrogen and Carbon Leaching—Results of a Long-Term Lysimeter Experiment

Holger Rupp [1,*], Nadine Tauchnitz [2] and Ralph Meissner [1]

[1] Department of Soil System Science, Helmholtz Centre for Environmental Research GmbH—UFZ, Dorfstrasse 55, 39615 Hansestadt Werben, Germany; ralph.meissner@ufz.de

[2] Centre for Agronomy and Crop Production, State Institute for Agriculture and Horticulture Saxony-Anhalt, Strenzfelder Allee 22, 06406 Bernburg, Germany; nadine.tauchnitz@llg.mule.sachsen-anhalt.de

* Correspondence: holger.rupp@ufz.de; Tel.: +49-391-8109-773

Abstract: As a result of global climate change, heavy rainfall events and dry periods are increasingly occurring in Germany, with consequences for the water and solute balance of soils to be expected. The effects of climate change on nitrogen and carbon leaching were investigated using 21 non-weighable manually filled lysimeters of the UFZ lysimeter facility Falkenberg, which have been managed since 1991 according to the principles of the best management practices and organic farming. Based on a 29-year dataset (precipitation, evaporation, leachate, nitrate and dissolved organic carbon concentrations), the lysimeter years 1995/96, 2018/19, and 2003/04 were identified as extremely dry years. Under the climatic conditions in northeastern Germany, seepage fluxes were disrupted in these dry years. The reoccurrence of seepage was associated with exceptionally high nitrogen concentrations and leaching losses, which exceeded the current drinking water limits by many times and may result in a significant risk to water quality. In contrast, increased DOC leaching losses occurred primarily as a result of increased seepage fluxes.

Keywords: climate change; drought; lysimeter; climatic water balance; nitrogen; dissolved organic carbon

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1. Introduction

The effects of global climate change have become increasingly evident in the recent past. For example, the observed increase in precipitation variability led to an increase in the frequency of extreme precipitation and drought events [1]. Germany is also one of the countries that have been strongly affected by extreme weather events in the recent past. In 2002 and 2013, high-yield precipitation events caused significant flood damage in the Elbe River catchment. In contrast, 2003, 2018, and 2019 were characterized by exceptionally high temperatures and low precipitation. Summer droughts (especially with higher summer temperatures) are likely to occur more often [2,3]. Besides precipitation, potential evaporation is also subject to change and will, on average, increase due to expected higher temperatures. Extreme weather events affect the soil water balance and seepage-linked solute fluxes in the soil [4,5]. Some authors reported that seasonal patterns of precipitation are also likely to change. Prolonged dry periods will alternate with more intense rainfall events, even in regions where mean precipitation decreases [6,7]. As already predicted by the IPCC [8], increased evaporation combined with less precipitation in summer can lead to lower groundwater tables, which may in turn amplify the impact of summer droughts in groundwater fed ecosystems. Therefore, climate change can result in significant changes (increase or decrease) in water cycle components due to changes in temperature and precipitation.

Recently, different approaches have been developed to characterize the soil water content of agricultural soils, respectively, for the identification of drought years. Doering et al. [9] compared eight different methods for the derivation of a drought index under the climatic conditions of Central Germany. Under these conditions, the Harlfinger–Knees Index turned out to be the best-fit approach. This procedure is predominately based on the calculation of the climatic water balance (CWB). To monitor and evaluate drought objectively, numerous drought indices have been developed [10–14]. Among them, the Palmer Drought Severity Index [12] is one of the most widely used, based on a water balance approach, which considers the cumulative departure (relative to local mean conditions) of atmospheric moisture supply and demand, and incorporates precipitation, soil water storage, runoff, and evapotranspiration into a hydrological accounting system [15,16]. The Palmer Drought Severity Index is deemed to be a comprehensive drought indicator, which considers the impact of climate change on hydrological systems, and is applicable to multiple types of drought identification and assessment [17–19]. The Standardized Precipitation Evapotranspiration Index was proposed by Vicente-Serrano et al. [14] as an approach that takes the potential evapotranspiration as water demand into account. It uses the difference between precipitation and potential evapotranspiration to assess the surface water balance and can be used to reflect the effects of both precipitation and temperature on the patterns of dry and wet weather.

Many drought indices have the major weaknesses that they were unable to reflect the course of the soil moisture status. This deficiency could be overcome in the Drought Monitor developed by the Helmholtz Centre for Environmental Research GmbH–UFZ (UFZ) [20]. Based on current meteorological data of 2500 weather stations operated by the German Meteorological Service (DWD) soil moisture is simulated by the mesoscale Hydrological Model (mHM) [21,22] for a 4 km grid. By comparing the soil moisture with the value expected from long-term data, the Soil Moisture Index is calculated (SMI, [22]) and the drought status determined.

As a result of drought events, cascading impacts of climate change on several sectors are to be expected. The changes in soil water balance that occur during droughts (e.g., decrease in seepage) and the associated increase in soil temperatures have sub-mediated consequences for the solute transport and transformation processes that take place in the soil. It is known that drought affect nitrogen (N)- and carbon (C)-cycling in soils substantially by changes in the soil water potential, destruction of water transport mechanisms and prevention of microbial mobility [23], increased microbial immobilization [24], reduced microbial activity and reduced plant uptake [25] leading to an accumulation of N in soils. Predicted changes in temperature, precipitation patterns and CO_2 concentrations in the future could significantly impact the fluxes of soil mineral N [26]. Model simulations on the impact of changes in climatic variables on both winter wheat yield and N leaching from soils in Denmark indicated that N leaching increased with temperature, particularly for coarse, sandy soils compared to the sandy, loam soils [27]. Soil N leaching in tile drainage under future climate conditions increased by 34% for a corn–soybean rotation cropping system compared to the historical climate in Iowa, USA, which was attributed to the reduced corn N uptake [28]. Otherwise, different authors reported reduced nitrate (NO_3) leaching in dry years caused by low seepage water amounts [29–31]. However, it was also shown that excess fertilizer N might accumulate in soils and will be leached time-delayed with the formation of seepage water [30]. Accordingly, it was observed in several studies that excess N of fertilizers was immobilized in the soil organic N pool where it can be mobilized again depending on mineralization conditions [32–34]. Thus, about 98 to 99% of NO_3 leaching were attributed to the organic N pool in lysimeter trials [34,35]. In turn, rewetting after drought can cause reactivation and rapid growth of microbes related to a rapidly mobilization of accumulated N [36–38], which can result in enhanced NO_3 leaching [39,40]. Comparable effects of increased temperature and alternating drying–rewetting events on mobilization of dissolved organic carbon (DOC) and increased DOC leaching were also reported for organic soils [41–43] and for mineral soils [44–46].

Significant effects of global warming are also expected on soil carbon and on the leaching behavior of DOC. Drought events can have significant impacts on ecosystem

C fluxes. For climate warming (similar to +2 °C) significantly increased DOC leaching rates for intensive and extensive mountain grassland management will be expected [47,48]. Warming and drying can accelerate the production of potential dissolved organic material (DOM) within organic horizons [49].

From studies on tropical soils, a breakout of respiration and nitrification during the rewetting of dry soils is known (“Birch Effect”) [36,50–52]. It can be assumed that these mechanisms will become more important under the conditions of climate change.

Detailed knowledge of the soil water and solute balance under changing climatic conditions is urgently needed for assessing the resilience of agriculturally used soils and for decision-making on key issues for the most sustainable land management possible.

Based on the current state of knowledge, we establish the working hypothesis that the water and solute balance of agriculturally used soils is adversely affected by drought events (amount of seepage and solute concentration).

Accordingly, a 29 years’ time series of lysimeter measurements was evaluated with following objectives (i) to identify experimental years with extremely dry weather (dry years), (ii) to characterize the influence of extreme drying on seepage formation, and (iii) to reveal the associated effects on the N and DOC leaching and their hazard potentials regarding water quality.

2. Materials and Methods

2.1. Lysimeter Facility

For studies on the effects caused by climatic changes, long-term measurement series under comparable boundary conditions are required. Lysimeter are especially suited to investigate water and solute fluxes in soils [47,53–57]. They enable us to investigate the effects of a changed climate based on long-term measurement series [54,58–60]. Long-term lysimeter experiments were carried out at the Lysimeter facility of the UFZ in Falkenberg (coordinates 52.859780 N, 11.812595 E). The site is located in the North-East German lowlands and belong to the temperate zone of Central Europe within the transition zone from maritime to continental climate with an average precipitation of 524.5 mm (1968–2007) and an average temperature of 9.2 °C (1994–2007).

This study is based on 21 non-weighing gravity-flow (free drainage) lysimeters (NWLYS). The simple NWLYS type is used often in Germany and other central European countries for applied research on land management and its impact on drainage water quantity and quality [61,62]. They were constructed in the form of a sheet steel vessel with a quadratic surface area of 1 m^2 and a total depth of 1.25 m. A drainage pipe (inner diameter 63 mm) was installed inside the filter layer (25 cm thick filter layer-sand over gravel over stone gravel) to collect the seepage and to discharge it into a storage tank located at the lysimeter cellar [53,63]. The lysimeter vessels were filled with soil material from an agricultural site located 15 km to the west in 1981. The soil type of the topsoil (0–30 cm) and subsoil (31–100 cm) was characterized as loamy sand (LS). During manual filling of the lysimeters, special emphasis was placed on restoring the soil structure of the extraction site within the lysimeter [53]. In the course of previous coupled investigations in lysimeters and in small catchment areas it could be shown that, despite the design deficiencies of the NWLYS type used here with regard to seepage formation and capillary rise, reliable results can be obtained with regard to the water and solute balance of sandy soils studied [53,63].

The main soil physical and soil chemical properties of the soil incorporated in the lysimeter vessels are shown in Table 1. The content of total organic carbon was low, as well as soil pH.

Table 1. Basic parameters of the lysimeter soils. Soil texture class (WRB, 2006), soil texture with sand (2.0–0.06 mm), silt (0.06–0.002 mm) and clay (<0.002 mm). Bulk density (ζd), saturated conductivity (Ks), soil pH, total organic carbon (TOC) in topsoil (0–30 cm) and subsoil (31–100 cm) in the lysimeters measured at the agricultural site from which the lysimeter soil was taken.

Soil Texture	Sandy Loam (SL)	Sandy Loam (SL)
Layer	**Topsoil**	**Subsoil**
Sand (%)	73.6	75.2
Silt (%)	14.3	17.4
Clay (%)	12.1	7.4
ζ_d (g cm^{-3})	1.48	1.84
K_S [(1)] (cm d^{-1})	21	43
pH^{KCl} [(2)]	4.8	5.6
TOC (%)	1.13	0.17

[(1)] Stationary procedure. [(2)] Potassium chloride method.

The initial lysimeter experiment was started in the lysimeter 1983/84 year (lysimeter year extending from May to April of the following year). Results presented here were from the period 1991/92–2019/20.

In addition, selected climate parameters were also measured at the UFZ lysimeter facility. Precipitation was measured daily at ground level and at a height of 1 m above the ground using rain gauges with a collecting surface of 200 cm^2 (standard rain gauge of the DWD). With the help of a land evaporation pan (surface area 3 m^2, water depth 0.6 m) the evaporation from a free water surface was measured in the months April–October. For November, December, January, February, and March, an additional evaporation of 61 mm was considered in the calculation of the annual evaporation rate according to DWD [64]. In evaluating the experimental results, we calculated the CWB as the difference between the precipitation (P) in the lysimeter year and the measured evaporation rate (EP).

To characterize the drought situation present in the individual years from 1991 to 2020, the results of both the UFZ drought monitor and the specifically calculated CWB for the UFZ Lysimeter facility site were used.

2.2. Cultivation of the Lysimeter Soils

Table 2 provides an overview of the different agricultural management systems for arable land and the associated fertilizer applications. Manure was applied in liquid or solid form. The cultivation was typical for agricultural production in the reunified Germany in 1991, while fertilization was more experimentally designed. The effects of extreme events were studied using the agricultural management systems Organic Farming (OF) and Best Management practice (BMP). Both mineral and organic fertilizers are used on lysimeters managed according to BMPs. In contrast, only the application of organic fertilizers is permitted at OF. In our lysimeter study, we used catch crops such as a mixture of corn and sunflowers, which were harvested in late autumn and removed from the lysimeters in both, OF and BMP. The established crop rotations have been maintained since the lysimeter year 1991/92. The significant differences in the level of N fertilization between the OF and BMP experimental agricultural management systems are due to the experimental design, which aimed to clearly differentiate the two management systems.

Table 2. Overview on the experimental lysimeter management practices and fertilization (W. = winter).

Designation of Experiment	Number of Lysimeters	Crop Rotation	Mineral N-Fertilization (kg ha^{-1})	Organic N-Fertilization (kg ha^{-1})
Organic Farming (OF)	12	W. Wheat and catch crop Pea and catch crop. W. Wheat and catch crop Clover mixture Oats and underseed Potatoes	0 0 0 0 0 0	80 (1) - 80 (1) - - -
Best Management Practice (BMP)	10	Wheat and catch crop Potatoes W. Barley and catch crop Corn Sugars beets	145 120 145 100 80	- 150 (2) - - 125 (2)

(1) Beef liquid manure. (2) Manure from cattle, N-content 5–6 kg N/t.

Nitrogen was fertilized at BMP in the form of calcium ammonium nitrate (CAN, 26% N, 10% Ca). Crop protection products (herbicides, fungicides, insecticides, and others) were not used on the lysimeters.

The lysimeters were irrigated from 1991/92 until 2003/04 according to the plant physiological needs for yield maximization. Depending on crop and specific climate conditions, irrigation water was additionally applied (Figure 1). This irrigation regime was changed in the lysimeter year 2004/05. From this date onwards, the crops were irrigated exclusively for safeguarding plant stocks, which resulted in a significant reduction in the amount of irrigation water applied (up to 50 mm annually).

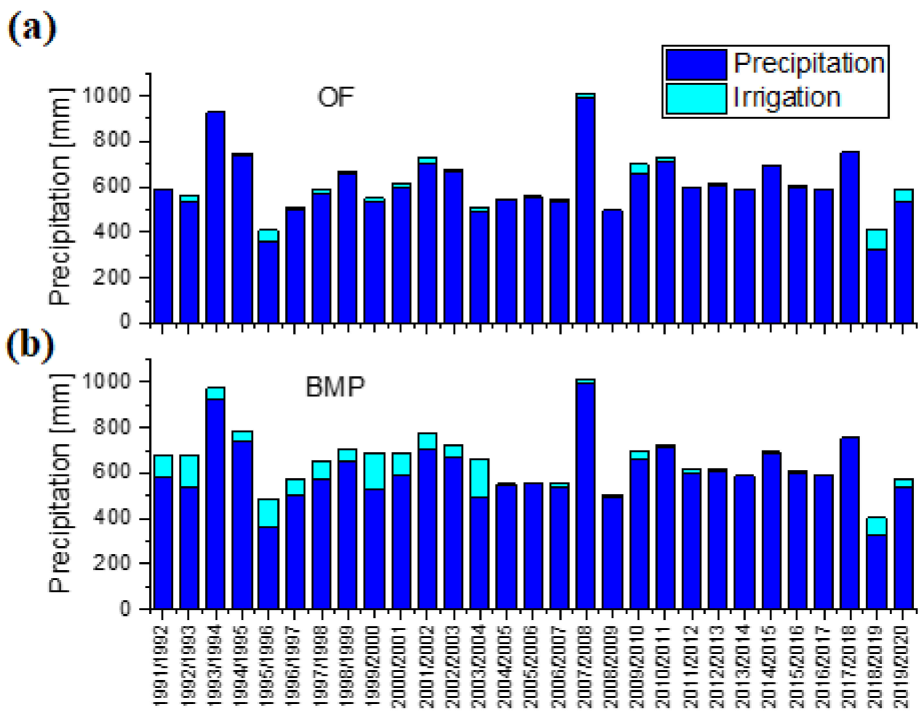

Figure 1. Water supply (precipitation and irrigation) of Organic Farming (OF (**a**)) and Best Management Practice (BMP (**b**)) management types during the study period 1991/92–2019/20.

2.3. Leachate Sampling, Water Analyzes and Assessments

Lysimeter leachates were continuously sampled in the storage tanks when discharge occurred (predominantly in the months of November to April). The amount of leachate was determined monthly by weighing the leachate collection tanks once a month. Monthly samples were taken, filtered through 0.45 µm Millipore syringe filters and analyzed in the UFZ facility laboratory for concentrations of Nitrite (NO_2-N), NO_3-N, and ammonium (NH_4-N) according to German Industrial Standards (DIN 38,405–38,406) by ion-exchange chromatography (IC, Thermo Fisher Scientific, Dreieich, Germany). The further evaluations refer to the N concentration as the sum of NO_3-N, NO_2-N, and NH_4-N.

DOC was determined using a C-analyzer (Dimatec, Essen, Germany), in accordance with German Industrial Standards (DEV, H3).

We calculated monthly loads based on monthly N and DOC concentration and amount of seepage water, which were finally used for the calculation of average annual N and DOC concentrations and annual loads (weighted averages), respectively. Lysimeter results were evaluated in time steps of lysimeter years (period April of the current year to March of the following year).

2.4. Statistics

Descriptive statistical methods with linear regression function were applied for data assessment and performed using the software package ORIGIN (OriginLab Corporation, Northampton, MA, USA). Since measured values were not normally distributed, Spearman rank values (r_s) were estimated. This coefficient is robust against outliers. Correlations with probability values (p) < 0.05 were regarded as statistically significant and $p < 0.001$ as highly significant. Box-whisker plots were calculated using the OrginPro software package. Using the available data series of precipitation, evaporation, and the resulting CWB, outliers (trial years that deviated decisively from the trend of the data series) were identified. Experimental years were accordingly considered extremely dry if the CWB fell below the interquartile range (IQR). Wet years, on the other hand, were characterized by an exceedance of the IQR. Furthermore, the Kruskal–Wallis test (One-way ANOVA on ranks) as a non-parametric method was used for testing whether lysimeter data of the different agricultural management systems originate from the same distribution.

3. Results and Discussion

3.1. Identification of Drought Years

Figure 2 shows the CWB calculated for the site of the UFZ lysimeter facility in the study period 1991/92 to 2019/20. The lysimeter years 1993/94, 2007/08, and 2017/18 were characterized by a significant CWB surplus of 343.8 mm, 447.8 mm, and 242.9 mm, respectively. In contrast, the CWB showed a deficit in 18 of 29 lysimeter years considered. Using the box plot of CWB, the experimental years 1995/96, 2003/04, and 2018/19 were identified as dry years because in these years the CWB was equal or below the value of −250.7 mm (=1.0 IQR) (Figure 2). In doing so, a procedure commonly used in statistics was used to identify outliers. In a modification of the common procedure, a value is considered an outlier if it exceeds 1.0·IQR above the upper quartile (Q3) or below the lower quartile (Q1).

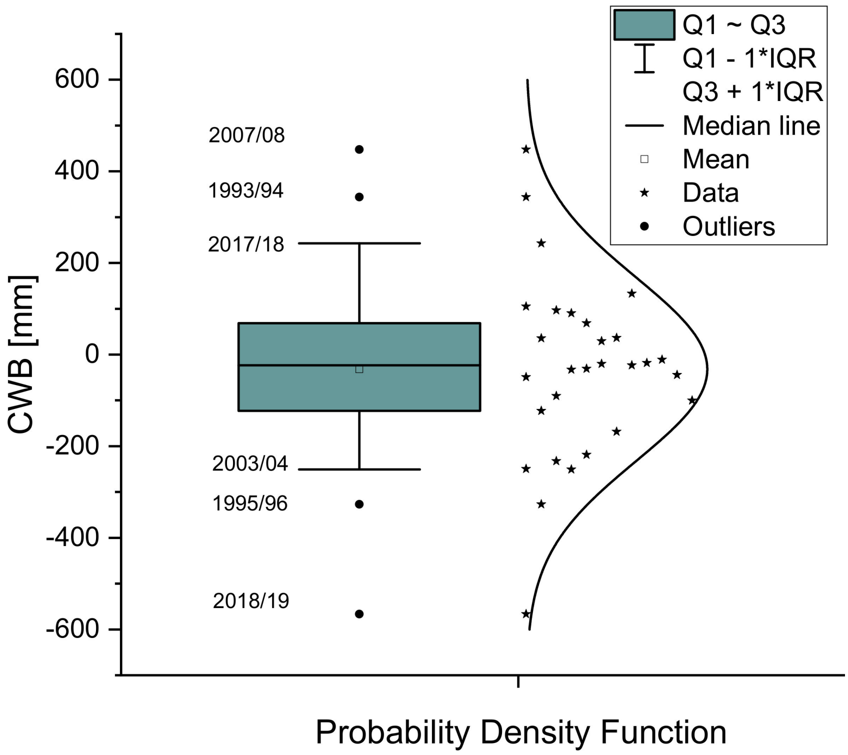

Figure 2. Box plot and probability density function of the Climatic Water Balance for the identification of years with extreme weather conditions during the study period 1991/92–2019/20.

The calculation of the CWB according to the basic principles of the Standardized Precipitation Evapotranspiration Index is a suitable approach for the approximate characterization of dry years [9,14]. Using the drought magnitudes in the topsoil (annual values) calculated by the UFZ Drought Monitor [20,65], periods of extreme drought could be identified in 1996, 2003, 2011, 2018, 2019 and 2020 (Figure 3). Thus, a comparable result regarding the identification of years with extreme drought (with exception of the years 2011, 2019 and 2020) could be achieved using different approaches. The Drought Magnitudes were used to characterize the soil moisture profile in the topsoil during the growing season and were calculated based on the change in soil water content in the topsoil. In contrast, the CWB calculation considered evaporation over the course of the entire year. Furthermore, the climatic water balance was calculated for lysimeter years (period April of the current year to March of the following year). The differences between the two approaches to characterizing drought years can therefore be attributed to the consideration of different time periods. The CWB is of particular importance from the point of view of hydrology, since its calculation considers the precipitation and evaporative losses of a whole year.

3.2. Seepage in Drought Years

In the dry years 1995/96 and 2018/19, seepage fluxes in the lysimeters of the OF and BMP land management were largely interrupted (Figure 4). This effect occurred despite the additional irrigation water supply spread to maintain stands and yields (1995/96: 45 mm (OF) and 123 mm (BMP), 2018/19: 87 mm (OF) and 75 mm (BMP), respectively). In 1996/97, hardly any seepage occurred either, as the CWB showed a deficit that could not be compensated by the precipitation (and by the supplemental water supplies).

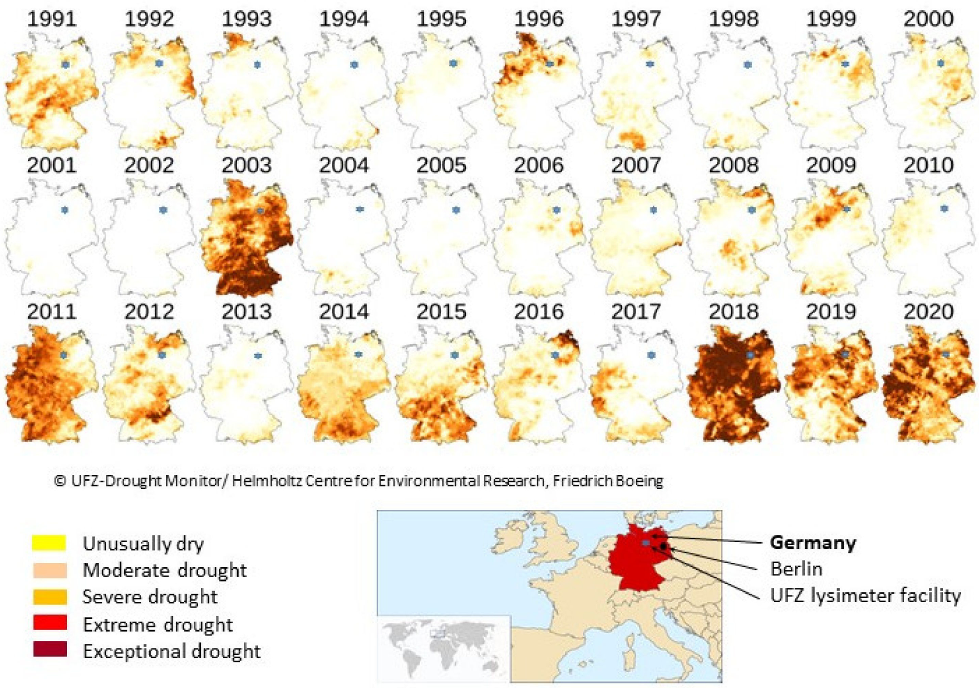

Figure 3. UFZ Drought Monitor—Drought magnitudes in the topsoil in the growing season April to October and location of the study area (the circles indicate the location of the UFZ lysimeter facility).

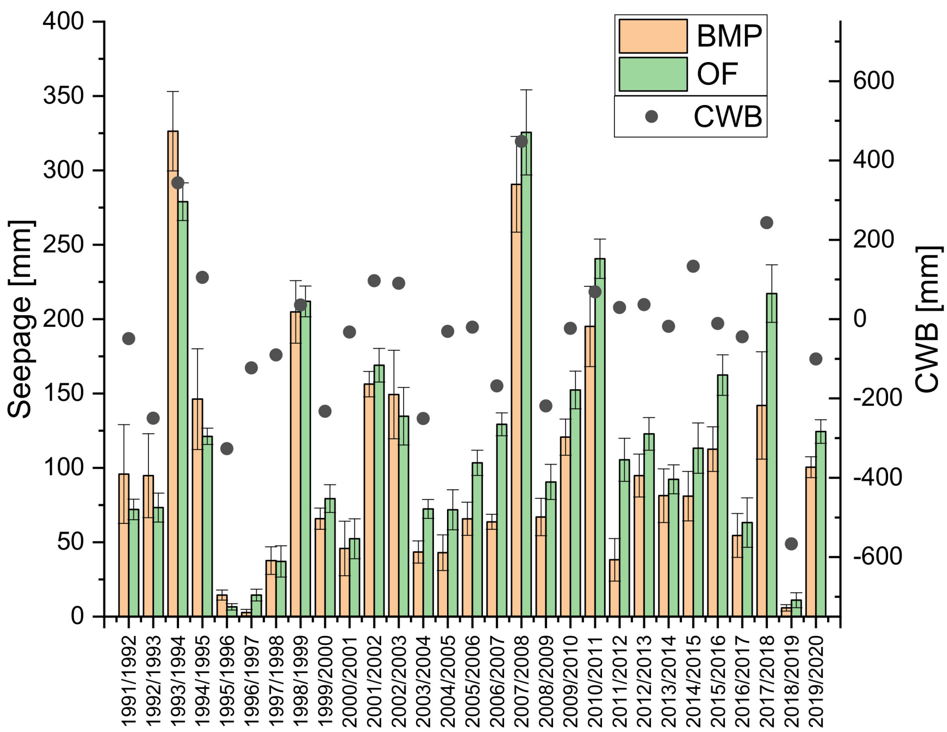

Figure 4. Mean seepage of Organic Farming (OF) and Best Management Practice (BMP) and the corresponding values of the climatic water balance for the study period 1991/92–2019/20 (bars for standard error of means, dots for the climatic water balance).

The year 2003/04 was an exception. Due to the extreme weather situation, the lysimeters were intensively irrigated with 20 mm (OF) and 175 mm (BMP), respectively. As a result, seepage amounts of 67.8 mm (OF) and 43.5 mm (BMP) were measured in this lysimeter year. Seepage flux was found to be mainly controlled by evaporative demand, precipitation, and land cover type [66]. As already described by Maeder et al. [67], plant stands on lysimeters managed according to OF principles were less developed due to the lower nutrient supply compared to lysimeters managed according to BMP. Accordingly, less water was consumed by evapotranspiration and could reach infiltration, resulting in the higher seepage fluxes under OF. This effect was observed throughout the study period, except for the first five years after land use conversion. Seepage of OF and BMP showed highly significant differences at a significance level (α) of 0.1% (Kruskal–Wallis-ANOVA, $n = 29$). The intensive irrigation of the crops in BMP land management practiced until 2004 primarily resulted in increased biomass production. Thus, a dry matter yield of 17.702 t ha^{-1} was achieved on lysimeters managed according to BMP principles from 1991/92 to 2003/2004. In the management system OF, on the other hand, it was only 12.997 t ha^{-1}. After changing the irrigation intensity, mean dry matter yields decreased in both management systems to 9.408 t ha^{-1} (OF) and 16.164 t ha^{-1} (BMP) from 2004/05 to 2019/20, respectively. The irrigation met the plant physiological needs of the crops and did not result in increased seepage formation.

3.3. N and DOC Leaching

As a result of the drying out of the soil profile and the lack of free soil water, no matter fluxes with seepage water took place in the dry years. It can therefore be assumed that existing nutrient surpluses as a result of the management measures initially remained in the soil reservoir and could only be mobilized after the onset of seepage flux, as also shown in other studies [30]. Soil moisture was an important parameter that controls N solubility at the scale of individual soil pedotopes. Soil drying and rewetting promoted the release of dissolved inorganic N [68]. Rewetting of dried soils caused an immediate but short-lived N mobilization [37,69].

From our investigations with conservative tracers (Cl, Br, ^{15}N or deuterium) we know that a mean annual seepage of 100 mm results in a leaching depth of about 50 cm [70]. Thus, a nutrient or contaminant front requires about 2 years to flow through the lysimeter soil column with 1 m thickness (at piston flow) under average precipitation conditions. Numerous authors point out the great importance of preferential flow processes for rapid solute transport in soils [71–76]. Therefore, a time lag between drought and measurable effects on the substance concentration in the seepage have to be taken into account. Measurable consequential effects of nutrient accumulation in the topsoil of the lysimeter on leachate concentration due to drying out are to be expected in the presence of preferential flow paths within one year, but at the latest in the following year or with a time lag of 2 years.

A box plot of mean N concentrations (Figure 5) shows significantly elevated mean N concentrations (outliers) of 111.6 mg L^{-1} for BMP lysimeters in the 2019/20 lysimeter year. These elevated N concentrations occurred as a direct result of the drought in 2018/19 with a CWB of −566.6 mm. In the lysimeter years 2012/13, 2009/10, and 2008/09, the mean N concentration measured was 57.7 mg L^{-1}, 50.8 mg L^{-1}, and 50.3 mg L^{-1}, respectively, which met or exceeded the 1.0 IQR range. Here, intense nitrogen leaching occurred due to comparatively high precipitation in the lysimeter years 2010/11 and 2007/08, amounting to 705 mm and 993.6 mm, respectively.

At OF, the highest N concentration exceeding the 1.0 IQR was recorded immediately after the changing of the experimental scheme in the lysimeter year 1991/92 with 86.6 mg L^{-1} and thus could be characterized as an outlier. Elevated mean N concentrations in 1996/97, and 1997/98 were noticeable. They are considered to be a late consequence of exceptionally high precipitation of 927.3 mm in the lysimeter year 1993/94.

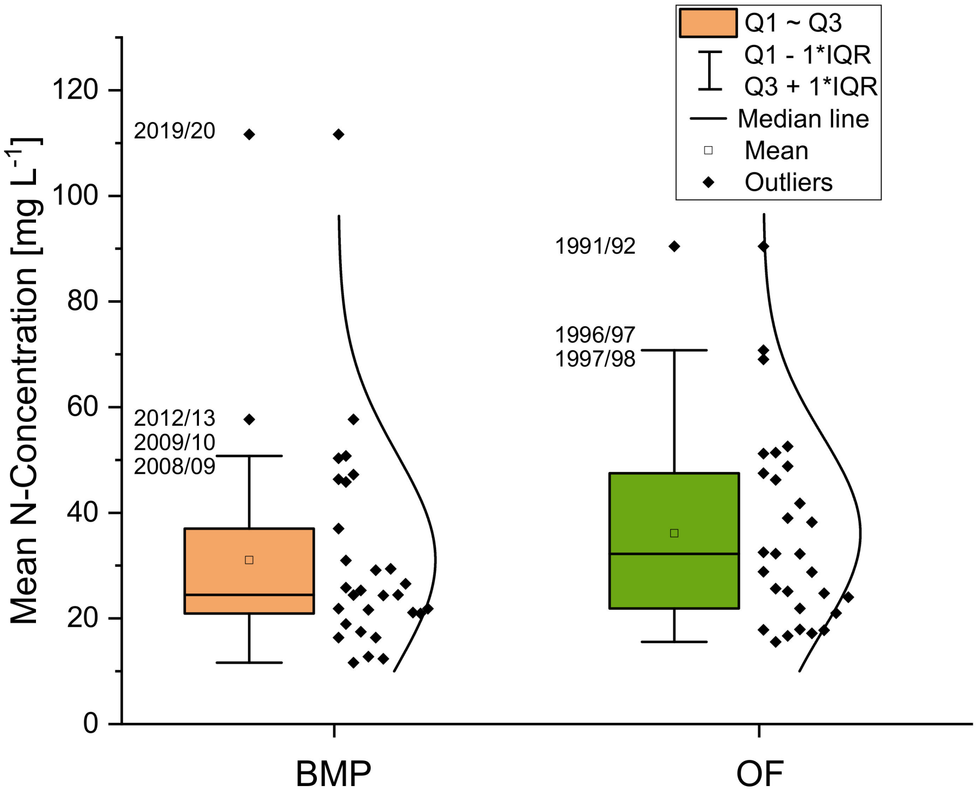

Figure 5. Box plot and frequency distribution of mean N concentration and identification of lysimeter years with distinct increasing of mean N-concentration of Organic Farming (OF) and Best Management Practice (BMP) for the study period 1991/92–2019/20.

Overall, however, the higher level of mean N concentrations at OF compared to BMP is striking. In contrast to BMP, N concentrations measured at OF show a significant decreasing trend at a probability level of 0.05 ($r_s = -0.48$). However, the differences between the mean N concentrations measured in the two management options were not significant (Kruskal–Wallis ANOVA). Nitrogen consumption by the cultivated crops was reduced due to the lower nutrient supply at OF. Thus, this management option showed a mean annual crop N harvest removal of 158 kg ha^{-1}. In comparison, 194 kg N ha^{-1} per year were absorbed under BMP management. The reduced nutrient removal in OF compared to BMP is due to poorer crop stand development as a result of suboptimal fertilization. Overall, the level of mean N concentrations was comparatively high in both agricultural management systems. The drinking water limit for NO_3 of 50 mg NO_3 L^{-1} (11.3 mg N L^{-1}) [77] was frequently exceeded. This was especially true for the lysimeter year 2019/20, when an average N concentration in seepage of 111.6 mg N L^{-1} was calculated.

Figure 6 shows the DOC concentrations measured during the study period for OF and BMP lysimeter management. For BMP, the highest mean DOC concentrations of 20.4 and 18.6 mg L^{-1} were recorded in the lysimeter years 2004/05 and 2003/04, respectively. Thus, in the dry year 2003/04, high soil temperatures (according to DWD information, the highest mean soil temperatures of 25 °C were measured in August 2003 within the 1976–2015 time series) combined with improved water supply due to intensive irrigation resulted in mobilization and leaching of dissolved organic carbon compounds, leading to the elevated DOC concentrations in seepage. The increased DOC concentrations were decisively influenced by temperature-dependent biological turnover processes [78–80]. Increased DOC concentrations in seepage of lysimeters managed according to OF principles in 1996/97 resulted from the rewetting of the topsoil and subsoil after two consecutive years (1994/95 and 1996/97) of little or no seepage. The DOC concentrations measured in both agricultural management systems showed a comparatively low level compared to other sandy soils [81,82]. Mean DOC concentrations of lysimeters ranged from 2.1 to 23.2 mg L^{-1} during the study period with median values of 10.7 mg L^{-1} (OF) and 11.8 mg L^{-1} (BMP), and thus were in line with values reported for loamy sand soils in previous studies [83]. The elevated DOC concentrations were the result of altered soil water contents [78,84,85] and a succession of wet and dry periods [86].

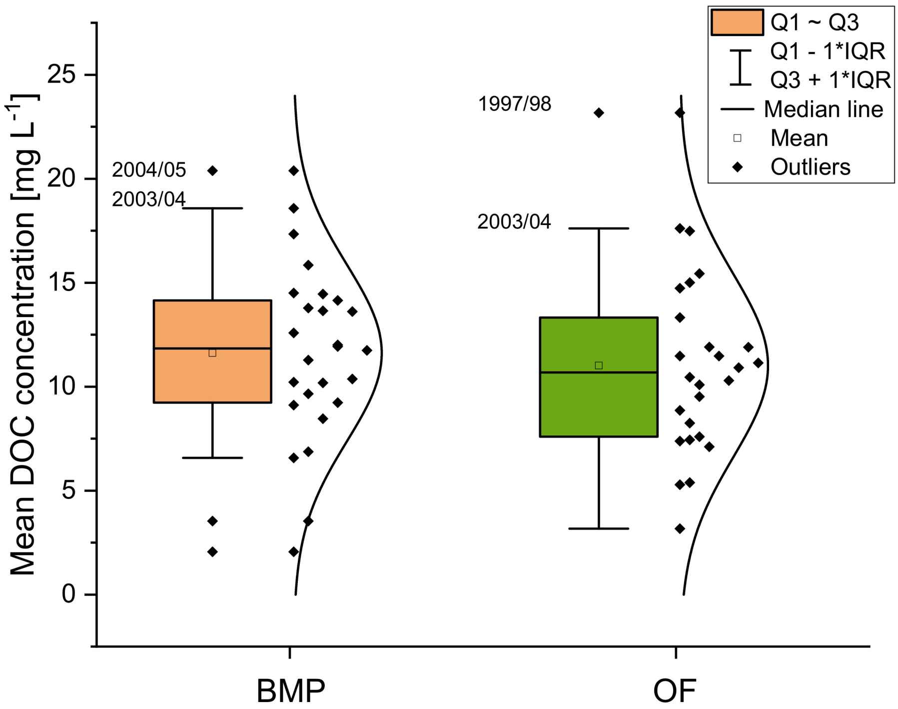

Figure 6. Box plot and frequency distribution of mean DOC concentration and identification of lysimeter years with distinct increasing of mean DOC concentration of Organic Farming (OF) and Best Management Practice (BMP) for the study period 1991/92–2019/20.

The DOC concentrations measured in the management systems OF and BMP did not show a statistically reliable trend during the study period. At the 0.05 level, the mean values of the statistical populations did not differ significantly (Kruskal–Wallis ANOVA). The mean level of DOC measured was comparably low in both management systems, although nutrients were supplied to OF exclusively via organic fertilizers (beef liquid manure and cattle manure). Thus, a different effect of mineral and organic fertilizers on the DOC concentrations in seepage as shown by other authors [81,87–89] could not be confirmed in our study. Several studies reported enhanced DOC concentrations and DOC export with seepage after application of solid animal fertilizers like manure [83,87,89]. Otherwise, the effect of mineral fertilizers on DOC concentrations were discussed contradictory comprising both, studies reporting enhanced DOC concentrations after mineral fertilization [90] and studies observing reduced effect of mineral fertilization on DOC concentrations in seepage [83]. It can be assumed that in our study differences between management variants could not be proved because organic fertilizers were applied in both variants.

Significant impacts of drought events on ecosystem carbon fluxes were also observed by Johnson et al. [48]. High microbial activity, high fungal abundance, and any conditions that enhance mineralization all promote high DOC concentrations. DOC is the most mobile soil organic carbon fraction. DOC in soils plays an important role in the transport of pollutants as well as in the biogeochemistry of pollutants and nutrients in soils. However, under field conditions, hydrologic variability in soil horizons with high carbon contents may be more important than biotic controls. There are strong indications that microbial degradation of dissolved organic matter also controls the fate of DOC in the soil [45].

DOC leaching is subject to seasonal fluctuations, is influenced by site and environmental factors. There tends to be a positive correlation between DOC concentration and temperature, humidity and pH [91]. Furthermore, there are indications that the DOC concentration in the soil solution depends on the redox potential (E_H) of the soil. As a result of lysimeter and field experiments, we have found that DOC increased with decreasing E_H [92].

Sudden pulse-like events of rapidly increasing CO_2-efflux are reported in soils under seasonally dry climates in response to rewetting after drought. These occurrences, termed "Birch effect", can have a marked influence on the ecosystem carbon balance. Current hypotheses indicate that the "Birch" pulse is caused by rapidly increased respiration and mineralization rates in response to changing moisture conditions, but the underlying mechanisms are still unclear [50,51]. Intense drying periods can also cause a decrease in cumulative N-mineralization. Short drying of the soil—below a site-specific threshold of desiccation intensity—followed by periods where air temperature and soil moisture are near their optimal values, can lead to a significant increase [93]. It can therefore be assumed that the N and DOC concentrations measured in the seepage are influenced by these temperature- and moisture-dependent processes.

Mean nitrogen loads measured were roughly comparable in both management systems at 31.2 (BMP) and 38.0 (OF) kg ha^{-1}, respectively, and showed low levels compared to literature data (Figure 7) [94–97]. The highest N loads were observed at 86.6 and 60.1 kg ha^{-1} (OF) and 85.4 and 112.1 kg ha^{-1} (BMP), respectively, in the 2007/08 and 2019/20 experimental years. The high N loads in 2007/08 were caused by a significantly increased rainfall of 993.6 mm, which was accompanied by increased seepage fluxes. In contrast, the extraordinarily high N load measured in the lysimeter year 2019/20 was the consequential effect of the dry year 2018/19. As a result of the rewetting of the dried soil profile, nitrogen conversion and mobilization processes resumed. N present in the soil profile was mobilized and leached out. A significant risk to groundwater quality may result from these processes.

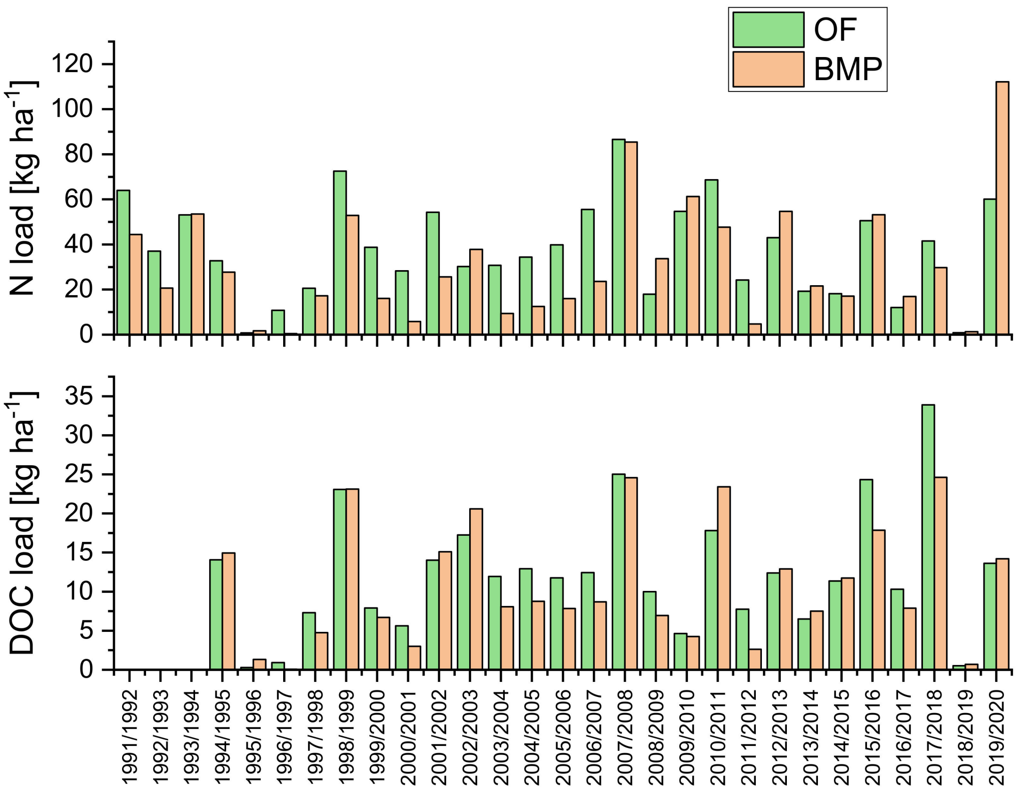

Figure 7. Loads of Nitrogen (N) and Dissolved Organic Carbon (DOC) of Organic Farming (OF) and Best Management Practice (BMP) for the study period 1991/92–2019/20.

The mean annual DOC loads of 10.9 kg ha^{-1} (OF) and 9.7 kg ha^{-1} (BMP) were also comparable for both management systems (Figure 7). Significantly increased DOC loads were measured for OF and BMP in the experimental years 2007/08 and 2017/18, which were considered wet years due to increased CWB. Increased leachate formation led to the elevated DOC loads in these years [81]. An effect of dry years comparable to the N loads could not be proven on the basis of the DOC loads.

4. Conclusions

Thanks to long-term lysimeter investigations, it could be confirmed that extreme weather situations had adverse effects on the water and substance balance of agriculturally used soils. In the seepage following a dry phase, extraordinarily high N fluxes were observed. Thus, seepage that flows into groundwater via the vadose zone after dry years has the potential to threaten the quality of these water resources. The measured DOC concentrations were also affected by soil temperature and soil moisture regime. Increased DOC leaching losses occurred primarily as a result of increased seepage fluxes. Hence, the study showed that increasing alternation of dry and rewetting phases caused by climate change can have a decisive influence on agriculturally used soils on the quality of surface and subsurface waters that should be addressed in reduction measures.

Agriculture, in particular, is faced with the challenge of implementing appropriate management measures (e.g., reduction of N-fertilization), and thus contributing to an improvement of the water quality. In doing so, agricultural measures should be primarily focused on an improved calculation of N-fertilizer amounts to avoid an accumulation of excess N in the soils, caused by reduced plant N uptake in dry years. In this context, there is an urgent need to better model weather and mineralization conditions considering soil moisture, temperature, soil mineral N, and organic C contents of soils, e.g., as a practicable tool for farmers to calculate N-fertilizer amounts more efficiently. As an important parameter for the calculation of the N-fertilizer requirement of plants, an improved assessment of N supply by mineralization throughout the vegetation period should also be considered in further research.

Above this, there is still a need for research on the processes and relevant influencing factors (soil properties, humus quality, etc.) that lead to increased N and DOC fluxes in soils under strongly varying soil water contents.

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