water

MDPI

Article

Influence of Climatic Factors on the Water Footprint of Dairy Cattle Production in Hungary—A Case Study †

István Waltner, Attila Ribács, Borbála Gémes and András Székács *

Institute of Environmental Sciences, Hungarian University of Agriculture and Life Sciences, Páter Károly u. 1, H-2100 Gödöllő, Hungary; waltner.istvan@uni-mate.hu (I.W.); ribacs.attila@uni-mate.hu (A.R.)
* Correspondence: szekacs.andras@uni-mate.hu

† OECD disclaimer: The opinions expressed and arguments employed in this publication are the sole responsibility of the authors and do not necessarily reflect those of the OECD or of the governments of its member countries.

Abstract: Our study aims to provide a look at how the production of dairy cattle is affecting water resources in Hungary. Utilizing the AquaCrop model and field data from a selected field in Hungary, we focused on the evapotranspiration (*ET*) and water footprint (*WF*) of maize (the dominant component of silage mixes), while for other feed crops, we obtained data from scientific literature sources. We also considered drinking and servicing water consumption of dairy cattle, utilizing observations from a specific farm, as well as estimating potential heat stress at the country level. Our findings indicated increasing trends of crop *ET* as well as biomass production for maize, without significant correlations between the two parameters. Spatiotemporal analysis revealed a significant rise in the number of days with potential heat stress based on temperature-humidity indices, manifesting in practically the entire area of Hungary. Thus, while crop *ET* rates and corresponding crop water use values (4989–5342 m^3/ha) did not show substantial changes, maize *WF* in silage cultivation rose from 261.9 m^3/t dry biomass in 2002 to 378.0 m^3/t dry biomass in 2020. Feed and water intake was subsequently recorded on a cattle farm and assessed as green and blue water use. Drinking (blue) water uptake, ranging between 74.7 and 101.9 L/dairy cow/day, moderately correlated with temperature-humidity indices as heat stress indicators (r^2 = 0.700–0.767, $p < 0.05$). Servicing water was not recorded daily, but was calculated as a daily average (18 L/dairy cow/day), and was also considered in blue water usage. In contrast, feed consumption at the cattle farm corresponded to 13,352 ± 4724 L green water/dairy cow/day. Our results indicate that while the *WF* of animal feed remains a dominant factor in the total water use of dairy cattle farms, drinking water consumption and related costs of adaptive measures (such as adaptive breeding, modified housing, and technological measures) are expected to increase due to potential heat stress, particularly in selected regions where farmers should focus more on housing and technological solutions, as well as selecting for thermotolerance.

Keywords: dairy production; water footprint; maize; Hungary; temperature-humidity index; evapotranspiration; dairy cow; grey and blue water

Citation: Waltner, I.; Ribács, A.; Gémes, B.; Székács, A. Influence of Climatic Factors on the Water Footprint of Dairy Cattle Production in Hungary—A Case Study. *Water* **2023**, *15*, 4181. https://doi.org/10.3390/w15234181

Academic Editor: Xinchun Cao

Received: 27 October 2023
Revised: 30 November 2023
Accepted: 1 December 2023
Published: 4 December 2023

1. Introduction

The official slogan of FAO's World Food Day has been "Water is life, water is food" [1], emphasizing the heavy impact of water scarcity on food production and the potential mitigating effect of the economic use of water in food production. It also refers to the fact that agriculture, including livestock production, is responsible for nearly three-quarters of our overall freshwater consumption [2]. Worldwide agricultural production, based on the FAO's Gross Production Index, increased by 280% between 1961 and 2021, with an average annual increase of 2.3 ± 1.5% (ranging between −2.8% and 5.6%) [3]. In parallel, agricultural production in Europe increased by 45% with an average annual increase of

0.7 ± 3.8% (ranging between −16.7% and 9.1%). Within the same period, worldwide cattle production in livestock units increased by 55%, with an average annual increase of 0.7 ± 0.8% (ranging between −1.6% and 2.9%), but it tremendously dropped in Europe by −36%, with an average annual decrease of 0.7 ± 2.4% (ranging between −11.9% and 4.4%) [3].

The production of food of animal origin, particularly cattle, is known to have the largest water footprint (*WF*) in agriculture [4–6], and 43–98% or even a higher proportion of the total *WF* of animal products corresponds to the water required to grow feed crops [4,7–9]. This water use is the highest in feedlot systems, somewhat lower in fertilized irrigated pasture systems, and substantially lower in extensive unmodified pasture systems and semi-intensive silvopastoral systems [10]. To improve insight into the transparency, consistency, reproducibility, and credibility of assessing the water demand of livestock products, the Livestock Environmental Assessment and Performance Partnership (LEAP) was created in 2012 as an FAO multi-stakeholder initiative that seeks to improve the environmental sustainability of the livestock sector through harmonized methods, metrics, and data [11]. LEAP published its guidelines for water footprinting for livestock supply chains in 2019 [12], providing methodologies for data quality assurance, water use inventory, as well as for water scarcity impact and water productivity assessment; and published further recommendations for quantification of green and blue water consumed [13].

The *WF* of dairy livestock production has been assessed internationally [4,6,7,9,10,14–17] and in case studies from the US [18,19], Australia [20], New Zealand [21], China [22,23], Brazil [24], Ireland [25], South Africa [8,26], Tunisia [27], and other countries of the world. Studies have been published evaluating the issue in Hungary as well [28–30]. Dairy cattle can be heavily affected by heat stress [31]. Among the multiple potential effects of heat stress, water intake will typically increase, and milk production could decrease [32]. Heat stress can be monitored through both ambient temperature-humidity indices (*THI*s) or body temperature [33]. Multiple measures have been shown to reduce the effects of heat stress, including proper housing, shading, and the application of different cooling systems [34].

While the abovementioned previous studies have focused on aspects of heats stress or water footprint separately, we have found that there were no studies linking the two aspects together, directly addressing the effects of climatic changes on the water use of dairy cattle, especially for Hungary. The current study, therefore, aims to assess the potential effects of climatic factors (rainfall, evapotranspiration, temperature, humidity) on the water footprint of dairy cattle production (considering both feed and drinking water) by answering the questions: (a) What is the proportion of green water incorporated in animal feed?; (b) How do cattle respond to heat stress, and what are the spatial/temporal trends of heat stress days in Hungary?

2. Materials and Methods

2.1. Crop Cultivation

The commercial maize (*Zea mays*) cultivar of variety DK-440 was grown in two regions in Hungary, namely the Nagykovácsi region (Pest County) in 2002 and 2020, and the Zsámbék region (Pest County) in 2007, under field conditions, in crop densities of 60,000, 75,000, and 120,000 plants/ha for commodity, silage, and green silage, respectively. The experimental sites were selected for their moderate climatic conditions, not affected by frequent extreme meteorological events. The sites were located in the vicinity of the nature conservation area of Pilisi Parkerdő Zrt. (Visegrád, Hungary), owned by the Hungarian state, near Nagykovácsi, covering an area of 18.4 hectares, and a similar area with comparable characteristics located about 12 km away, near Zsámbék. Both sites showed common soil characteristics typical for Hungary. The topography of the experimental sites was flat, with a uniform surface, belonging to the chernozem brown forest soil type (according to the traditional Hungarian classification system), with predominantly silt texture throughout. Each experimental plot was set to a size of 5 × 30 m, where experiments on maize cultivation for grain, silage, and green silage were conducted (crop densities of 6–12 plant/m^2).

The experimental plots were arranged in a randomized block design. The typical practice of non-irrigated cultivation, commonly used in the region to reduce cultivation costs, was applied. Maize phenological stages were followed according to Ritchie et al. [35]. Maize plants cultivated for commodity, silage, and green silage purposes were sampled at harvest times in the R6, VT, and V12 phenological stages, respectively. Wet biomass data at the time of harvest were collected and measured by organs. At the time of sampling, four entire plants were collected and dissected, and organs (including, when appropriate: leaves, stem, root, anther, pollen, and grain) were separated. Plant samples were immediately processed upon sampling for fresh and dry weight measurements.

2.2. Water Footprint Calculation for Maize

Crop evapotranspiration (*ET*) of the cultivated commodities considered was estimated using AquaCrop software version 7.1 (Food and Agriculture Organization of the United Nations, Rome, Italy) [36]. AquaCrop software provides regional and annual prediction of above-ground biomass (as dry biomass/ha), yield, and crop *ET*. A direct calibration of the actual crop cultivation data and those predicted by AquaCrop could be established only as a formal correlation, because the two systems differed in several parameters: maize variety (DK-440 for Hungary, and multiple varieties suitable for Davis, NC, USA [37]), cultivation mode (silage and commodity maize), and reported biomass data (wet and dry biomass/ha). Climate data were obtained from the national gridded dataset from the Data Repository of the Hungarian Meteorological Service (Budapest, Hungary) [38]. The point-based estimation of *ET* provided an approximation of Green Water footprint. AquaCrop simulations were run for the 52-year period of 1971–2022, and maize crop *ET* rates obtained for the years of 2002, 2007, and 2020 were used for further calculations. Crop water use (*CWU*) values calculated from these total *ET* rates (of crop cultivation within the cropping period) were attributed to the overall above-ground maize biomass produced. *CWU* values were partitioned for different tissues of the main crop based on the ratios of the wet biomass data obtained in the given year (as seen in Section 2.1).

2.3. Cattle Production

Lactating Hungarian Simmental cows were raised on the Southern Great Plain (Békés County) [30]. Feed and drinking water intake were determined daily within the period of 1 July–31 in 2019 and 2020. Daily feed included 8 kg maize silage, 3 kg grass hay, 3 kg alfalfa hay, and 6.1 kg concentrate (containing 49% maize, 33% barley, 16% soybean meal, 2% feed supplement with dextrose and calcium carbonate). Thus, feed was of moderate dry matter content (13.3 kg), a high proportion of fodder concentrate (about 50% of the net energy for lactation), and crude fiber content (18% of the dry matter content) adequate to heat stress. Drinking water of 12–14 °C temperature was provided *ad libitum* via automatic drinkers equipped with flow meters. Water quality complied with livestock production quality requirements, and 24 hr drinking water consumption was registered daily at 6 PM. Animals were milked twice daily at 7 AM and 6 PM. External body temperature was measured individually, once daily at 3 PM (at the end of the warmest period) using non-contact thermometers (Medisana TM-750). Dry bulb air temperature (T_d) and relative humidity (*RH*) were determined simultaneously, daily at 3 PM using a digital measuring instrument. Wet bulb air temperature (T_w) was calculated online using a h-x calculator to obtain temperature-humidity indices (*THI*s).

2.4. Spatio-Temporal Assessment of Temperature-Humidity Indices

*THI*s have been developed to express the level of heat stress exerted on affected livestock. *THI*s are defined based on T_d and *RH*, typically expressed as T_w [39]. There are a number of *THI*s (*THI*1 through *THI*7, in which T_d and T_w-values are expressed in degrees

Celsius, and *RH* is a percentage), from which *THI*1 and *THI*2 [40,41], most typically applied in Hungary [42], were calculated using the formulae below [40,41]:

$$THI1 = (0.15 \times T_d + 0.85 \times T_w) \times 1.8 + 32 \quad (1)$$

$$THI2 = (0.35 \times T_d + 0.65 \times T_w) \times 1.8 + 32 \quad (2)$$

Spatial and temporal variation of *THI*1 and *THI*2 was carried out for the years 1971–2022, utilizing mean daily temperature and mean daily *RH* data for the entire area of Hungary, obtained from the gridded dataset of the Data Repository of the Hungarian Meteorological Service [38]. The spatial resolution of the dataset was $0.5° \times 0.5°$.

In order to assess the presence and direction of potential trends in the occurrence of above critical *THI* values, we applied the Mann–Kendall Test [43], which focuses on the detection of monotonic trends, with a null hypothesis of no trend being present [44]. All calculations and parts of the statistical analysis have been carried out using the R software environment version 4.3.1 (The R Foundation, Wien, Austria) [45]. Spatial processing was carried out using the free open-source software SAGA GIS (System for Automated Geoscientific Analyses; SAGA User Group Association, Hamburg, Germany) [46], and QGIS version 3.28 (Open Source Geospatial Foundation, Beaverton, OR, USA) [47], while further statistical evaluation was done in MS Excel (Microsoft Corp., Seattle, WA, USA).

2.5. Quantification of Water Footprint of Dairy Cattle

As our study focuses on the effects of climatic factors, e.g., *THIs*, on dairy cattle (and not specifically on milk production), the *WF* has been approached not as a value related to unit product mass but quantified as *WF* per animal. Thus, the *WF* of livestock production was calculated as the sum of indirect water consumption (through feed production) and direct water use (drinking and servicing water) per animal:

$$WF_{animal} = WF_{feed} + WF_{drink} + WF_{serv} \quad (3)$$

where WF_{feed}, WF_{drink}, and WF_{serv} refer to the partial WFs related to the cultivation of feed crops, as well as the consumption of drinking water and service water, respectively. Since no irrigation (blue water) needs to be involved in silage maize production, the crop utilized natural precipitation (green water) and used it as its constituent (moisture content) and for *ET*. *CWU* values obtained from the estimated total *ET* rates of crop cultivation were calculated only for the duration of the cropping period. Therefore, the green *WF* (*GWF*) of the crop, calculated from the green water *CWU* divided by the crop yield, indicates the green water amount required by a unit mass of the crop. Consequently, WF_{feed}, the amount of green water corresponding to the amount of the feed consumed by the animal, can be calculated from the amount of feed consumed by the animals. In this study, WF_{feed} was not recorded individually daily but calculated based on green water content needed for the cultivation of the daily amount of feed the animals consumed. In contrast, WF_{drink} and WF_{serv} were measured daily at the dairy farm. Thus, WF_{animal} in the present study is expressed as m^3 water per day per animal. The reason for not using annual values to express *WF* is that dairy farm animals were not studied throughout the entire year but only for the one-month duration of the study periods.

The feed of the dairy cows consisted altogether of 54.7% (mass/mass) maize (if maize silage and maize content in the concentrate are considered). Other crop components were grass hay, alfalfa hay, barley, soybean meal, and a minor amount of feed supplements (see Section 2.3). Moreover, certain feed components (e.g., soybean meal and the concentrate including it) were imported products; therefore, their *WF* could not be related to local weather conditions in Hungary. Therefore, while *WF* for maize was determined from local conditions, *WF*s of the other feed components were obtained from the scientific literature [48]. *WF*s for alfalfa hay (*Medicago sativa*) and barley (*Hordeum vulgare*) were calculated from reported yield and *ET* data for these crops cultivated in Hungary in 2017 at Gödöllő (Pest County) [48], in agreement with worldwide water productivity data reported for alfalfa cultivation [49]. Thus, *WF*s were 1363.6 and 877.7 m^3 green water/t dry biomass for alfalfa hay and barley, respectively. *WF* values for grass hay were reported [19], and an average *WF* value of nine different grasses was calculated to be 521.8 ± 83.7 m^3 green water/t wet biomass, corresponding to approximately 715 m^3 green water/t dry biomass. The *GWF* of soybean has been reported to be 2037 m^3 green water/t dry biomass [50] with high variability by worldwide location and cultivation type [50,51].

3. Results and Discussion

3.1. Crop Cultivation and Its Water Footprint

Biomass (above-ground mass/ha) values estimated by the AquaCrop model had a mean error of 4%, with a maximum error of ±30% when compared to field data. Maize wet biomass production data were analyzed for selected years between 2001 and 2021 in the Nagykovácsi and Zsámbék regions (Pest County) in Hungary. Phenological stages were followed according to Ritchie et al. [35]. Wet biomass data at the time of harvest, measured by organs, are listed for three representative cases in Table 1. Over the studied period (2001–2021), the average total wet biomass production was found to be 32.2 ± 19.2, 29.1 ± 7.6, and 43.1 ± 14.8 t wet biomass/ha for maize cultivated for commodity, silage, and green silage, respectively. The moisture content of the crop varied between 35.2% and 43.1%.

Table 1. Biomass production and water footprint (*WF*) of maize cultivation by crop tissue. Total evapotranspiration (*ET*), crop water use (*CWU*), and green *WF* were calculated by the AquaCrop crop-water productivity model [36].

Year	2002 [1]		2007 [1]		2020 [1]	
	Biomass (t wet mass/ha)	***CWU*** **(m^3/ha)**	**Biomass (t wet mass/ha)**	***CWU*** **(m^3/ha)**	**Biomass (t wet mass/ha)**	***CWU*** **(m^3/ha)**
Crop tissue						
Root	7.1	–	9.4	–	3.1	–
Stem	18.5	2943.2	19.5	3087.9	11.5	2805.1
Leaf	14.5	2309.1	13.2	2081.8	8.6	2107.8
Tassel	0.6	89.7	0.9	142.4	0.3	76.0
Total above surface biomass	33.5	5342.0	33.6	5312.0	20.4	4989.0
Total *ET* (mm)	534.2		531.2		498.9	
CWU use (m^3/ha)	5342.0		5312.0		4989.0	
Green *WF*						
(m^3/t wet biomass)	159.5		158.2		244.8	
(m^3/t dry biomass)	261.9		278.1		378.0	

Note: [1] Cultivation parameters: silage maize production; maize variety: DK-440, crop density: 75,000 plants/ha, location: Nagykovácsi, Pest County, Hungary in 2002 and 2020; Zsámbék, Pest County, Hungary in 2007.

In order to assess model performance, wet biomass data obtained experimentally in field cultivation at Nagykovácsi and Zsámbék, Hungary in 2002, 2007, and 2020 were correlated with corresponding predicted wet biomass data by AquaCrop (calculated from dry biomass with a ~15% moisture content at harvest [52]). The experimental data showed +2.4%, +21.4%, and −34.0% deviation from the predicted values. These divergences can be attributed to differences in maize varieties and cultivation modes. While field experiments were carried out with maize variety DK-440, maize biomass predictions in AquaCrop are based on multiple varieties suitable for Davis, CA. In addition, above-ground biomasses in field experiments corresponded to maize silage cultivation (75,000 plants/ha, harvested in R6, phenological stage), while AquaCrop predictions refer to maize commodity cultivation (60,000 plants/ha, harvested in VT phenological stage). Moreover, the actual moisture content in the maize crop commodity may substantially differ from the 15% assumed for the correlation, which further increases variability. Such deviations are not uncommon in the scientific literature [37,53–56].

Crop biomass production and total *ET* during maize silage cultivation in Hungary between 1971 and 2022 were modeled using the AquaCrop software v.7.1 [36]. Although the two cultivation descriptors show similar increasing trends visually in temporal plots (Figure 1), direct numerical correlation analysis between these two parameters indicated a poor linear correlation ($r^2 = 0.399$; $p < 0.05$). However, it is observable that the biomass provides larger variation than the *ET* values. As biomass and *ET* (i.e., green water) are both used in calculating *WF* (in this case *GWF*), the increasing trend was not observable in case of *GWF*, with the exception of extremes.

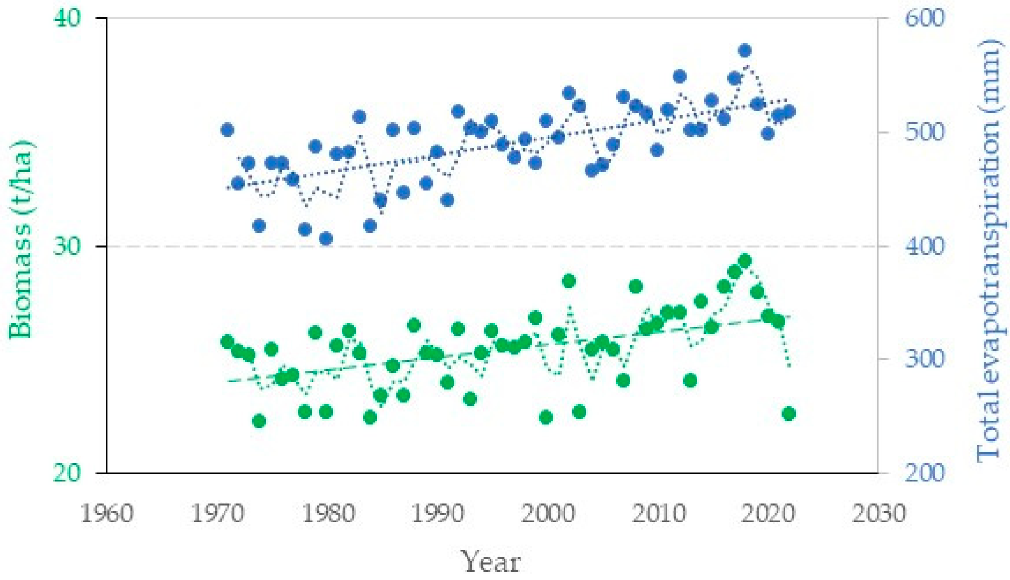


Figure 1. Crop biomass production (green circles) and total evapotranspiration (blue circles) in maize cultivation in Hungary between 1971 and 2022 modeled by the AquaCrop software v.7.1 [36]. Trendlines obtained by linear regression (dashed lines) and by moving average (dotted lines) display pattern similarities, but the linear correlation between the two datasets is poor ($r^2 = 0.399$).

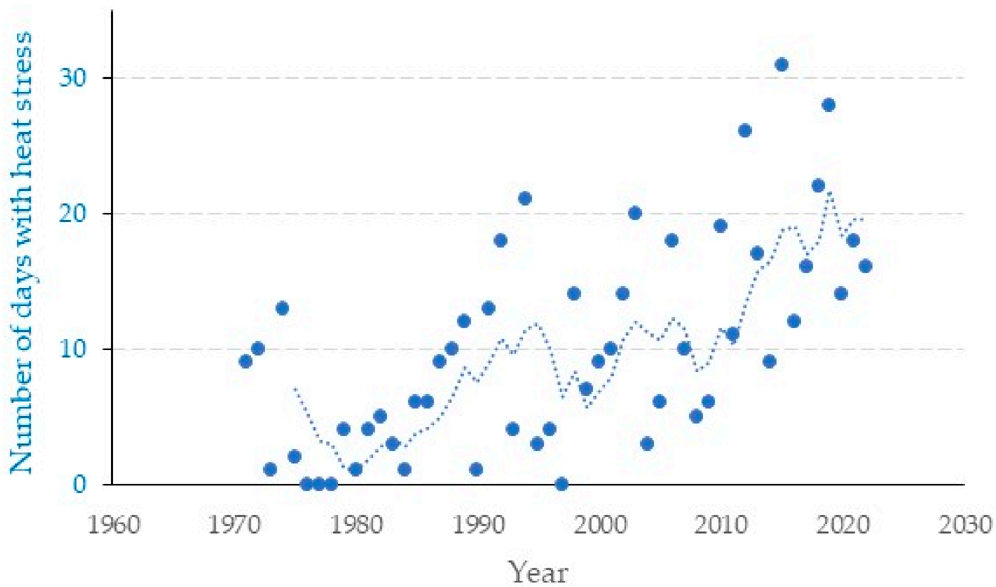
As specific crop parameters were not available for different varieties of maize, AquaCrop's general crop coefficients have been applied for the estimation of *ET*, and differences in yield and tissue biomass ratios have been applied to estimate differences in the *WF* of maize silage biomass. As crop yield values in the scientific literature typically do not focus on feed crops (maize silage in this case) but rather on commodity cultivations, estimations based on field measurements for different parts of the total above-ground silage crop biomass have been used in the calculations (Table 1). These results indicate that while total *ET* within the cropping period presented little variation for the selected three years, total above-ground biomass has significantly varied. This could indicate the effect of alternative factors, such as differences in soil water storage (assumed to be at field capacity at the start of simulations), nutrient availability, or diseases and pests. Proportions between different crop tissues have remained fairly consistent for the observed years. These findings are in line with the observations regarding the differences in the variations of biomass and *ET* observed in Section 3.1.

Based on the average total wet biomass production (29.1 ± 7.6 t wet biomass/ha) and the corresponding *CWU* values (4989.0–5342.0 m^3 green water/ha; average: 5214.3 ± 195.7 m^3 green water/ha) for maize cultivated for silage, *WF* values of the raw crop biomass were 159.5, 158.2, and 244.8 m^3 green water/t wet biomass for cultivation years 2002, 2007, and 2020, respectively (Table 1). The corresponding average *WF* was, therefore, 187.5 ± 49.6 m^3 green water/t wet biomass. Based on the moisture content of the crop at harvest, this corresponded to *WF*s related to dry biomass of 261.9, 278.1, and 378.0 m^3 green water/t dry biomass for cultivation years 2002, 2007, and 2020, respectively (average *WF*: 306.0 ± 62.9 m^3 green water/t dry biomass). These maize *WF* values were used to calculate the green water demand of the maize component used as animal feed in cattle production (see Section 2.3). The *WF* of the dairy cows' feed was calculated based on the feed composition using locally determined *WF*s where possible and *WF*s obtained from the scientific literature (see Section 2.5), where necessary. A cumulative value of these partial *WF*s weighed by the composition of the feed (m/m) added up to 664.3 m^3 green water/t dry biomass of the feed commodity used for feeding the cows at the cattle farm (see Section 3.3). Therefore, even though more than half (54.7%) of the feed biomass was maize, the *WF* of this maize silage corresponded only to one-quarter (25.2%) of the overall *WF* of the feed.

3.2. Spatial and Temporal Variations in Temperature-Humidity Index Calculations

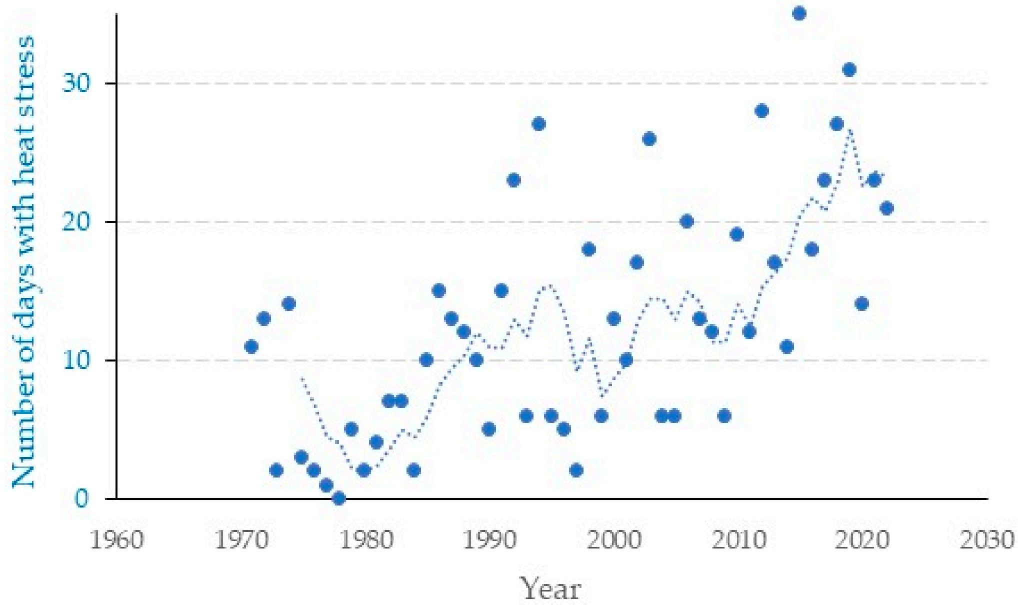
Evaporation in humid air is known to be less effective than in dry air for the cattle to lower their body temperature [57]. Therefore, wet and dry air temperatures need to be considered in parallel to assess body temperature control by the cows. Consequently, numerous *THI*s have been defined of which *THI*1 or *THI*2 are recommended in Hungary [42] as the ratio of T_w to T_d appears to be the highest for *THI*1 and *THI*2 among all *THI*s.

Results of the *THI*1 calculation provide a spatial and temporal look at the meteorological heat stress potentially affecting dairy cattle. Based on the time series of calculated *THI*1 and *THI*2 data, we can clearly conclude that there is an upward trend in the number of days with potential heat stress for the animals (Figure 2). Thus, the average number of days with heat stress in the Nagykovácsi region in Hungary during each decade from 1970 to 2020 based on *THI*1 increased from 4.00 ± 4.85 (range: 0–13) in 1971–1980 to 18.60 ± 7.69 (range: 9–31) in 2011–2020, showing a good correlation over the decades (r^2 = 0.922; $p \leq 0.05$). A similar trend was observed based on *THI*2 with an increase from 5.30 ± 5.29 (range: 0–14) in 1971–1980 to 21.60 ± 8.41 (range: 14–35) in 2011–2020 (correlation r^2 = 0.934; $p \leq 0.05$). The same trend illustrated by other parameters: the number of years with less than 5 days with heat stress during the decades 1971–1980, 1981–1990, 1991–2000, 2000–2010, and 2011–2020 dropped as 7, 4, 7, 1, 0 based on *THI*1, and 7, 3, 1, 0, 0 based on *THI*2, respectively.



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. Number of days with heat stress based on temperature-humidity indices (*THI*s) *THI*1 (**a**) and *THI*2 (**b**) from 1971 to 2022 (blue circles), with a 5-year moving average (dotted lines) for the area of Nagykovácsi (Pest County, Hungary). The corresponding *THI* threshold values are *THI*1 $\geq$ 68 and *THI*2 $\geq$ 69.

The trends presented above were not exclusive to the Nagykovácsi region but were present throughout the country. In order to assess the spatial distribution of potential trends, we utilized the Mann–Kendall test for both *THI*s, as seen in Figure 3. The tau value of the test represents the presence of a trend, from −1 (strong negative trend) to 1 (strong positive trend). The test also provides a significance level (*p*-value), with the null hypothesis that there is no trend. It is clear that based on the 52-year dataset, similar, upward trends are visible throughout the country, with stronger trends present in the southern and western regions for *THI*1 and in the central regions for *THI*2. In general, it can be observed that areas with higher elevations had less expressive trends. All upward trends have proved to be significant (with *p*-values less than 0.01), with the notable exception of two cells for *THI*1, both located in the highest mountains in the country, which are not suitable for cattle and thus not relevant as exceptions within the scope of our study (Figure 3b).

3.3. Potential Impact of Temperature-Humidity on the Water Footprint of Dairy Cattle Production

T_d in the stables ranged from 22.9 to 33.5 °C, while *RH* ranged from 31 to 64%. The dry and wet air temperatures followed a similar trend but with, in some cases, a slight delay in the onset of changes in the wet air temperature (Figure 4). The two air temperatures exhibited poor correlation with each other (r^2 = 0.55; $p \leq 0.05$). Drinking water consumption of the cows varied between 74.7 and 101.9 L/cow/day during the study period. It weakly correlated with the dry air temperature (r^2 = 0.76; $p \leq 0.05$), and, to an even lesser extent, with the wet air temperature (r^2 = 0.64; $p \leq 0.05$), as the wet air temperature is highly dependent on *RH*. A physiological explanation for the better correlation with the dry air temperature could be that the mucous membranes of the cows' mouths dry out sooner in dry air, causing higher stimuli for thirst. In contrast, water intake showed no correlation with the detected *RH* (r^2 = 0.01; $p < 0.1$).

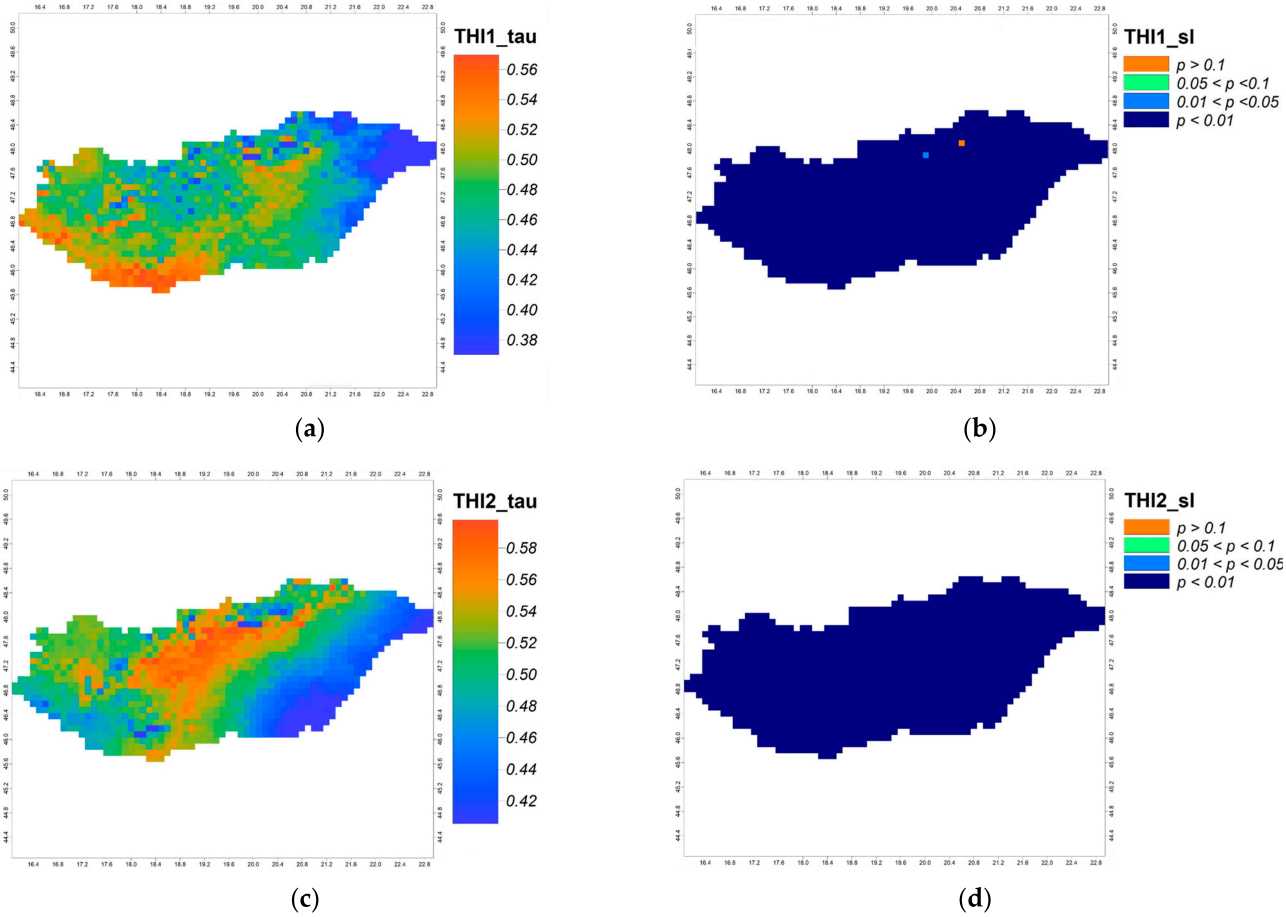


Figure 3. Spatial distribution of tau (**a**,**c**) and *p* (**b**,**d**) values of the Mann–Kendall test for *THI*1 (**a**,**b**) and *THI*2 (**c**,**d**). (Coordinate Reference System: WGS84).

Figure 4. Dry and wet bulb air temperature in the stables of the dairy cow farm during the study period in July 2019: dry bulb temperature (orange line) and wet bulb temperature (blue line).

THI values, specifically *THI*1 and *THI*2, recommended for use in Hungary [42] during the 31-day study period at the dairy farm, are depicted in Figure 5. As expected, *THI*2 is monotonously 2–4 units higher than *THI*1 and shows a very similar temporal pattern. This is consistent with the definition of these two *THI* parameters. *THI*1 was originally derived from the discomfort index developed by climatologist Earl C. Thom [58], specified to monitor discomfort due to temperature and humidity in humans [59], which could obviously be extended to other mammalians. *THI*2 has been empirically determined in cattle exposed to heat stress conditions in climatic chambers [40,41]. Thus, *THI*1 and *THI*2 strongly correlate with each other ($r^2 = 0.966$; $p < 0.05$), which is expected as they both depend on temperature. The correlation with drinking water intake indicates that an increase in days with heat stress will likely result in an increase in water intake. Considering the results of Section 3.2, we can generally expect such effects in Hungary.

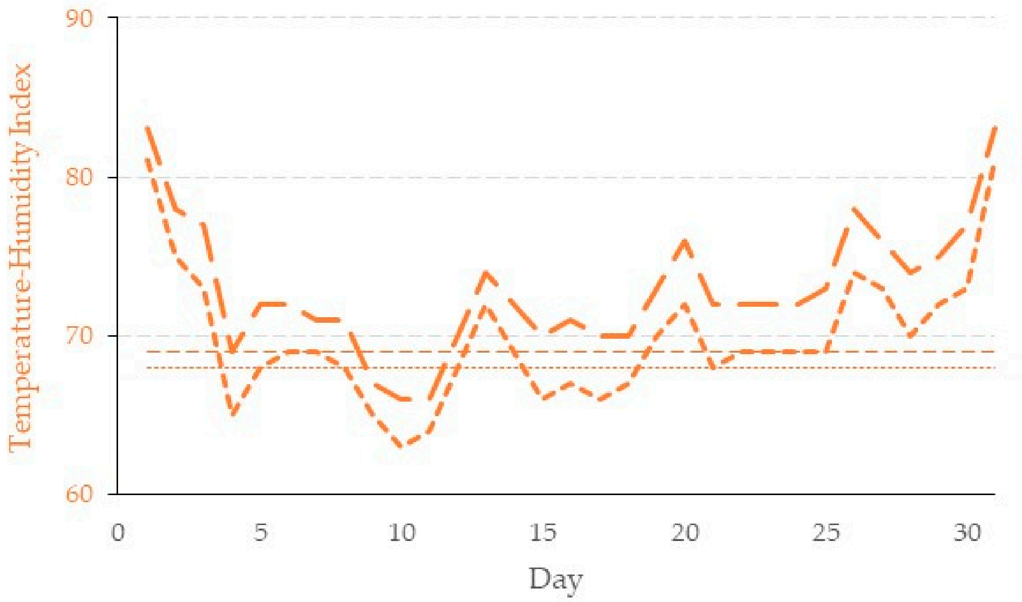


Figure 5. Temperature-humidity indices (*THI*) in the stables of the dairy cow farm during the study period in July 2019: *THI*1 (orange dotted line) and *THI*2 (orange dashed line). The corresponding threshold values for *THI*1 (68) and *THI*2 (69) are indicated as thin dotted and dashed horizontal lines.

Water and feed intake were recorded at the cattle farm and are depicted in Figure 6. Feed was provided to the animals in constant amounts daily, but feed consumption was not registered on a daily basis; it was only observed that the previously given portion had been consumed by the time of daily feeding. Therefore, feed consumption is presented as corresponding (green) water use and as a daily average value with minimal and maximal levels. Drinking (blue) water consumption was registered daily; therefore, it is represented as variable daily rates. The amount of servicing (blue) water was not recorded daily but was calculated as a daily average value (18 L/dairy cow/day). The moderate correlation between heat stress and the drinking water intake by dairy cows (see above) is not surprising and indicates that *THI*1 and *THI*2 are indeed suitable parameters to reveal heat discomfort in dairy cows.

This interpretation also sheds light on the proportions of green and blue water usage. The feed used for feeding the cows at the cattle farm represented a cumulative *WF* of 664.3 m^3 green water/t dry biomass of the feed commodity (see Section 3.2). Considering the 20.1 kg feed/day/dairy cow feed consumption at the cattle farm, this corresponds to 13,352 ± 4724 L green water/dairy cow/day, adding up to 413,900 ± 146,400 L green water/dairy cow during the 31-day study period. The drinking water intake, recorded daily at the cattle farm, ranged between 74.7 and 101.9 L blue water/dairy cow/day, with a daily average value of 83.4 ± 6.5 L blue water/dairy cow/day, and total consumption during the 31-day study period was 2586 ± 202 L blue water/dairy cow. Service water use is estimated to be 18 L blue water/dairy cow/day and 558 L blue water/dairy cow during the study period.

Taking the above water use values into consideration, green, blue, and combined water use during the 31-day cattle study periods totaled 413,900 ± 146,400, 3100 ± 200, and 417,600 ± 147,700 L water/dairy cow, respectively. This means that in the current case, approximately 99% of the overall (green and blue) water use is represented by the green water demand of the feed used to forage the dairy cows. Limitations to this value are that this proportion does not consider blue water used for irrigation (no maize irrigation was applied in the current case), related water demands of the cultivation technology (fertilization, etc.), and does not include grey water. Nonetheless, it is in good agreement with corresponding data from the scientific literature [7–10].

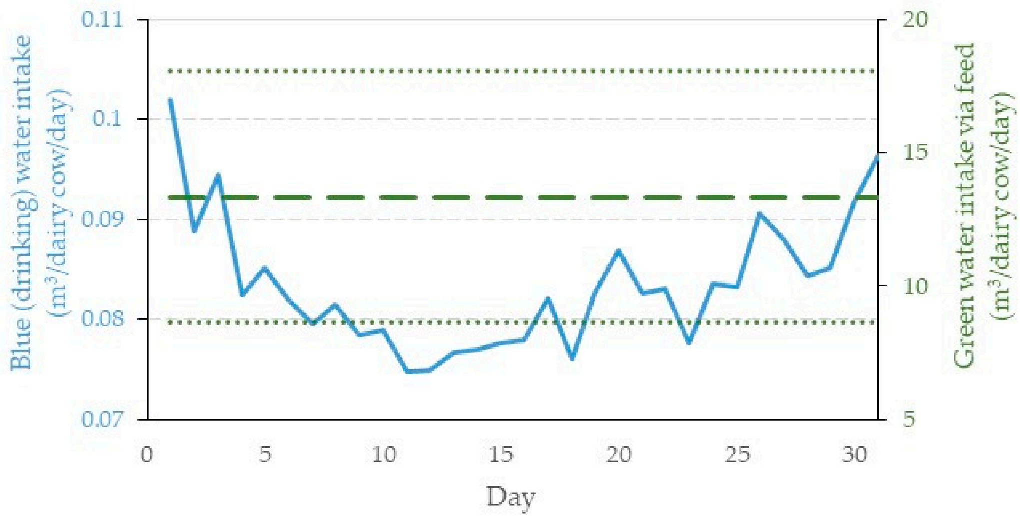


Figure 6. Water intake of the dairy cow farm during the study period in July 2019. Drinking water intake (blue solid line) was recorded daily. Green water intake corresponding to the amount of feed was calculated and considered constant during the study period and is depicted as an average (green slashed line) and minimal and maximal values (green dotted lines). The amount of servicing (blue) water was 0.018 m^3/dairy cow/day on an average (not shown in the graph).

4. Conclusions

Main conclusions drawn from the findings in the present study revealed information regarding the overall amount and the composition of water consumption by the dairy farms, as well as on certain factors affecting water use. The composition of the water use included 13.4 ± 4.7 m^3 green water/dairy cow/day as water content in the feed, as well as 0.08 ± 0.007 m^3 blue water/dairy cow/day as drinking water, and 0.018 m^3 blue water/dairy cow/day for service water needs. Thus, green water demand represented by the feed corresponded to 99.1% of the overall *WF.* This did not include gray water or blue water use associated with feed production, as corn production in Hungary (for animal feed) typically only relies on rainwater. Limitations, yet at the same time specific features of these calculations, are that biomass production data corresponded (a) to maize silage cultivation (while data in the scientific literature mostly refer to maize commodity cultivation), (b) to no irrigation maize cultivation, and (c) to a single country, Hungary. In turn, maize silage content in the feed represented 54.7% (m/m), but that corresponded only to 25.2% of the overall *WF* of the feed. In the herd and under the conditions studied, the intake of drinking water was dependent on meteorological factors, showed no direct correlation with the *RH*, weakly correlated with T_d and T_w, but a better correlation occurred with two types of *THI*s (*THI*1 and *THI*2). Water consumption was less related to the external body temperature of the livestock than to ambient temperature.

Spatiotemporal analysis of *THI*1 and *THI*2 indicated an increasing trend in potential heat stress, in line with previous research [42]. This will likely lead to increased drinking water consumption and/or other management issues for farmers, such as increased energy consumption or relevance of water quality issues. It is also clear that while the upward trend in the occurrence of days with heat stress is clearly present in the whole area of Hungary, there is a clear spatial pattern indicating that farmers in certain regions (generally in the South, West, and Central regions) are more likely to be affected. Farmers in such regions should consider that such effects might increase in the future and therefore implement appropriate measures to control ambient temperatures affecting the animals. Alternatively, selection for thermotolerance might also be an option [32].

In general, in can be concluded that while increasing trends in *ET* (green water) and biomass lead to a reasonably consistent mean *GWF* of animal feed, its year-to year variation seems to increase, leading to higher uncertainties, with water used for the production of feedstocks remaining the dominant portion of total water use. Similarly, the increase in the occurrence of heat stress in dairy cows is expected to lead to increasing water use and force farmers to apply adaptive measures, such as the selection of dairy cow breeds with better thermotolerance, and modifications in animal housing and technological steps.

Author Contributions: Conceptualization, I.W. and A.S.; methodology, I.W., A.R. and A.S.; validation, I.W. and A.S.; formal analysis, I.W., B.G., A.R. and A.S.; investigation, I.W., A.R., B.G. and A.S.; writing—original draft preparation, I.W. and A.S.; writing—review and editing, A.R. and B.G.; visualization, I.W. and A.S.; supervision, A.S.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Hungarian National Research, Development, and Innovation Office, grant number TKP2021-NVA-22.

Data Availability Statement: Data are contained within the article.

Acknowledgments: This work was presented at the workshop "Assessment of Water Use in Livestock Production Systems and Supply Chains", which took place in Potsdam, Germany on 14–16 December 2022. The Workshop was sponsored by the OECD Co-operative Research Programme: Sustainable Agricultural and Food Systems, whose financial support made it possible for some of the invited speakers to participate in the Workshop.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FAO. *World Food Day. Water Is Life, Water Is Food. Leave No One Behind*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2023. Available online: https://www.fao.org/3/cc6758en/cc6758en.pdf (accessed on 30 November 2023).
2. FAO. *The State of the World's Land and Water Resources for Food and Agriculture—Systems at Breaking Point*; Main report; FAO: Rome, Italy, 2022. [CrossRef]
3. FAO. *FAOSTAT Online Database*; FAO: Rome, Italy, 2023. Available online: https://www.fao.org/faostat/en/#home (accessed on 30 November 2023).
4. Mekonnen, M.M.; Hoekstra, A.Y. A global assessment of the water footprint of farm animal products. *Ecosystems* **2012**, *15*, 401–415. [CrossRef]
5. Hoekstra, A.Y. Water for animal products: A blind spot in water policy. *Environ. Res. Lett.* **2014**, *9*, 091003. [CrossRef]
6. Mekonnen, M.M.; Gerbens-Leenes, W. The water footprint of global food production. *Water* **2020**, *12*, 2696. [CrossRef]
7. Hoekstra, A.Y. The hidden water resource use behind meat and dairy. *Anim. Front.* **2012**, *2*, 3–8. [CrossRef]
8. Harding, G.; Courtney, C.; Russo, V. When geography matters. A location-adjusted blue water footprint of commercial beef in South Africa. *J. Clean. Product.* **2017**, *151*, 494–508. [CrossRef]
9. Maré, F.A.; Jordaan, H.; Mekonnen, M.M. The water footprint of primary cow–calf production: A revised bottom-up approach applied on different breeds of beef cattle. *Water* **2020**, *12*, 2325. [CrossRef]
10. Broom, D.M. Land and water usage in beef production systems. *Animals* **2019**, *9*, 286. [CrossRef]
11. FAO. *LEAP—Livestock Environmental Assessment and Performance Partnership*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2012. Available online: https://www.fao.org/policy-support/mechanisms/mechanisms-details/en/c/458117 (accessed on 30 November 2023).
12. FAO. *Water Use in Livestock Production Systems and Supply Chains. Guidelines for Assessment. Version 1*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2019; ISBN 978-92-5-131713-6. Available online: https://www.fao.org/documents/card/fr/c/ca5685en (accessed on 30 November 2023).
13. Boulay, A.-M.; Drastig, K.; Amanullah; Chapagain, A.; Charlon, V.; Civit, B.; DeCamillis, C.; De Souza, M.; Hess, T.; Hoekstra, A.Y.; et al. Building consensus on water use assessment of livestock production systems and supply chains: Outcome and recommendations from the FAO LEAP Partnership. *Ecol. Ind.* **2021**, *124*, 107391. [CrossRef]

14. Webster, J.; D'Silva, J. (Eds.) *The Meat Crisis: Developing More Sustainable Production and Consumption*; Routledge: London, UK, 2010; pp. 22–33. [CrossRef]
15. Antonelli, M.; Greco, F. (Eds.) *The Water We Eat. Combining Virtual Water and Water Footprints*; Springer Water: Cham, Switzerland, 2015. [CrossRef]
16. Sultana, M.N.; Uddin, M.M.; Ridoutt, B.; Hemme, T.; Peters, K. Benchmarking consumptive water use of bovine milk production systems for 60 geographical regions: An implication for Global Food Security. *Glob. Food Secur.* **2015**, *4*, 56–68. [CrossRef]
17. Legesse, G.; Ominski, K.H.; Beauchemin, K.A.; Pfister, S.; Martel, M.; McGeough, E.J.; Hoekstra, A.Y.; Kroebel, R.; Cordeiro, M.R.C.; McAllister, T.A. Quantifying water use in ruminant production. *J. Anim. Sci.* **2017**, *95*, 2001–2018. [CrossRef]
18. Capper, J.L. The environmental impact of beef production in the United States: 1977 compared with 2007. *J. Anim. Sci.* **2011**, *89*, 4249–4261. [CrossRef] [PubMed]
19. Kannan, N.; Osei, E.; Gallego, O.; Saleh, A. Estimation of green water footprint of animal feed for beef cattle production in Southern Great Plains. *Water Resour. Ind.* **2017**, *17*, 11–18. [CrossRef]
20. Ridoutt, B.G.; Page, G.; Opie, K.; Huang, J.; Bellotti, W. Carbon, water and land use footprints of beef cattle production systems in southern Australia. *J. Clean. Product.* **2014**, *73*, 24–30. [CrossRef]
21. Zonderland-Thomassen, M.A.; Lieffering, M.; Ledgard, S.F. Water footprint of beef cattle and sheep produced in New Zealand: Water scarcity and eutrophication impacts. *J. Clean. Prod.* **2014**, *73*, 253–262. [CrossRef]
22. Huang, J.; Xu, C.C.; Ridoutt, B.G.; Liu, J.J.; Zhang, H.L.; Chen, F.; Li, Y. Water availability footprint of milk and milk products from large-scale dairy production systems in Northeast China. *J. Clean. Prod.* **2014**, *79*, 91–97. [CrossRef]
23. Lu, Y.; Payen, S.; Ledgard, S.; Luo, J.; Ma, L.; Zhang, X. Components of feed affecting water footprint of feedlot dairy farm systems in Northern China. *J. Clean. Product.* **2018**, *183*, 208–219. [CrossRef]
24. Palhares, J.C.P.; Pezzopane, J.R.M. Water footprint accounting and scarcity indicators of conventional and organic dairy production systems. *J. Clean. Prod.* **2015**, *93*, 299–307. [CrossRef]
25. Murphy, E.; de Boer, I.J.M.; van Middelaar, C.E.; Holden, N.M.; Shalloo, L.; Curran, T.P.; Upton, J. Water footprinting of dairy farming in Ireland. *J. Clean. Product.* **2017**, *140*, 547–555. [CrossRef]
26. Owusu-Sekyere, E.; Scheepers, M.E.; Jordaan, H. Economic water productivities along the dairy value chain in South Africa: Implications for sustainable and economically efficient water-use policies in the dairy industry. *Ecol. Econ.* **2017**, *134*, 22–28. [CrossRef]
27. Ibidhi, R.; Ben Salem, H. Water footprint and economic water productivity assessment of eight dairy cattle farms based on field measurement. *Animal* **2020**, *14*, 180–189. [CrossRef]
28. Nagypál, V.; Mikó, E.; Hodúr, C. Sustainable water use considering three Hungarian dairy farms. *Sustainability* **2020**, *12*, 3145. [CrossRef]
29. Hodúr, C.; Nagypál, V.; Fazekas, Á.; Mikó, E. Blue and gray water footprint of some Hungarian milking parlors. *Water Pract. Technol.* **2022**, *17*, 1378. [CrossRef]
30. Ribács, A.; Komlósi, K.K. Investigation of some factors influencing the water intake by dairy cows. In Proceedings of the 5th International Scientific Conference on Water, Szarvas, Hungary, 22–24 March 2022.
31. Kadzere, C.T.; Murphy, M.R.; Silanikove, N.; Maltz, E. Heat stress in lactating dairy cows: A review. *Livestock Prod. Sci.* **2002**, *77*, 59–91. [CrossRef]
32. Cartwright, S.L.; Schmied, J.; Karrow, N.; Mallard, B.A. Impact of heat stress on dairy cattle and selection strategies for thermotolerance: A review. *Front. Vet. Sci.* **2023**, *10*, 1198697. [CrossRef] [PubMed]
33. Liu, J.; Li, L.; Chen, X.; Lu, Y.; Wang, D. Effects of heat stress on body temperature, milk production, and reproduction in dairy cows: A novel idea for monitoring and evaluation of heat stress—A review. *Asian-Australas. J. Anim. Sci.* **2019**, *32*, 1332–1339. [CrossRef] [PubMed]
34. Polsky, L.; von Keyserlingk, M.A.G. Effects of heat stress on dairy cattle welfare. *J. Dairy. Sci.* **2017**, *100*, 8645–8657. [CrossRef]
35. Ritchie, W.W.; Hanway, J.; Benson, G.O. *How a Corn Plant Develops*; Special Report 48; Iowa State University of Science and Technology Cooperative Extension Service: Ames, IA, USA, 1992.
36. FAO. *Standard AquaCrop Programme with Users' Interface and Database—Version 7.1*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2023; Available online: https://www.fao.org/aquacrop/software/aquacropstandardwindowsprogramme/en (accessed on 30 November 2023).
37. Hsiao, T.C.; Heng, L.; Steduto, P.; Rojas-Lara, B.; Raes, D.; Fereres, E. AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize. *Agron. J.* **2009**, *101*, 448–459. [CrossRef]
38. Hungarian Meteorological Service (OMSZ) Meteorological Database. 2023. Available online: https://odp.met.hu (accessed on 30 November 2023).
39. Bohmanova, J.; Misztal, I.; Cole, J.B. Temperature-Humidity Indices as indicators of milk production losses due to heat stress. *J. Dairy. Sci.* **2007**, *90*, 1947–1956. [CrossRef]
40. Bianca, W. Relative importance of dry- and wet-bulb temperatures in causing heat stress in cattle. *Nature* **1962**, *195*, 251–252. [CrossRef]
41. Bianca, W. Reviews of the progress of dairy science. Section A. Physiology. Cattle in a hot environment. *J. Dairy. Res.* **1965**, *32*, 291–345. [CrossRef]

42. Solymosi, N.; Torma, C.s.; Kern, A.; Maróti-Agóts, Á.; Barcza, Z.; Könyves, L.; Reiczigel, J. Az évenkénti hőstresszes napok számának változása Magyarországon a klímaváltozás függvényében. In Proceedings of the 36. Meteorológiai Tudományos Napok, Magyar Tudományos Akadémia, Budapest, Hungary, 18–19 November 2010. Available online: https://www.met.hu/doc/rendezvenyek/metnapok-2010/13_Solymosi.pdf (accessed on 25 October 2023).
43. Mann, H.B. Nonparametric tests against trend. *Econometrica* **1945**, *13*, 245–259. [CrossRef]
44. Hipel, K.W.; McLeod, A.I. *Time Series Modelling of Water Resources and Environmental Systems*; Elsevier Science: Amsterdam, The Netherlands, 1994; ISBN 978-00-8-087036-6.
45. The R Foundation. *An Introduction to R. Notes on R: A Programming Environment for Data Analysis and Graphics*; Version 4.3.2 (2023-10-31); The R Foundation: Wien, Austria, 2023. Available online: https://cran.r-project.org/doc/manuals/r-release/R-intro.pdf (accessed on 30 November 2023).
46. SAGA User Group Association. *SAGA System for Automated Geoscientific Analyses*; SAGA User Group Association: Hamburg, Germany, 2023. Available online: https://saga-gis.sourceforge.io/en (accessed on 30 November 2023).
47. The QGIS Development Team. QGIS A Free and Open Source Geographic Information System. *The QGIS Development Team.* 2023. Available online: https://www.qgis.org/en (accessed on 30 November 2023).
48. Mekonnen, M.M.; Hoekstra, A.Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1577–1600. [CrossRef]
49. Jolánkai, M.; Kassai, K.M.; Tarnawa, Á. Water footprint of field crop species based on their protein yield. *Acta Hydrol. Slovaca* **2019**, *20*, 89–93. [CrossRef]
50. Djaman, K.; Smeal, D.; Koudahe, K.; Allen, S. Hay yield and water use efficiency of alfalfa under different irrigation and fungicide regimes in a semiarid climate. *Water* **2020**, *12*, 1721. [CrossRef]
51. Ercin, A.E.; Aldaya, M.M.; Hoekstra, A.Y. *The Water Footprint of Soy Milk and Soy Burger and Equivalent Animal Products*; Value of Water Research Report Series No. 49; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2011.
52. Ercin, A.E.; Aldaya, M.M.; Hoekstra, A.Y. The water footprint of soy milk and soy burger and equivalent animal products. *Ecol. Indicat.* **2012**, *18*, 392–402. [CrossRef]
53. USDA. *Production, Supply and Distribution Official Statistics*; United States Department of Agriculture (USDA): Washington, DC, USA, 2023. Available online: https://apps.fas.usda.gov/psdonline/app/index.html#/app/home (accessed on 30 November 2023).
54. Abedinpour, M.; Sarangi, A.; Rajput, T.B.S.; Singh, M.; Pathak, H.; Ahmad, T. Performance evaluation of AquaCrop model for maize crop in a semi-arid environment. *Agric. Water Manag.* **2012**, *110*, 55–56. [CrossRef]
55. Paredes, P.; de Melo-Abreu, J.P.; Alves, I.; Pereira, L.S. Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization. *Agric. Water Manag.* **2014**, *144*, 81–97. [CrossRef]
56. Sandhu, R.; Irmak, S. Performance of AquaCrop model in simulating maize growth, yield, and evapotranspiration under rainfed, limited and full irrigation. *Agric. Water Manag.* **2019**, *223*, 105687. [CrossRef]
57. West, J.W. Effects of heat-stress on production in dairy cattle. *J. Dairy. Sci.* **2003**, *86*, 2131–2144. [CrossRef]
58. Thom, E.C. The Discomfort Index. *Weatherwise* **1959**, *12*, 57–61. [CrossRef]
59. Kovács, L.; Kézér, F.L.; Ruff, F.; Szenci, O.; Jurkovich, V. Association between human and animal thermal comfort indices and physiological heat stress indicators in dairy calves. *Environ. Res.* **2018**, *166*, 108–111. [CrossRef] [PubMed]