ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROMs)

DEFICIÊNCIA HÍDRICA E EXCEDENTE HÍDRICO PROVÁVEIS PARA MILHO E SOJA NO ESTADO DO PARANÁ, SUL DO BRASIL[1]

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1 RESUMO

Teve-se por objetivo calcular os valores prováveis de deficiência hídrica (*Def*) e excedente hídrico (*Exc*) para o milho e a soja no estado do Paraná a fim de obter os melhores períodos de semeadura. Os dados climáticos (1980 a 2013) foram espacializados em grid regular de 0,25º x 0,25º. O balanço hídrico agrícola foi calculado diariamente com o programa AquaCrop, sendo os valores somados e agrupados em 37 decêndios por ano. Foram realizadas distribuições de frequência e aplicados testes de aderência aos decêndios para ajustá-los a funções densidade de probabilidade (FDP's). Determinou-se os valores decendiais prováveis de *Def* e *Exc* a 10%, 25% e 50% de probabilidade. Gama e Exponencial foram as FDP's que apresentaram aderência a maior quantidade de locais, enquanto a Uniforme pode ser descartada para ajustes futuros. No estado do Paraná, em média, a menor *Def* ocorre quando a soja é semeada de 27 a 31 de dezembro e o menor *Exc* ocorre de 08 a 17 de outubro. Para o milho 1ª e 2ª safras, os menores *Def*'s ocorrem quando são semeados de 17 a 26 de dezembro e 22 a 31 de março, respectivamente, e os menores *Exc*'s dependem do nível de probabilidade.

Palavras-chave: déficit, excesso, balanço hídrico agrícola, função densidade de probabilidade, Aquacrop.

GURSKI, B. C.; SOUZA, J. L. M.; XAVIER, A. C.; SANTOS, A. A.
PROBABLE WATER DEFICIENCY AND SURPLUS FOR CORN AND SOYBEAN IN THE STATE OF PARANÁ, SOUTHERN BRAZIL

2 ABSTRACT

We aimed to calculate the probable values of water deficiency (*Def*) and surplus (*Exc*) for corn and soybean in the state of Paraná, to obtain the best sowing periods. Climatic data (1980 to 2013) were spatialized in a regular grid of 0.25º x 0.25º. The agricultural water balance was calculated daily using the AquaCrop program, with the values added up and grouped into 37 ten days per year. Frequency distributions were carried out and adherence tests were applied to ten days periods to adjust them to probability density functions (PDF's). The probable decennial

Received on 11/16/2020 and approved for publication on 05/06/2021
DOI: http://dx.doi.org/10.15809/irriga.2021v26n2p293-314

values of *Def* and *Exc* were determined at 10%, 25% and 50% of probability. Gamma and Exponential were the PDF's that showed adherence to the greatest number of locations, while Uniform can be discarded for future adjustments. In the State of Paraná, on average, the lowest *Def* occurs when soybean is sown from December 27th to 31, while the lowest *Exc* occurs from October 8th to 17. For season and off-season corn, the smallest *Def*'s occur when they are sown from December 17th to 26 and March 22nd to 31, respectively, and the smallest *Exc*'s depends on the level of probability.

Keywords: deficit, excess, agricultural water balance, probability density function, Aquacrop.

3 INTRODUCTION

Agriculture plays a major economic role in the state of Paraná, accounting for almost 7% of its gross domestic product (IPARDES, 2020). In the 2019/2020 harvest, 2,630 thousand hectares of corn and 5,503 thousand hectares of soybeans were cultivated in this state, accounting for 12% of the total agricultural area in Brazil. Corn production is 14,948 thousand tons, accounting for 15% of Brazilian production, and soybean production is 21,598 thousand tons, accounting for 17% of the country's production (CONAB, 2020a, 2020b).

On the other hand, agriculture has been suffering from droughts primarily related to water deficits, which can result in soil moisture depletion. For example, a 20% increase in water deficit over a prolonged three-year period (2013--2015) was enough to create water scarcity conditions in Brazil, causing serious social and economic problems (GETIRANA, 2016).

In this context, the agricultural water balance (ABH) is essential for obtaining the actual water conditions in the soil–plant–atmosphere system for different locations and periods. Its components can be measured directly in the field or estimated from different data via specific models (RAES et al., 2016). However, Vanuytrecht et al. (2014) emphasized the difficulty of field measurement, which is extremely costly from an economic and practical point of view, in addition to the great intrinsic spatial variability of its components. Therefore, the AquaCrop model, made available by the *Food and Agriculture Organization of the United Nations* (FAO), stands out because it does not require direct measurements, is easy to use, requires little input data and provides accuracy in estimating the water components and productivity of various agricultural crops, including those in Brazil (STEDUTO et al., 2012).

However, several authors consider that simply calculating the BHA is insufficient, requiring more in-depth studies, especially for large regions, considering spatial variability and the probability of occurrence of water components, since the use of average values can result in errors (SILVA et al., 2015; FERNANDES et al., 2019). In turn, the probabilistic study of the distribution of water components demonstrates that their occurrence consists of random phenomena influenced by geographic location. Therefore, many studies are limited to small regions, such as municipalities, which do not contribute to macroplanning, as has been the case in the state of Paraná. Another difficulty lies in obtaining consistent historical series that are long, without gaps or fluctuations in the number of years, and that present the same instrumental measurement standard (SOUZA; JERSZURKI; DAMAZIO, 2013; JERSZURKI; SOUZA; EVANGELISTA, 2015).

Therefore, studies in large regions that minimize the aforementioned problems should be prioritized and valued (STAGGE et al., 2015; VICENTE-SERRANO et al., 2015). This makes it possible to increase the applications of BHA: improve the accuracy of estimates; assist in the planning of agricultural operations; improve irrigation management; and enhance crop forecasting and the definition of agricultural zoning, among others (FERNANDES et al., 2019).

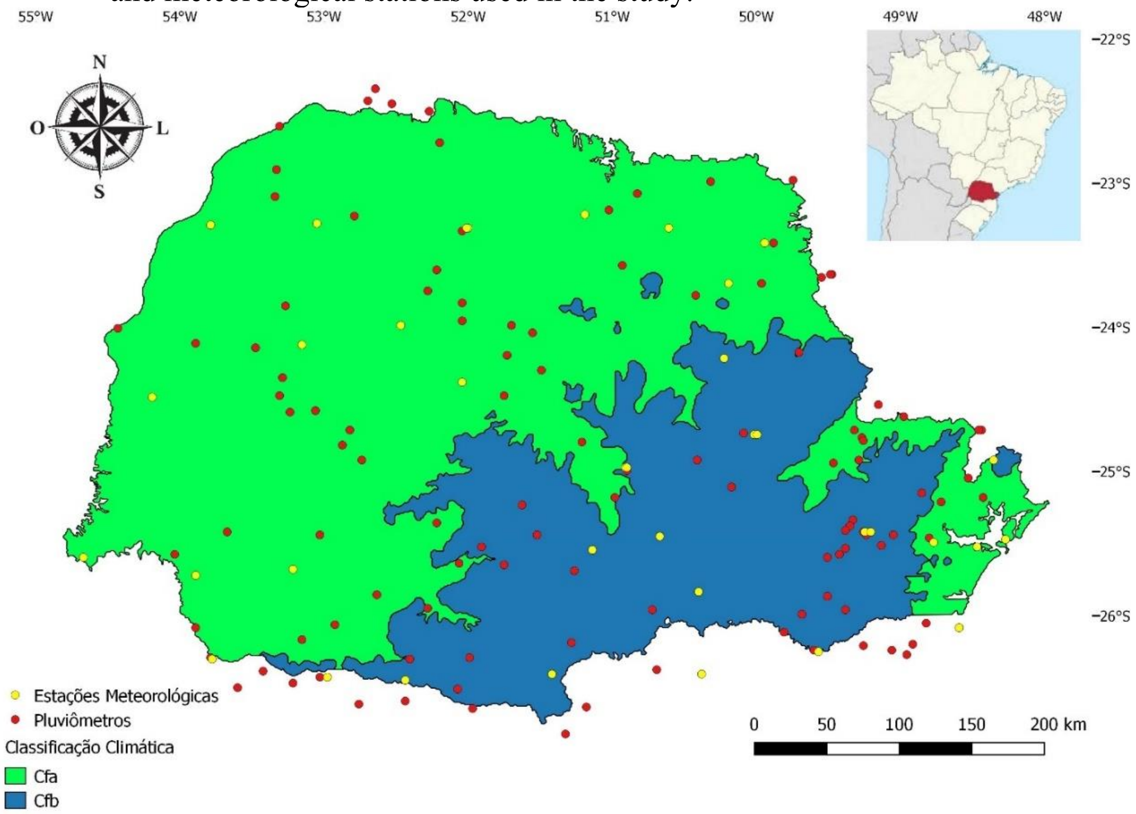
Given these considerations, the objective of this work was to define the best-fit probability density functions and calculate the probable values of water deficiency and water surplus for corn and soybean crops in the state of Paraná to obtain the best sowing periods and promote irrigation planning.

4 MATERIALS AND METHODS

4.1 Characterization of the study area and meteorological data

In the state of Paraná, two main climate types predominate, according to the Köppen classification: Cfa and Cfb (Figure 1). However, in the southern part of the state and higher-altitude parts of the plateaus, more than ten days of frost are recorded per year (MAACK, 2012). The Cfa climate, which is subtropical, has a good rainfall distribution, an average annual temperature of 19°C, and total rainfall of 1,500 mm per year. The Cfb climate, which is subtropical, has a good rainfall distribution throughout the year and mild summers. The average annual temperature is 17°C, and rainfall exceeds 1,200 mm per year (ALVARES et al., 2013).

Figure 1. Köppen climate classification for the state of Paraná and locations of the rain gauges and meteorological stations used in the study.

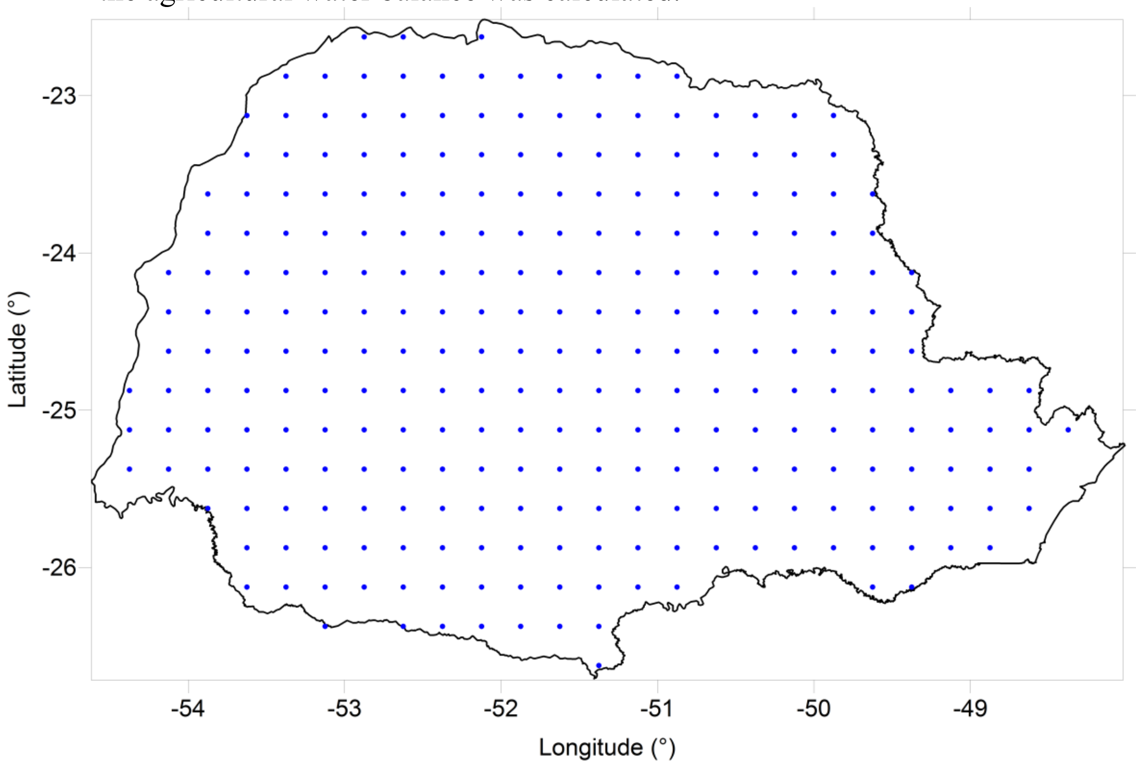


Source: Adapted from ITCG (2006)

The meteorological dataset included observed data collected daily from rain gauges (151 units), as well as from conventional and automatic weather stations (38 units), from January 1, 1980, to December 31, 2013 (34 years) (Figure 1). The data sources used were the National Institute of Meteorology (INMET) and the National Water Agency (ANA). The ANA data were limited to rainfall (*P*). The INMET data consisted of maximum (T_{max}; °C), minimum (T_{min}; °C), and mean (T_{med}; °C) air temperatures, relative humidity (*RH*; %), wind speed at 2 m height (u_2, m s $^{-1}$), rainfall (*P*; mm), daily solar brightness (*n*; hours), and daily solar radiation (*Rs;* MJ m $^{-2}$).

Several interpolators were tested by Xavier, King, and Scanlon (2015) to spatialize meteorological data: inverse distance weighting; ordinary *kriging; splines*; natural interpolation; and arithmetic means. The best interpolator was obtained through cross-validation, and the meteorological data were spatialized into a regular 0.25° × 0.25° *grid* covering the entire state of Paraná. As a result, the authors obtained daily (34 years) meteorological data (*P*, T_{max}, T_{min}, T_{med}, *RH*, U_2, *n*, *and Rs*) for a regular *grid* containing 279 points (Figure 2).

Figure 2. The regular *grid* of 0.25° × 0.25° contained 279 points in the state of Paraná where the agricultural water balance was calculated.



4.2 Calculation of the agricultural water balance (AWB)

The calculation of the agricultural water balance (BHA) was performed for corn and soybeans on the basis of meteorological data provided by Xavier, King and Scanlon (2015), with the AquaCrop model, version 5.0, made available by the FAO (RAES et al., 2016). The stresses resulting from salinity and fertility were not considered. The BHA was performed daily, resulting in a 34-year series of output data for each point of the regular *grid* (Figure 2). The input data were divided into categories: climatic (discussed in the previous item), soil and crop of interest. The reference evapotranspiration (*ETo*) (climatic data) was calculated via the adapted Penman–Monteith method (ASCE--EWRI, 2005).

The soil parameters considered the soil classification (BHERING et al., 2007) and predominant textures in the location of the state of Paraná where the climate data (Figure 2) were obtained (Table 1).

Table 1. Parameters of the soils of the state of Paraná used in the AquaCrop model to calculate the agricultural water balance.

Soil/ Texture	Prof (m)	θ_{PMP} (m³ m⁻³)	θ_{CC}	θ_S	K_S (mm day⁻¹)	AFE (mm)	cc (dimensionless)	the	b
Rocky outcrop	0.5	0.01	0.03	0.05	0	0	77	-9.00	-9.00
Sandy/medium argisol	1.5	0.20	0.32	0.47	225	9	72	-0.58	-0.51
Sandy argisol	0.5	0.27	0.39	0.5	35	10	77	-0.57	-1.61
Clayey argisol	1.0	0.39	0.54	0.55	35	10	77	-0.61	0.59
Clayey/medium argisol	1.5	0.27	0.39	0.5	35	10	77	-0.57	-1.61
Medium argisol	1.5	0.2	0.32	0.47	225	9	72	-0.58	-0.51
Clayey Cambisol	1.0	0.39	0.54	0.55	35	14	77	-0.61	0.59
Medium Cambisol	1.0	0.20	0.32	0.47	225	9	72	-0.58	-0.51
Sandy/medium gleysol	1.5	0.10	0.22	0.41	1200	7	46	-0.32	0.22
Clayey Gleisol	1.5	0.39	0.54	0.55	35	14	77	-0.61	0.59
Clayey Latosol	2.0	0.39	0.54	0.55	35	14	77	-0.61	0.59
Medium Latosol	2.0	0.27	0.39	0.5	35	10	77	-0.57	-1.61
Sandy/medium Neosol	0.5	0.20	0.32	0.47	225	9	72	-0.58	-0.51
Clayey Neosol	0.5	0.39	0.54	0.55	35	14	77	-0.61	0.59
Neosol average	0.5	0.20	0.32	0.47	225	9	72	-0.58	-0.51
Clayey Nitosol	2.0	0.39	0.54	0.55	35	14	77	-0.61	0.59

* Prof – maximum depth of the soil profile; θ_{PMP} – soil moisture at the permanent wilting point; θ_{CC} – soil moisture at field capacity; θ_S – soil moisture at saturation; K_S – hydraulic conductivity of saturated soil; *AFE* – easily evaporable water; *cc* – curvature coefficient; *a* and *b* – soil hydraulic parameters.
Source: Adapted from Bhering et al. (2007) and Raes et al. (2016)

Four development periods were considered parameters for the corn and soybean crops, as proposed by Allen et al. (1998), with period III (flowering/grain filling) extending throughout the year (Table 2). Therefore, in periods I, II, and IV, the crops had only one day. Thus, period III, which has the highest water demand, lasted throughout the entire year in the 34 years of simulated BHA; that is, it was assumed that the crops were established in the field throughout the year. This hypothetical scenario was established to quantify the water deficit and water surplus that could occur with maximum evapotranspiration throughout the entire year in the 34 years of calculated water balances.

Table 2. Parameters of agricultural crops used in the AquaCrop model to calculate the agricultural water balance for corn and soybeans.

----------------------------- Parameter -----------------------------	Corn	Soy
Total cycle (days)	365	365
Development stage I – sowing to emergence (days)	1	1
Development stage II – vegetative growth to beginning of flowering (days)	1	1
Development stage III – flowering/grain filling (days)	362	362
Development stage IV – maturation (days)	1	1
Canopy (plants ha $^{-1}$)	65,000	300,000
Lower base temperature (°C)	15.5	13
Upper base temperature (°C)	30	40
Fraction of available soil water (*p)* in the topsoil (dimensionless)	0.25	0.20
Fraction of available soil water (*p)* in the bottom soil layer (dimensionless)	0.55	0.50
Minimum aeration-free porosity (β_{min} ; m ^{3} m $^{-3}$)	0.10	0.10
Maximum cultivation coefficient (Kc_{Tx}) (dimensionless)	1.20	1.10
Initial depth of root system (z_o ; m)	0.10	0.10
Maximum effective depth of the root system (z_m ; m)	1.35	1.00
Form factor (*n* ; dimensionless)	15	15
Maximum canopy cover (*CDm* ; %)	85	85

Source: Adapted from Allen et al. (1998) and Raes et al. (2016).

2.3 Probable water deficiency and water surplus for the state of Paraná

Considering the methodological procedures of Souza, Jerszurki and Damazio (2013), the following steps were carried out:
a) Grouping by the sum of the daily values of water deficiency and water surplus (*Def* and *Exc*) in periods of ten days (decdays);
b) Establishment of frequency distributions with data from the observed series;
c) Calculation of the statistical parameters of the probability density functions (PDFs) exponential, gamma, normal, triangular and uniform, with a series of decennial values;
d) Verification of the adherence of the decennial values to the five FDPs with the Kolmogorov–Smirnov test at 5% probability;
e) Select the FDP that best suits each observed decade;
f) Determination of probable values at different levels of probability of occurrence.

The daily values of water deficiency (*Def*) and water surplus (*Exc*) were added and grouped into 37 ten-day periods per year. The thirty-seventh ten-day period of each year was composed of the last five or six (leap year) days of the year.

PDFs were tested, namely, Gamma, Normal, Exponential, Triangular and Uniform, in an Excel spreadsheet specifically designed for this purpose. The statistical parameters determined were alpha and beta for the gamma distribution; mean and standard deviation for the normal distribution; highest value, lowest value and mode for the triangular distribution; mean for the exponential distribution; and highest and lowest values for the uniform distribution (ASSIS; ARRUDA; PEREIRA, 1996; BUSSAB; MORETTIN, 2010).

The adherence of the decennial values to the PDFs was obtained with the Kolmogorov–Smirnov test at 5% probability. The test evaluates, through the *Dmax value*, the fit between the theoretical cumulative frequency distribution $F'(x)$ and another, $F(x)$, from the sampled data.

$$D_{max} = Max|F(x) - F'(x)| \quad (1)$$

where *Dmax* = *the* critical value for the Kolmogorov–Smirnov statistic; $F(x)$ = the theoretical probability distribution function; and $F'(x)$ = the observed probability distribution function.

For the condition "calculated *Dmax* < tabulated *Dmax* ", the hypothesis that the sample values fit well to the probability distribution at 5% significance was accepted; otherwise, the hypothesis was rejected.

The *Dmax* value was estimated via Equations 2 and 3, as recommended by Assis, Arruda and Pereira (1996) and Souza, Jerszurki and Damazio (2013):

$$D_{max} = 0{,}971 - 0{,}2388 \times \ln N \quad \text{For } N < 16 \quad (2)$$

$$D_{max} = \frac{1{,}37}{\sqrt{N}} \quad \text{For } N \geq 16 \quad (3)$$

where D_{max} = the critical value D_{max} of the Kolmogorov–Smirnov statistic and N = the number of sample elements (dimensionless).

After testing the adherence of the PDF that was best adjusted to the *Def* and *Exc data series, for each ten-day period, the probable* ten-day values were determined at 10%, 25% and 50% probabilities (Equations (4) to (9)) for each location (Figure 2):

$$Def_{10\%} = P(Def_{10\%} \in Def \mid Def_i \geq Def_{10\%}) = 10\% \quad (4)$$

$$Def_{25\%} = P(Def_{25\%} \in Def \mid Def_i \geq Def_{25\%}) = 25\% \quad (5)$$

$$Def_{50\%} = P(Def_{50\%} \in Def \mid Def_i \geq Def_{50\%}) = 50\% \quad (6)$$

$$Exc_{10\%} = P(Exc_{10\%} \in Exc \mid Exc_i \geq Exc_{10\%}) = 10\% \quad (7)$$

$$Exc_{25\%} = P(Exc_{25\%} \in Exc \mid Exc_i \geq Exc_{25\%}) = 25\% \quad (8)$$

$$Exc_{50\%} = P(Exc_{50\%} \in Exc \mid Exc_i \geq Exc_{50\%}) = 50\% \quad (9)$$

Therefore, for each ten-day period, $Def_{25\%}$ refers to the deficiency value Def_i that has a 25% probability of being equaled or exceeded, which corresponds to the probability of deficiency Def_i occurring once every four years or with a return time T = 4 years, on average.

With the calculated probable decennial values, maps of the entire state of Paraná were generated by interpolating the probable data obtained from $Def_{10\%}$ and $Exc_{10\%}$ for each grid point (Figure 2). The method used for data interpolation was ordinary kriging, which uses a 1000 × 637 grid. The data were subsequently grouped into 10 geographic mesoregions (MAACK, 2012), and the average of all values contained in the respective mesoregions was calculated.

5 RESULTS AND DISCUSSION

5.1 Best-fit probability density functions

There was no difference between the best-fit probability density functions (PDFs) obtained for corn or soybean. Therefore, the nature of the *Def* and *Exc phenomena* did not change according to the type of crop (grass or legume), only the probable values (mm descending $^{-1}$). Therefore, the difference in the frequency of occurrence between the crops will not be addressed, only aspects related to the *Def* and *Exc phenomena* themselves.

The gamma and exponential PDFs presented greater adjustments to the decennial values of *Def* and *Exc* at the tested points (Figure 2). The Uniform had a minimal number of adjustments and could be discarded for future adjustments (Tables 3 and 4).

Table 3. Frequency of the probability density functions (N – normal; G – gamma; T – triangular; E – exponential; and U – uniform) of best fit for water deficiency and water surplus in corn crops in the state of Paraná.

Decade	Water Deficiency					Water Surplus				
	N	**G**	**T**	**AND**	**U**	**N**	**G**	**T**	**AND**	**U**
1	84	124	17	48	2	8	211	2	54	2
2	2	99	2	172	0	8	107	1	161	0
3	2	131	2	140	0	10	170	0	97	0
4	4	146	0	125	0	8	158	1	110	0
5	0	199	0	76	0	6	108	7	156	0
6	1	157	0	117	0	33	104	17	119	4
7	32	151	13	78	1	3	220	1	53	0
8	89	98	35	49	4	9	187	1	80	0
9	23	107	12	132	1	3	158	3	113	0
10	29	179	11	56	0	12	153	0	112	0
11	4	170	6	95	0	11	102	4	158	2
12	0	169	3	103	0	1	207	0	69	0
13	58	163	14	39	1	1	195	0	81	0
14	16	134	0	122	3	1	130	0	146	0
15	12	87	4	172	0	2	157	2	116	0
16	20	104	21	129	1	1	242	0	34	0
17	17	128	11	119	0	1	193	0	83	0
18	0	157	0	118	0	0	246	0	31	0
19	9	184	0	82	0	3	165	1	108	0
20	55	120	16	84	0	5	199	0	73	0
21	51	107	10	68	39	8	118	7	143	1
22	56	113	11	81	14	3	234	0	40	0
23	139	78	12	45	1	6	237	0	33	1
24	135	35	22	61	22	8	160	2	106	1
25	45	72	1	116	41	6	121	5	144	1
26	2	90	3	180	0	27	71	11	162	6
27	129	97	9	36	4	6	85	7	179	0
28	114	37	8	34	82	6	117	10	143	1
29	123	44	48	35	25	35	137	19	85	1
30	122	44	46	23	40	38	165	6	67	1
31	173	43	37	21	1	23	164	16	74	0
32	177	88	4	5	1	37	119	10	110	1
33	176	61	24	12	2	24	131	4	116	2
34	151	74	22	25	3	37	124	11	101	4
35	131	100	21	15	8	69	133	13	56	6
36	110	103	11	22	29	19	154	7	94	3
37	47	166	16	44	2	9	170	2	93	3
Sum	2338	4159	472	2879	327	487	5852	170	3700	40
Percentage (%)	23.0	40.9	4.6	28.3	3.2	4.7	57.1	1.7	36.1	0.4

Table 4. Frequency of the probability density functions (N – normal; G – gamma; T – triangular; E – exponential; and U – uniform) of best fit for water deficiency and surplus in soybean crops in the state of Paraná.

Decade	Water Deficiency					Water Surplus				
	N	G	T	AND	U	N	G	T	AND	U
1	166	81	24	8	0	10	183	0	84	0
2	80	154	27	18	0	44	132	25	71	5
3	8	125	6	139	1	38	148	9	82	0
4	1	152	0	126	0	11	132	4	130	0
5	0	207	0	72	0	11	103	4	158	1
6	1	159	0	119	0	34	96	15	128	4
7	35	147	15	80	2	6	225	1	45	0
8	93	117	30	34	5	11	172	2	92	0
9	23	108	8	140	0	5	151	2	119	0
10	35	190	13	41	0	7	178	0	92	0
11	6	168	5	100	0	11	94	2	168	2
12	8	170	1	100	0	1	201	1	74	0
13	61	158	13	46	1	0	189	0	88	0
14	10	126	0	140	3	0	141	0	136	0
15	17	90	9	163	0	4	150	0	123	0
16	26	101	24	128	0	2	262	0	13	0
17	14	133	13	117	2	0	180	0	97	0
18	2	147	1	129	0	0	183	0	94	0
19	4	188	2	85	0	1	166	0	110	0
20	45	131	15	88	0	4	165	0	108	0
21	56	101	13	65	44	7	132	3	135	0
22	62	98	15	92	12	3	213	0	61	0
23	131	88	10	48	2	6	230	0	40	1
24	155	22	20	37	45	8	150	0	119	0
25	61	107	4	56	51	9	129	1	138	0
26	14	97	6	162	0	40	76	8	148	5
27	16	158	15	90	0	8	104	2	163	0
28	25	89	19	146	0	2	119	1	155	0
29	13	157	2	106	1	38	132	16	89	2
30	45	161	22	48	3	10	129	4	134	0
31	171	62	27	17	2	9	127	5	136	0
32	164	57	40	14	4	19	103	3	151	1
33	171	69	22	11	6	22	137	4	113	1
34	174	44	33	26	2	40	132	11	92	2
35	190	57	6	22	4	59	123	24	68	3
36	197	48	8	25	1	35	132	2	103	5
37	173	56	16	32	2	4	163	2	108	0
Sum	2453	4323	484	2870	193	519	5582	151	3965	32
Percentage (%)	23.8	41.9	4.7	27.8	1.8	5.1	54.5	1.5	38.7	0.3

Silva et al. (2008) noted that the frequency distribution of *Def data* resembles the distribution of precipitation data; however, the frequency concentration is close to zero. This finding makes the distribution of *Def data* tend more toward the PDF form. Lognormal, followed by exponential and gamma distributions.

In a way, the results found by Silva et al. (2008) for southern Rio Grande do Sul agree with those obtained in the present work, since the best fits were obtained for the Gamma PDFs and exponential PDFs. However, the authors did not use the mixed distribution methodology for the Gamma function, which may have considerably reduced its fit to the *Def values*. Perhaps for this reason, Nied et al. (2005) concluded that the best PDF for *Def* in Santa Maria-RS (climate type Cfa) was Gamma, as did Stagge et al. (2015), who highlighted the good results of this last function after several other PDFs were tested. (Gumbel, Logistics, Log-Logistics, Lognormal, Normal and Weibull) for all of Europe.

Additionally, in Santa Maria, southern Brazil, Bortoluzzi et al. (2017) adjusted the *Exc* for soybeans via exponential, gamma, lognormal, normal and Weibull PDFs and concluded that the best distributions were Gamma, followed by Weibull. Notably, the *Exc values* used were the total sum of the soybean cycle and not the values with ten-day periodicity, which may have influenced the choice of the best FDP.

The parameters of the best-fit PDFs for all ten-day periods of the year, for any probability of occurrence (1% to 99%), in any location in the state of Paraná are available in Gurski (2018). These parameters have a series of applications focused on agricultural planning, such as irrigation management, crop forecasting, and the definition of agricultural zoning (SOUZA; JERSZURKI; DAMAZIO, 2013; SILVA et al., 2015; FERNANDES et al., 2019).

5.2 Probable values of water deficiency and water surplus

The complete probable values of water deficiency and water surplus (*Def* and *Exc*) for each ten-day period of the year throughout the state of Paraná are available for consultation [1].

On average, corn had higher *Def* and *Exc values* than did soybean (Tables 5 and 6). This result is partly justified, according to Doorenbos and Pruitt (1977), by the fact that corn has an average crop coefficient (kc) approximately 5% higher than that of soybean; that is, the water consumption (evapotranspiration) of the latter is generally lower.

Table 5. Average probable values (mm decendia $^{-1}$) of water deficiency (*Def*) for different probability levels for corn and soybean crops in the state of Paraná.

Decade	Corn				Soy			
	Average *Def*	*Def* $_{50\%}$	*Def* $_{25\%}$	*Def* $_{10\%}$	Average *Def*	*Def* $_{50\%}$	*Def* $_{25\%}$	*Def* $_{10\%}$
1	12.66	10.69	17.62	25.41	27.86	26.68	30.89	35.45
2	12:30	8:30	16.75	28.02	21.37	20.51	24,24	28.24
3	11.64	8.14	15.89	26.07	9.70	7.70	12.90	19.33
4	11.38	7.89	15.54	25.64	9.89	6.77	13.52	22.40
5	9.32	6.14	12.68	21.52	9.26	6.22	12.72	21.37
6	9.25	6.71	12.67	20.38	9.29	6.73	12.81	20.53
7	13.56	11.07	18.65	27.74	13.64	11,13	18.86	28.05
8	12.37	10.61	17.42	24.97	12.68	11.05	17.79	25.19
9	12.60	9.58	17.40	27.14	12.71	9.61	17.54	27.57
10	12.47	10.51	16.79	24.21	12.76	10.92	17.12	24.41
11	11.34	8.66	15.46	24.02	11.46	8.70	15.61	24.45
12	9.09	6.61	12.32	19.64	8.70	6.44	11.80	18.69
13	9,12	7.54	12.55	18.38	8.95	7.40	12:30	18.04
14	7.15	4.96	9.66	15.77	7.17	4.88	9.67	15.94
15	5.83	3.91	7.78	12.81	5.98	4.08	8.03	13.07
16	5.51	3.90	7.36	11.64	5.60	3.98	7.50	11.84
17	5.65	4.04	7.66	12.24	5.80	4.16	7.88	12.52
18	5.10	3.12	6.66	11.43	5.23	3.31	6.95	11.68
19	6.13	4.45	8.23	13.07	6.21	4.43	8.40	13.39
20	6.88	5.53	9.45	14.00	6.81	5.37	9.41	14.05
21	8.08	6.96	11.18	15.65	8.24	7.17	11.54	15.90
22	10.26	8.76	14.07	20.04	10.06	8.59	13.87	19.65
23	14.01	12.75	19:45	26.58	13.99	12.61	19.51	26.88
24	12.49	11.44	17.68	23.98	16.11	15.24	22.89	30.12
25	11.66	9.85	16.40	23.70	17.04	14.95	23.84	33,35
26	11.21	8.11	15.41	24.92	15.98	11.84	22.00	35.17
27	9.20	8.31	12.22	16.49	11.90	9.23	16.24	24.93
28	12.56	11.93	17.55	22.50	9.27	6.89	12.88	20.12
29	17.86	17.54	23.43	28.78	6.85	5.20	9.48	14.62
30	21.66	21.42	28.15	33.70	6.99	5.84	9.75	13.99
31	26.08	25.84	31.21	36.05	11.82	11.40	15.33	18.91
32	29.62	29.09	33.66	38.13	22.42	22.13	27.13	31.70
33	32.42	31,33	35.39	39.56	27.89	27.48	31.58	35.55
34	33.83	32.71	36.83	41.32	29.80	28.73	33.08	37.51
35	32.37	31.13	35.11	39.53	29.28	28.11	32.74	37.28
36	31.01	29.55	34.78	40.59	30.38	29.25	33.93	38.76
37	8.34	7.58	10.47	13.67	15.47	14.78	17:45	20.12
Average	13.84	12.07	17.61	24.03	13.37	11.61	17:00	23.26
Sum (mm)	512	447	652	889	494	430	629	861

Table 6. Average probable values (mm ten days $^{-1}$) of water surplus (Exc) for different probability levels for corn and soybean crops in the state of Paraná.

Decade	Corn				Soy			
	***Exc* average**	***Exc** 50%*	***Exc** 25%*	***Exc** 10%*	***Exc* average**	***Exc** 50%*	***Exc** 25%*	***Exc** 10%*
1	28.32	14.07	32.71	59.45	13.43	12.60	16.65	21.00
2	38.79	17.91	45.23	82.95	12.68	11.96	15.62	19.51
3	35.48	16.34	41.85	77.29	16.73	16:45	19.16	21.82
4	30.52	15.32	36.86	66.21	34.69	34.81	38.79	42.23
5	34.44	17.64	41.34	72.96	32.74	32.79	37.21	41.08
6	29.21	17.49	36.19	59.54	31.74	31.88	36.69	40.90
7	19.81	8.40	22.81	43.84	28.42	28.59	33,33	37.30
8	21.55	7.06	22.18	45.50	26.07	26,27	31.06	35.14
9	23.63	7.85	24.67	49.07	23.85	23.98	28.58	32.36
10	19.05	5.14	18.51	37.69	21.82	22.05	26.34	29.86
11	24.90	9.40	26.68	49.78	19.53	19.66	23.62	26.91
12	34.24	13.09	38,38	75.28	18.81	19.03	22.50	25.51
13	26.10	8.05	26.92	55.68	15.76	15.92	19.14	21.86
14	41.52	14.11	43.32	85.77	14.61	14.72	17.97	20.73
15	42.73	15.99	46.41	88.70	14.39	14.48	17.13	19.40
16	30.57	9.51	32.30	67.99	13.29	13:35	15.63	17.60
17	29.17	12.47	33.81	64.35	13.08	13,13	15.49	17.46
18	42.03	14.57	45.56	92.20	13.25	13:30	15.82	17.93
19	28.39	11.62	32.48	62.34	13.60	13.63	16.37	18.71
20	26.55	9.31	28.64	58.28	13.60	13.53	16.37	18.93
21	23.62	8.64	24.73	48.77	14.22	14.12	17.39	20.41
22	19.60	4.62	18.08	41.13	14.05	14.06	17.28	20.11
23	20.66	2.21	12.88	36.84	13.43	13.08	17.06	20.77
24	31.68	2.03	19,18	51.59	13.84	13.18	18.41	23.46
25	27.06	3.63	20.47	46.61	15:30	14.92	20.58	25.78
26	38.24	9.21	36.08	70,70	17.36	17.50	22.67	26.76
27	40.74	16.95	45.05	82.15	21.96	22.05	26.25	29.94
28	46.32	22.81	55.10	97.68	20.46	20.57	24.08	27.11
29	44.36	28.98	56.63	90.53	21.98	22.02	25.07	27.74
30	43.23	29.36	55.52	88.24	23.46	23.46	26.07	28.39
31	36.65	26.13	47.63	74.26	23.50	23.33	26.28	29.02
32	37.75	25.80	48.97	79.17	18.67	17.68	22.76	28.17
33	34.47	20.17	41.36	70.26	17.70	16:35	21.36	27.11
34	39.91	24.21	47.37	79.40	16.42	14.74	20.06	26.42
35	48.14	33.90	57.01	86.80	14.60	13.56	17.75	22.42
36	43.22	26.11	50.77	84.76	14.55	13.56	17.83	22.53
37	22.62	12.06	26.36	47.29	7.16	6.68	8.82	11.20
Average	32.58	14.65	36.22	66.79	18.40	18,19	21.98	25.50
Sum (mm)	1205	542	1340	2471	681	673	813	944

Importantly, both the mean *Def* and *Exc values were not always equal to the* ten-day *Def* $_{50\%}$ and *Exc* $_{50\%}$ values, especially when the component was better adjusted to a PDF other than normal (Tables 5 and 6). For example, when the values of the sum between the mean *Def* and *Def* $_{50\%}$ *were compared,* a difference of approximately 65 mm was observed in the year for both corn and soybean crops. (Table 5). The results agree with those of Nied et al. (2005) and Stagge et al. (2015), who considered that the normal function and consequently its mean do not adequately reflect the trend in studies of probable values of *Def*. In this situation, obtaining a better fit with other PDFs makes it possible to obtain more reliable probable values.

Sentelhas, Santos, and Machado (2008) established *Def* and *Exc* for all of Brazil, using grass as a standard crop and the Thornthwaite and Matter methodology to calculate the agricultural water balance (ABW). They reported annual values ranging from 0–100 mm year^{-1} and 100–700 mm year^{-1}, respectively, for the state of Paraná. These values are much lower than those reported in the present study. Although the crops used are quite different, this large variation in the values found may be due to differences in the methodologies used to calculate the ABW. In the AquaCrop model (RAES et al., 2016), the available water capacity (AWC) is variable, and surface runoff is accounted for in Exc. In the Thornthwaite and Matter methodology, all rainfall is considered water input to the system. The AWC is fixed and previously established/calculated according to the scenario studied.

BHA calculations assume that crops are cultivated year-round; for the purposes of sowing season simulations, the average soybean cycle is considered to be 130 days, and that of corn is 110 days (BRASIL, 2020a, 2020b, 2020c). In this sense, Tables 7 and 8 demonstrate the balance of *Def* or *Exc*, considering the initial date of the ten-day period as the crop sowing date and adding the values occurring during the crop cycle to account for *Def* or *Exc*. For example, if corn were sown in ten-day period 1 (Jan 1), a *Def of 10% = 313 mm* would occur throughout the 110-day cycle.

Table 7. Balance (*) of probable decennial water deficiency (*Def*) (mm cycle $^{-1}$) for different probability levels for corn and soybean crops in the state of Paraná.

Decade	Corn				Soy			
	Average *Def*	*Def* $_{50\%}$	*Def* $_{25\%}$	*Def* $_{10\%}$	Average *Def*	*Def* $_{50\%}$	*Def* $_{25\%}$	*Def* $_{10\%}$
1 (01/Jan)	147	112	202	313	168	140	194	314
Jan 11)	142	107	194	304	148	118	175	294
Jan 21)	135	102	185	288	132	102	163	279
Jan 31)	129	98	176	274	128	98	160	272
5 (10/Feb)	123	94	168	260	124	95	154	262
Feb 20)	119	91	162	250	120	92	149	252
7 (02/Mar)	116	89	158	243	117	90	144	245
8 (12/Mar)	109	83	149	229	110	84	132	231
9 (22/Mar)	105	80	143	220	106	80	123	222
10 (01/Apr)	103	79	139	213	103	79	115	214
11 (11/Apr)	104	81	142	215	104	81	109	216
Jan 21)	105	84	144	215	109	88	107	222
13 (01/May)	108	87	148	219	117	96	115	236
May 11)	110	88	151	226	124	101	126	254
May 21)	112	91	154	227	129	105	140	263
May 31)	119	99	163	236	132	108	154	270
June 10)	131	113	179	253	133	109	163	272
June 20)	147	130	200	275	135	111	168	274
June 30)	168	153	224	299	141	119	170	281
20 (10/Jul)	192	178	250	325	157	136	171	299
July 20)	217	203	276	350	179	159	177	321
July 30)	243	229	301	376	200	180	193	343
23 (09/Aug)	265	251	322	395	219	200	211	360
Aug 19)	282	268	338	409	236	216	224	372
Aug 29)	284	270	339	412	249	229	234	380
26 (08/Sep)	285	269	340	415	257	238	244	378
27 (18/Sep)	286	269	341	417	256	240	255	367
28 (September 28)	288	269	345	426	254	238	266	363
29 (Oct 8)	286	264	341	427	254	238	272	365
30 (Oct 18)	277	253	330	419	257	239	276	371
31 (Oct 28)	267	241	318	410	261	242	279	381
Nov 7)	254	226	305	400	263	242	277	389
Nov 17)	237	207	289	388	253	230	265	384
Nov 27)	217	185	270	374	238	213	252	374
35 (December 7th)	195	162	250	357	220	194	237	361
36 (Dec 17)	173	139	228	339	201	173	221	345
37 (Dec 27)	151	116	206	318	179	151	204	325

(*) Sum of the average *Def values* in the cycle of each crop – 13 and 11 ten days for corn and soybeans, respectively, with the respective ten days as the beginning of the cycle (sowing).

Table 8. Balance [(*)] of the probable ⁻decadal water surplus (*Exc.*) (mm cycle [1]) for different probability levels for corn and soybean crops in the state of Paraná.

Decade	Corn				Soy			
	***Exc* medium**	***Exc* *50%***	***Exc* *25%***	***Exc* *10%***	***Exc* medium**	***Exc* *50%***	***Exc* *25%***	***Exc* *10%***
1 (01/Jan)	366	158	414	775	262	261	307	348
Jan 11)	379	158	425	802	267	267	313	353
Jan 21)	383	156	426	807	270	271	316	355
Jan 31)	378	149	417	798	268	270	315	354
5 (10/Feb)	377	146	414	796	248	249	294	331
Feb 20)	385	143	418	815	228	230	272	308
7 (02/Mar)	384	137	414	818	210	211	251	284
8 (12/Mar)	390	138	420	833	194	196	233	265
9 (22/Mar)	392	140	422	836	182	183	219	248
10 (01/Apr)	388	137	416	828	172	173	206	235
11 (11/Apr)	390	134	410	827	164	165	197	225
Jan 21)	397	126	403	829	159	159	191	219
13 (01/May)	390	117	385	800	153	153	186	214
May 11)	402	118	394	815	151	151	185	216
May 21)	401	121	396	812	152	151	188	221
May 31)	405	128	404	821	155	154	193	228
June 10)	418	147	429	843	164	162	204	240
June 20)	432	164	450	867	171	170	212	250
June 30)	427	175	452	849	180	179	222	260
20 (10/Jul)	436	190	469	866	190	188	231	269
July 20)	444	201	482	878	200	198	241	279
July 30)	461	216	504	909	204	202	247	287
23 (09/Aug)	489	245	543	954	208	204	251	294
Aug 19)	512	269	581	1002	211	206	254	300
Aug 29)	517	286	605	1028	211	206	253	299
26 (08/Sep)	523	299	623	1052	211	205	250	296
27 (18/Sep)	522	307	631	1062	207	200	245	291
28 (September 28)	515	306	625	1051	198	191	235	281
29 (Oct 8)	501	299	609	1023	193	184	228	274
30 (Oct 18)	488	288	591	999	196	188	232	279
31 (Oct 28)	469	271	565	962	206	198	244	292
Nov 7)	453	253	540	933	215	207	254	304
Nov 17)	438	235	514	901	227	220	267	315
Nov 27)	425	221	495	874	236	231	277	324
35 (December 7th)	407	204	470	838	245	241	287	331
36 (Dec 17)	389	181	445	814	253	251	297	340
37 (Dec 27)	376	166	427	795	259	258	304	346

[(*)] Sum of the average *Exc values* in the cycle of each crop – 13 and 11 ten days for corn and soybeans, respectively, with the respective ten days as the beginning of the cycle (sowing).

According to the Ministry of Agriculture, Livestock and Supply-MAPA (BRASIL, 2020a), soybean sowing in Paraná can be carried out between September 10 and December 31 of the year (ten-day period 26--37) due to the imposition of the sanitary gap in the state. In this period (sowing window), the ten-day period in which the least *Def would occur*, regardless of the probability level, would be in the ten-day period 37 (sowing from December 27--31), whereas the lowest *Exc* would occur in the ten-day period 29 (October 8--17) (Table 7).

Farias et al. (2001), considering the entire state of Paraná, also reported that the sowing period between December 21st and 31st provided the lowest *Def* for soybean crops. The authors performed simulation scenarios considering *Def* at an 80% probability of occurrence for early cultivars (120 days) and soil with average water retention (50 mm).

According to Bortoluzzi et al. (2017), this sowing period (December 21st to 31st) was also when the lowest *Exc* values for soybeans occurred in Santa Maria-RS. The authors tested several sowing dates from October to December, as they are recommended for the state of Rio Grande do Sul, southern Brazil, and reported that the closer to the end of the year, the lower the *Exc* values are.

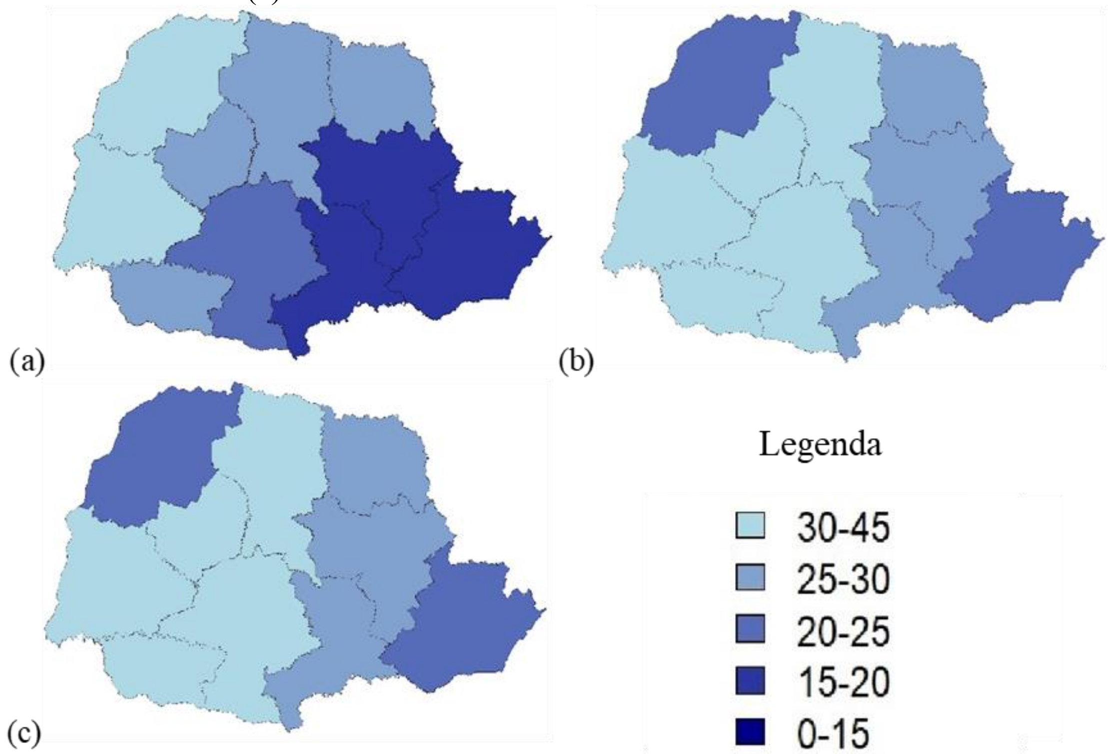
The corn crop can be grown in the state of Paraná in two periods of the year: the 1st harvest, from August 1st to December 27th (decades 22nd to 36th) (BRASIL, 2020b), and the 2nd harvest, from December 28th to March 31st (decades 37th to 9th) (BRASIL, 2020c). During these periods, on average throughout the state of Paraná, the lowest *Def values* occurred if the 1st- and 2nd-harvest corn were sown on the 36th (December 17th to 26th) and 09th (March 22nd to 31st) days, respectively. For the lowest *Exc values*, there was variation according to the probability level used.

In general, the lowest *Def* and *Exc* values for soybean and corn occurred at the end dates of the periods indicated for sowing. Considering that in the state of Paraná, except in specific regions (CARAMORI, 2003), there is at least one harvest in summer and one in winter, normally, the adopted/preferred sowing dates occur at the beginning of the recommended periods and not at the end to avoid the influence of other climatic risks (FARIAS et al., 2001).

This finding demonstrates the significant potential for supplemental irrigation in the state of Paraná, with the aim of sowing crops earlier than the recommended period. Considering that *Def* is particularly high when sowing occurs at these times, supplemental irrigation increases crop productivity, avoids other climatic risks, and, above all, enables better planning of crop succession, thus increasing efficient land use (FERNANDES et al., 2019).

However, Paraná has great climatic heterogeneity throughout the year and in its relief (MAACK, 2012; ALVARES et al., 2013), resulting in highly variable spatial distributions of *Def* and *Exc*. To illustrate this point, considering the respective recommended sowing periods for corn and soybeans in Paraná, as well as a $Def_{of\,10\%}$, it was found that the western portion of the state has the highest values (Figure 3), precisely the region where agricultural activity is most intense (IBGE, 2017).

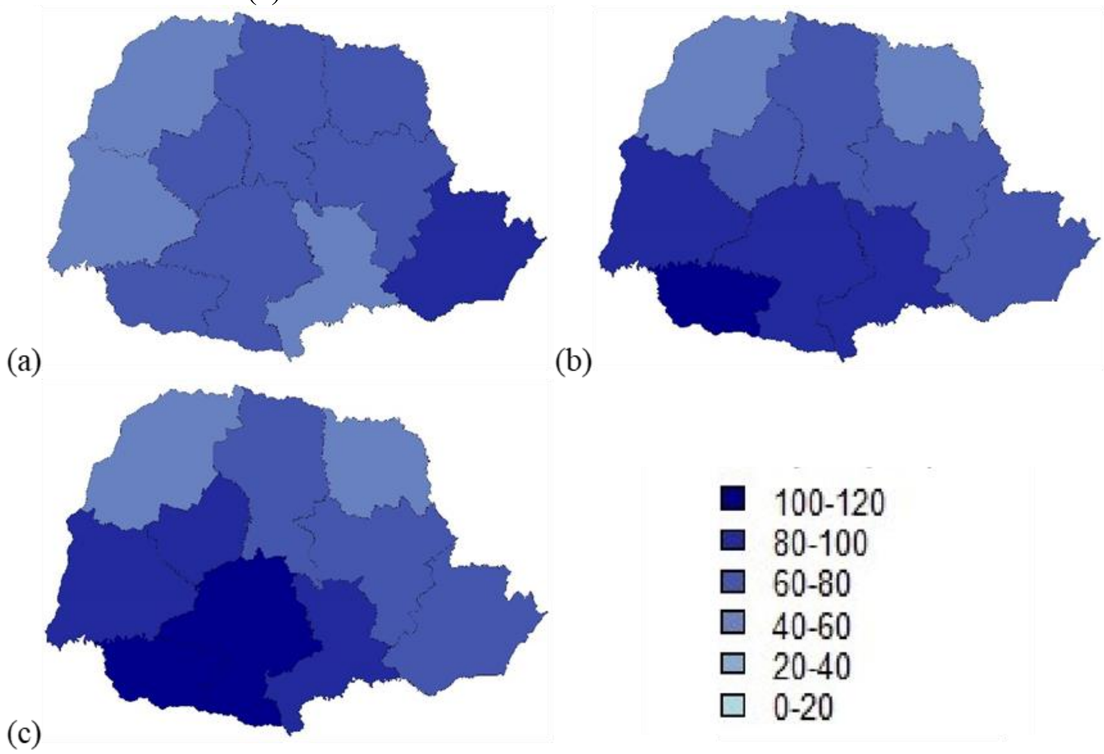
Figure 3. Average water deficiency (mm ten days $^{-1}$) at a 10% probability of occurrence in the ten days recommended for sowing* soybeans (a) and corn second harvest (b) and first harvest (c).



* Recommended decades for soybeans – 26--37; second-crop corn – 37--9; first-crop corn – 22--36 (BRASIL, 2020a; 2020b; 2020c).

With the exception of 10%, there was no well-established spatial distribution by mesoregion. Even so, the values were lower in the northern part of the state (Figure 4), a region where agricultural activity is also more intense (IBGE, 2017).

Figure 4. Average water surplus (mm ten days $^{-1}$) at a 10% probability of occurrence over the ten days recommended for sowing* soybeans (a) and corn second harvest (b) and first harvest (c).



* Recommended decades for soybeans – 26--37; second-crop corn – 37--9; first-crop corn – 22--36 (BRASIL, 2020c; 2020b; 2020c).

Carvalho and Stipp (2004) reported an average annual *Exc in Paraná of approximately 800 mm, whereas* Sentelhas, Santos and Machado (2008) reported a range of 0–700 mm. The results presented, including those of this work, demonstrate great potential for the storage and use of this *Exc*, which occurs in the state.

6 CONCLUSION

The gamma and exponential probability density functions were those that showed adherence to the greatest number of locations considering the deficiency values (*Def*) and surplus (*Exc*) water, whereas the uniform function can be discarded for future adjustments.

Considering the entire state of Paraná and the sowing window established by official agencies, on average, the lowest *Def* occurs when soybean is sown in the 37th decade (December 27th to 31st), and the lowest *Exc* occurs in the 29th decade (October 8th to 17th). For the first and second corn crops, the lowest *Defs* occur in the 36th decade (December 17th to 26th) and 09th decade (March 22nd to 31st), respectively, whereas the lowest Excs *depend* on the probability level used.

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