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Posted Date: 11 January 2024

doi: 10.20944/preprints202401.0873.v1

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Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 January 2024 doi:10.20944/preprints202401.0873.v1

Article

Assessing Drought Vulnerability in the Brazilian Atlantic Forest Using High Frequency Data

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Abstract: This research investigates the exposure of plant species to extreme drought events in the Brazilian Atlantic Forest, employing an extensive dataset collected from 205 automatic weather stations across the region. Meteorological indicators derived from hourly data, encompassing precipitation, maximum and minimum air temperature, were utilized to quantify past, current, and future drought conditions. The dataset, comprising 10,299,236 data points, spans a substantial temporal window and exhibits a modest percentage of missing data. Missing data were excluded from analysis, aligning with the decision to refrain from imputation methods due to potential bias. Drought quantification involved the computation of the Aridity Index, the analysis of consecutive hours without precipitation, and the classification of wet and dry days per month. Mann-Kendall trend analysis was applied to assess trends in evapotranspiration and maximum air temperature, considering their significance. The hazard assessment, incorporating environmental factors influencing tree growth dynamics, facilitated the ranking of meteorological indicators to identify regions most exposed to drought events. The results revealed consistent occurrences of extreme rainfall events, indicated by positive outliers in monthly precipitation values. However, significant trends were observed, including an increase in daily maximum temperature and consecutive hours without precipitation, coupled with a decrease in daily precipitation across the Brazilian Atlantic Forest. No significant correlation between vulnerability ranks and weather station latitudes and elevation were found, suggesting geographical location and elevation does not strongly influence observed dryness trends.

Keywords: brazilian atlantic forest; drought exposure; dryness

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1. Introduction

The Brazilian Atlantic Forest, once sprawling across 150 million hectares and dominating the country's coastal regions, has undergone significant transformations over the centuries. Originally contiguous, the forest has evolved into fragmented patches, especially along the Brazilian coast, due to historical land use changes and urban expansion [13]. This fragmentation, particularly noticeable in smaller fragments of less than 50 hectares, has placed a substantial portion of the forest's diverse biodiversity at risk of extinction [14–16]. Fragmented landscapes often experience edge effects driven by abiotic factors like water, wind, and temperature, pushing plant communities toward early successional stages [17–20].

As one of the planet's most biodiverse ecosystems, the Brazilian Atlantic Forest faces escalating threats, with climate change posing a formidable challenge. The biome's intricate web of life and ecological significance is now confronted with shifting aridity patterns, exacerbated by habitat fragmentation and ecological succession processes [1]. Recent ecological shifts in the Atlantic Forest have intensified, contributing to increased aridity and prompting concerns about the separation of Amazonian and Atlantic Forest lineages in Brazil [2].

Amidst these ecological transformations, environmental variables, particularly precipitation, play a pivotal role in shaping the vitality of the Atlantic Forest. Anthropogenic pressures and climate change effects loom large, and long-term forecasts signal a concerning decline in precipitation levels [3]. Such changes could significantly impact the delicate balance of this vulnerable ecosystem [4,5]. This study, conducted between 2000 and 2022, seeks to delve into the repercussions of evolving aridity patterns on the Brazilian Atlantic Forest.

This study focuses on meteorological indicators to unveil nuanced trends and pinpoint regions undergoing substantial alterations in aridity conditions. By scrutinizing the impact of changing climate patterns on the Atlantic Forest, this research aims to contribute valuable insights into the ecological dynamics of this biome. Subsequent sections provide a description of the methodology, data, and outcomes, shedding light on the complex relationship between climate variability and the status of the Brazilian Atlantic Forest.

2. Materials and Methods

We adopted the boundaries of the Brazilian Atlantic forest to be congruent with those delineated for the Atlantic forest biome by the Instituto Brasileiro de Geografia e Estatística (IBGE). The definition of the Atlantic forest biome by IBGE was based on an extensive process involving literature review, interinstitutional validation, and field surveys to verify the presence of the physical-biotic environment and historical evidence of the Atlantic forest within the demarcated boundaries [6]. These boundaries were sourced from TerraBrasilis, a platform managed by the Instituto Nacional de Pesquisas Espaciais (INPE), which facilitates data organization, accessibility, and utilization for Brazil's environmental monitoring efforts.

To assess the exposure of plant species to extreme drought events in the Brazilian Atlantic forest, we relied on meteorological indicators. These indicators were derived from hourly data of precipitation, maximum and minimum air temperature recorded at 205 automatic weather stations, accessible from the Instituto Nacional de Meteorologia (INMET) database [https://bdmep.inmet.gov.br, accessed in August 2023]. An overview of these datasets, including station codes, sample sizes, monitoring periods, and the percentage of missing data, is provided in the supplementary materials. The geographic distribution of the 205 automatic weather stations as well as the boundaries for the Atlantic forest used in this study are presented in 1. This dataset stands as an extensive and robust compilation, with a total of 10,299,236 data points. Spanning a broad temporal window, from distinct station-specific start dates to a standardized endpoint on December 31, 2022, the dataset exhibits a relatively modest percentage of missing data.

Past, current, and future drought conditions were quantified using several meteorological indicators, including the number of consecutive hours without precipitation, the number of dry and wet days per month, the Aridity Index, and the Mann-Kendall test statistic (Z) for trend analysis in evapotranspiration (ET) and maximum air temperature (T_{max}). The choice of these indicators was motivated by their relevance to recent severe drought events [11]. We opted against employing imputation methods to replace missing data, as this approach can introduce systematic bias into the meteorological indicators [7,8]. Consequently, all missing data were excluded from the analysis, and the accumulated or averaged values resulting from any missing hourly data from the 205 automatic weather stations were disregarded.

The Aridity Index was computed as the ratio of monthly precipitation to evapotranspiration. Monthly precipitation values were determined by aggregating the available hourly precipitation data, while monthly evapotranspiration values were calculated by aggregating daily reference crop evapotranspiration estimates. These daily estimates were generated using the Hargreaves and Samani equation [9], with input data encompassing measured hourly maximum and minimum air temperatures, elevation, and latitude.

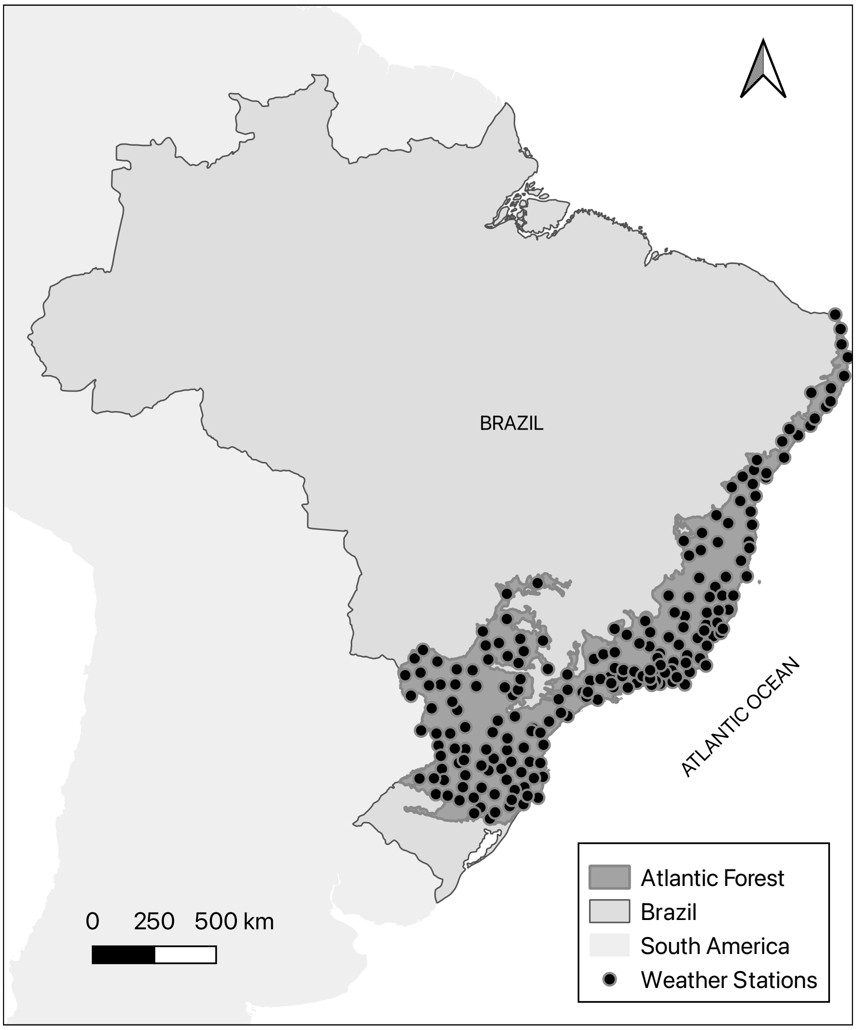

Figure 1. Weather stations localization

The classification of wet and dry days per month was performed using a precipitation threshold of 0 mm per weather station. Days with precisely 0 mm of precipitation were categorized as dry, while those with precipitation exceeding 0 mm were classified as wet. Subsequently, the median values for the number of wet and dry days per month were employed as meteorological indicators to gauge drought exposure.

To determine the duration of consecutive hours without precipitation, we analyzed sequences of hours with no recorded precipitation. In instances of missing data within a sequence, we adopted a conservative approach by considering two distinct sequences. This approach was necessary as missing data could inadvertently elongate the periods to be without precipitation.

Mann-Kendall (MK) trend analysis was employed to examine the daily evapotranspiration estimates and maximum air temperature data at each weather station. A trend was considered statistically significant when the associated p-value was less than 0.05. The MK test statistics, Z and S, were used to assess both the presence and the strength of a monotonic upward or downward trend in daily evapotranspiration and maximum air temperature. The MK test statistic Z was further utilized as an indicator for evaluating potential future drought exposure.

Lastly, we conducted a hazard assessment by ranking the meteorological indicators calculated for each weather station, which allowed us to identify the regions most exposed to drought events. This hazard assessment was developed, taking into consideration environmental factors that influence tree growth dynamics in the Brazilian Atlantic forest under drought conditions [10], as well as the amount of data available after the data filtering process for missing data.

 doi:10.20944/preprints202401.0873.v1

3. Results and Discussion

We used boxplots to visualize the distribution of accumulated monthly precipitation for all 205 automatic weather stations in the Brazilian Atlantic forest. They provide range, median, and distribution of values at each weather station during their monitoring period. The boxplots are presented in Figure 2. Figure 2 reveals the presence of positive outliers across most of the weather stations, which indicates instances of extreme rainfall events. These events are characterized by precipitation values significantly higher than the majority of the data points. The consistent occurrence of positive outliers across various weather stations implies that extreme rainfall events are a recurring phenomenon in the Brazilian Atlantic forest.

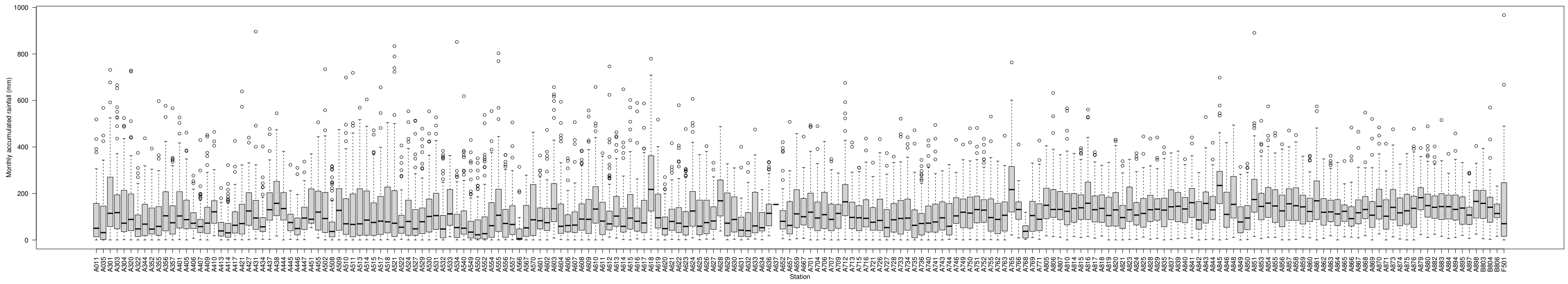

Figure 2. Boxplots of accumulated monthly precipitation for all 205 automatic weather stations in the Brazilian Atlantic forest.

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The Mann-Kendall (MK) test assessed the presence and strength of monotonic trends in the time series data. We assumed that trends were statistically significant when the p-value was less than 0.05. The results of the MK trend analysis are summarized in Figure 3. A substantial majority of the 205 weather stations exhibited a statistically significant upward trend in daily maximum temperature and number of hours without precipitation. In contrast, the majority of daily precipitation exhibited a statistically significant downward trend. Unlike the unidirectional trend observed in daily maximum temperature or daily precipitation, daily minimum temperature and daily evapotranspiration presented a spectrum of behaviors, including instances of no discernible, upward and downward trends. Despite the varied outcomes in the analysis of daily minimum temperature and daily evapotranspiration, the overarching findings of the MK test indicated an overall reduction in daily precipitation and an increase in both maximum daily temperature and number of consecutive hours without precipitation across the Brazilian Atlantic forest. This suggests a scenario in which the ecosystem may encounter drier conditions in the future.

It is noteworthy that aridity conditions, reflective of short-term extremes, could not be adequately captured through statistics based on monthly values of precipitation, evapotranspiration or even AI. As we evaluated hourly data for maximum temperature and consecutive hours without precipitation reveals that a significant portion of the Brazilian Atlantic forest is already undergoing dry conditions.

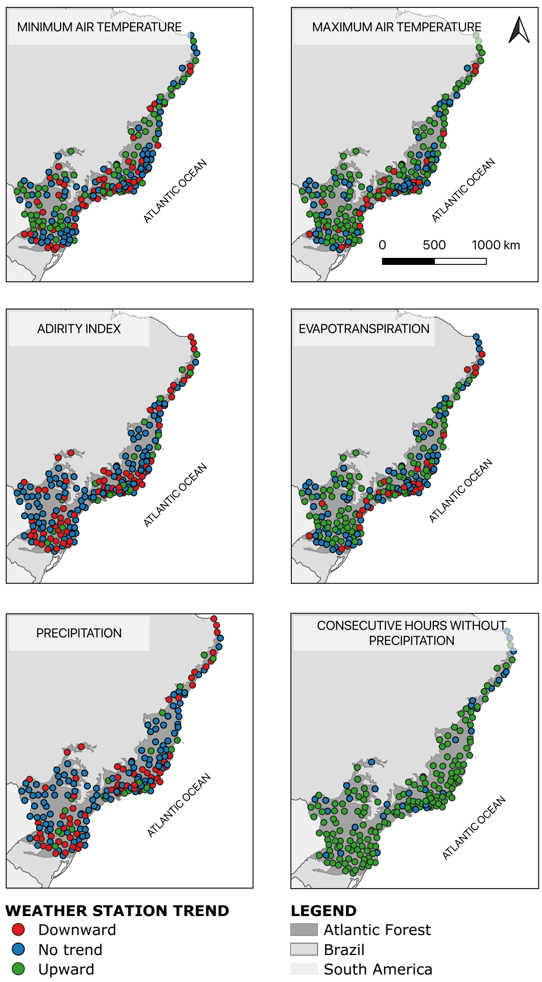

Figure 3. Spatial distribution of detected trend in minimum air temperature, maximum air temperature, aridity index, evapotranspiration, precipitation, and consecutive hours without precipitation by weather station.

 doi:10.20944/preprints202401.0873.v1

In an attempt of establishing a vulnerability ranking, the outcomes of the meteorological indicators were synthesized and organized in Table 1. The ranking reflects the ascending order of vulnerability, delineating the weather stations in terms of their susceptibility to drought events within the Brazilian Atlantic Forest. There is no significant correlation between the assigned rank numbers and the latitudinal positions and elevation of the weather stations (Figure 4. This observation suggests that neither geographical location, as represented by latitude, nor elevation play a significant role in influencing the trends of dryness observed at each weather station.

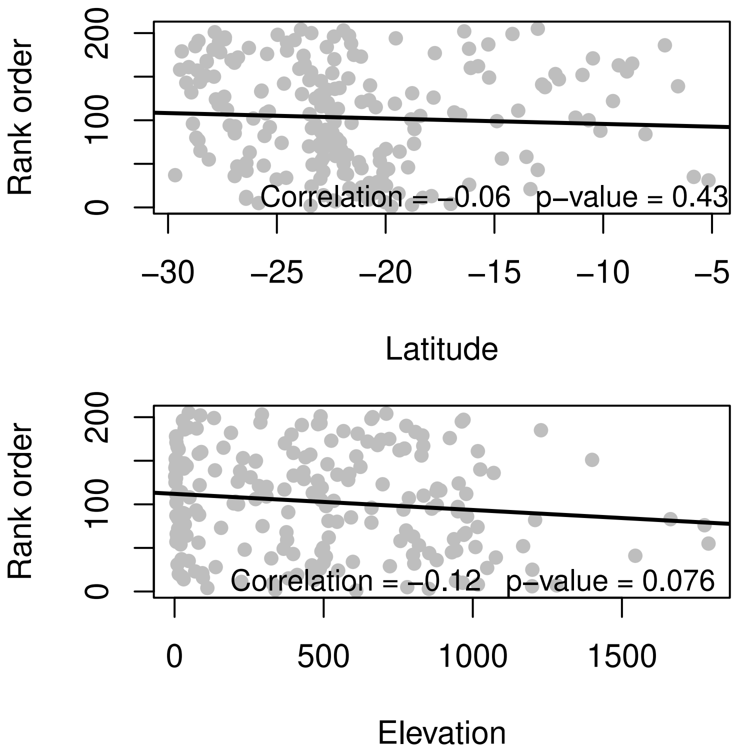

Figure 4. Scatter plots illustrating the relationship between latitude and elevation against the order of the weather station in the ranking of vulnerability to drought events. The black solid line represents the linear regression model fitted to the data.

Table 1. A vulnerability ranking for weather stations presented in ascending order according to their susceptibility to drought events within the Brazilian Atlantic Forest.

Station	NDD	NWD	AI	Trend in ET	Trend in Tmax	Trend in NCDH	Rank
A554	22	8	0.31	9.784	21.125	0.492	1
A752	27	3	0.40	3.016	3.613	0.616	2
A533	22	9	0.72	6.601	10.564	0.561	3
A455	19	11	0.28	8.297	6.572	0.517	4
A874	21	10	0.78	6.372	6.132	0.770	5
A555	21	9	0.19	2.827	3.102	0.565	6
A531	19	11	0.37	6.581	6.699	0.487	7
A529	19	11	0.72	12.163	12.430	0.496	8
A704	21	9	0.44	9.543	10.455	-0.227	9
A876	20	10	0.69	6.708	6.506	0.519	10
A631	18	13	0.57	9.400	5.845	0.587	11
A816	21	10	0.64	6.783	5.626	0.453	12
A527	20	10	0.54	4.666	4.580	0.488	13

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A621	22	8	0.39	3.003	4.029	0.413	14
A734	19	11	0.59	6.771	8.050	0.426	15
A632	18	12	0.59	5.988	3.571	0.595	16
A634	26	4	0.04	-0.064	0.347	0.599	17
A735	20	11	0.55	3.143	6.924	0.454	18
A557	17	13	0.53	1.860	13.693	0.590	19
A615	22	9	0.68	3.725	2.800	0.481	20
A444	18	13	0.28	6.937	3.985	0.479	21
A727	19	12	0.50	3.146	6.724	0.455	22
A622	17	13	0.55	4.953	4.225	0.605	23
A835	21	9	0.83	2.541	3.327	0.567	24
F501	24	7	0.35	1.055	-0.468	0.563	25
A552	18	12	0.34	1.336	5.535	0.561	26
A513	23	8	0.49	1.652	2.766	0.458	27
A617	18	13	0.63	5.477	6.011	0.499	28
A633	18	12	0.56	3.300	0.589	0.622	29
A733	25	6	0.16	1.172	2.341	0.360	30
A344	20	10	0.42	1.625	7.621	0.193	31
A818	20	11	0.78	5.122	8.088	0.295	32
A716	21	9	0.73	2.819	5.790	0.307	33
B803	16	15	0.85	8.013	10.117	0.580	34
A304	22	9	0.19	0.593	4.076	0.256	35
A858	18	13	0.96	6.904	7.064	0.492	36
A884	21	10	0.77	1.413	-1.292	0.677	37
A743	19	12	0.59	1.562	1.022	0.610	38
A530	17	13	0.63	8.100	7.903	0.316	39
A657	24	6	0.15	-0.743	-2.005	0.491	40
A509	19	12	0.61	5.506	6.322	0.159	41
A864	16	14	0.77	6.019	5.586	0.572	42
A434	21	9	0.30	-0.043	-0.243	0.457	43
A521	18	12	0.81	2.845	5.508	0.497	44
A514	16	14	0.72	5.565	6.682	0.515	45
A011	18	11	0.60	1.972	6.513	0.342	46
A859	17	13	1.23	6.082	6.210	0.579	47
A846	17	14	1.29	9.931	8.324	0.534	48
A869	16	15	0.80	6.755	7.496	0.517	49
A768	19	12	0.42	-0.903	-0.851	0.610	50
A875	18	13	1.33	6.840	6.071	0.519	51
A502	18	13	0.67	6.714	6.462	0.195	52
A556	19	12	0.45	-2.268	1.676	0.572	53
A636	20	10	0.35	-2.310	-3.657	0.564	54
A845	20	10	1.00	2.049	3.050	0.467	55
A410	15	16	0.73	6.889	13.642	0.465	56
A627	22	9	0.55	-0.827	-3.505	0.528	57
A407	16	15	0.48	4.552	7.147	0.351	58
A709	22	8	0.32	-1.305	1.845	0.240	59
A518	20	10	0.45	0.886	0.189	0.386	60
A612	21	9	0.86	1.791	2.235	0.385	61
A630	20	10	0.43	-2.644	-4.861	0.566	62
A862	17	13	1.12	4.609	4.799	0.557	63

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A614	20	10	0.43	-1.344	1.068	0.429	64
A880	18	12	1.07	3.388	3.295	0.515	65
A620	18	12	0.51	1.760	0.960	0.465	66
A613	20	11	0.41	-2.102	-1.265	0.497	67
A749	18	12	0.68	-0.742	1.263	0.602	68
A652	19	11	0.57	1.117	2.219	0.403	69
A755	18	12	1.29	2.837	2.914	0.581	70
A659	22	9	0.71	-2.382	-4.458	0.579	71
A602	19	12	0.72	3.200	4.103	0.224	72
A623	19	11	0.70	-0.788	-0.448	0.583	73
A819	18	12	0.76	2.361	4.858	0.315	74
A625	20	11	0.75	0.139	-1.269	0.558	75
A610	18	12	0.87	3.443	4.687	0.310	76
A866	15	15	1.04	1.839	7.543	0.650	77
A667	20	10	0.64	-4.085	-5.136	0.607	78
A763	16	15	0.78	3.434	1.801	0.610	79
A894	15	15	1.05	4.625	3.680	0.646	80
A626	20	11	0.76	0.130	-1.532	0.558	81
A823	17	13	1.43	3.169	3.622	0.588	82
A706	20	11	0.66	0.708	2.212	0.323	83
A301	16	14	0.51	1.334	12.855	0.303	84
A861	18	12	1.16	3.617	2.196	0.494	85
A618	20	10	0.46	-0.096	-0.981	0.338	86
A628	21	10	0.65	-2.927	-6.258	0.552	87
A355	17	14	0.43	2.012	4.467	0.274	88
A601	19	11	0.55	2.219	0.827	-0.096	89
A616	20	11	0.66	-1.960	2.470	0.396	90
A824	20	10	0.64	0.198	1.629	0.291	91
B806	17	14	0.88	2.114	1.102	0.605	92
A817	17	13	1.37	2.904	4.448	0.543	93
A841	14	17	1.01	8.740	12.219	0.469	94
A740	18	12	1.01	2.118	3.124	0.450	95
A837	20	11	1.20	1.579	2.699	0.457	96
A515	18	13	0.79	2.730	4.585	0.264	97
A637	21	10	0.60	0.195	-1.316	0.295	98
A414	15	15	0.48	3.229	3.956	0.330	99
A451	14	16	0.54	3.213	4.812	0.389	100
A532	17	14	0.46	0.419	0.848	0.503	101
A851	17	13	1.15	1.618	2.798	0.585	102
A417	14	17	0.77	6.709	9.262	0.355	103
A741	16	14	1.04	3.862	5.197	0.442	104
A035	16	15	0.64	2.800	6.656	0.248	105
A550	16	15	0.86	1.649	4.998	0.531	106
A701	18	12	0.81	0.644	3.687	0.362	107
A873	19	11	0.98	-4.112	-2.063	0.622	108
A566	14	16	0.77	3.761	-0.169	0.587	109
B804	17	14	1.14	1.723	1.482	0.613	110
A438	16	14	0.52	-0.188	5.500	0.373	111
A860	15	16	1.19	6.704	6.617	0.451	112
A721	18	13	0.53	1.664	0.847	0.250	113

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A603	20	11	0.60	1.386	-1.701	0.012	114
A524	15	16	0.46	1.506	3.518	0.421	115
A744	17	13	0.44	-6.271	-4.955	0.587	116
A849	9	21	1.01	7.824	8.805	0.512	117
A870	17	14	0.89	1.550	-1.348	0.591	118
A511	12	18	0.84	4.703	7.364	0.444	119
A850	12	18	1.45	5.874	8.729	0.529	120
A517	17	13	0.77	0.216	2.103	0.457	121
A303	14	16	0.35	2.866	3.502	0.153	122
A510	13	17	1.06	5.528	8.611	0.380	123
A865	14	16	1.00	1.937	1.806	0.640	124
A619	19	12	0.99	2.564	0.592	0.233	125
A522	17	13	0.57	-1.720	-1.237	0.491	126
A863	12	19	1.01	3.441	2.705	0.625	127
A728	19	11	0.86	-2.993	-2.883	0.497	128
A750	8	23	0.97	4.312	4.020	0.647	129
A765	18	12	0.91	-1.363	-6.509	0.584	130
A540	18	12	0.75	-1.258	-1.049	0.448	131
A867	14	15	1.07	0.270	2.669	0.667	132
A855	14	17	1.27	7.278	6.364	0.400	133
A843	17	13	1.24	1.805	1.277	0.494	134
A769	18	12	0.71	-3.805	-4.196	0.503	135
A624	13	18	0.58	0.710	1.238	0.587	136
A707	15	15	1.26	6.620	8.099	0.089	137
A406	16	15	0.52	2.129	1.537	0.235	138
A352	10	20	0.91	1.349	8.241	0.576	139
A570	17	14	0.69	-1.242	-3.115	0.565	140
A456	NA	NA	NA	2.593	1.548	0.541	141
A712	19	12	1.00	-3.146	1.676	0.414	142
A840	19	12	1.24	-0.178	-0.172	0.474	143
A814	13	17	1.60	2.773	2.852	0.627	144
A606	12	18	0.66	1.205	12.149	0.342	145
A821	14	16	0.80	1.816	3.084	0.442	146
A431	13	18	0.60	8.213	-1.750	0.378	147
A607	15	15	0.91	1.247	4.111	0.421	148
A446	8	22	1.08	4.987	5.122	0.530	149
A810	20	10	0.82	-4.139	-5.149	0.344	150
A815	8	22	0.84	1.737	2.952	0.625	151
A409	14	17	0.75	0.919	11.779	0.247	152
A413	14	17	0.51	1.654	2.066	0.298	153
A609	15	15	0.89	0.522	1.894	0.482	154
A713	13	18	1.15	3.582	4.669	0.429	155
A322	16	14	0.37	-4.627	-0.834	0.388	156
A883	16	14	1.18	-0.549	-1.582	0.621	157
A882	13	17	1.08	1.119	-0.040	0.676	158
A751	11	19	1.40	5.840	4.555	0.487	159
A447	11	20	0.59	1.967	2.493	0.433	160
A897	18	13	1.52	-2.877	-4.832	0.681	161
A549	8	22	1.11	3.178	3.598	0.567	162
A356	18	12	0.55	-5.689	-5.749	0.272	163

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A771	15	15	1.15	2.087	-2.456	0.550	164
A357	14	16	0.63	-5.420	-2.979	0.591	165
A868	16	14	1.32	-2.160	-2.248	0.712	166
A844	10	20	1.27	3.615	3.351	0.494	167
A839	13	18	0.79	2.736	2.453	0.308	168
A895	16	14	1.30	0.451	-1.966	0.528	169
A611	17	14	0.91	-2.020	-0.016	0.393	170
A421	12	18	0.76	-0.781	7.679	0.306	171
A857	9	22	1.54	3.271	4.571	0.501	172
A736	9	22	1.55	7.815	9.211	0.246	173
A871	13	18	1.10	1.922	1.729	0.481	174
A762	10	20	1.04	0.951	0.296	0.635	175
A807	10	20	1.26	5.506	4.792	0.343	176
A405	10	20	1.09	2.692	6.280	0.344	177
A806	13	17	0.89	2.105	2.600	0.265	178
A879	16	14	1.03	-4.895	-2.844	0.532	179
A820	14	16	1.08	1.605	1.769	0.377	180
A856	10	20	1.50	3.838	2.936	0.442	181
A508	12	18	0.72	-0.098	4.674	0.183	182
A848	5	25	2.69	2.799	3.804	0.526	183
A726	14	16	0.76	-0.170	0.800	0.269	184
A829	13	17	0.99	-1.408	-0.260	0.515	185
A320	12	18	0.87	-6.175	15.821	0.221	186
A437	10	21	1.25	2.669	5.656	0.306	187
A604	15	16	0.69	-1.921	-0.227	0.224	188
A766	13	17	1.11	-1.592	-4.499	0.587	189
A828	14	16	1.20	1.277	1.037	0.259	190
A853	14	16	1.37	-0.127	-0.433	0.410	191
A825	17	13	1.64	-4.363	-4.945	0.352	192
A854	10	21	0.99	0.373	0.637	0.439	193
A534	11	19	0.72	-5.127	-4.445	0.484	194
A898	11	20	1.53	0.650	-2.597	0.528	195
A608	12	19	0.95	-2.382	-1.017	0.431	196
A567	12	18	2.14	-3.901	-3.983	0.560	197
A746	13	18	1.53	-2.048	-0.585	0.412	198
A445	10	21	1.09	-0.760	-0.074	0.366	199
A842	12	19	1.97	-0.617	-1.314	0.453	200
A805	12	19	1.14	1.027	-0.813	0.080	201
A427	9	22	0.88	-3.188	-2.396	0.442	202
A629	9	22	1.17	-3.593	-6.473	0.553	203
A715	12	18	1.08	-4.048	-3.087	0.270	204
A401	6	24	0.99	-2.531	0.712	0.072	205

4. Conclusions

The findings of this study provide significant insights into the spatial-temporal dynamics of drought in the Brazilian Atlantic forest ecosystem. The consistent occurrence of extreme monthly precipitation values across various weather stations suggests that they are a recurring phenomenon in the Brazilian Atlantic forest. However, in spite of the regular incidence of extreme monthly precipitation, the findings from the Mann-Kendall (MK) test demonstrate a prevailing decrease in daily precipitation alongside an elevation in both maximum daily temperature and the duration of consecutive hours without precipitation throughout the Brazilian Atlantic Forest. Additionally, the vulnerability ranking synthesized from the outcomes of the meteorological indicators does not show a significant correlation with the latitudinal positions and elevation of the weather stations, which implies that geographical location and elevation do not significantly influence the trends of dryness observed at each weather station. This observed trend hints at a prospective scenario wherein the ecosystem is likely to face drier conditions, all the while maintaining a consistent range in monthly precipitation values. It aligns with the research conducted by [12], which also highlighted the vulnerabilities of the Brazilian Atlantic forest to climate change.

Author Contributions: Conceptualization, Chaves, M.B., Rivera, C. and Farias Pereira, F.; methodology, Rivera, C. and Farias Pereira, F.; formal analysis, Chaves, M.B., Cavalcante, N. and Farias Pereira, F.; investigation, Chaves, M.B., Cavalcante, N. and Farias Pereira, F.; writing—original draft preparation, Chaves, M.B. and Farias Pereira, F.; writing—review and editing, Chaves, M.B., Rivera, C. and Farias Pereira, F.; visualization, Chaves, M.B.; funding acquisition, Farias Pereira, F. All authors have read and agreed to the published version of the manuscript.

Funding: We are grateful to Fundação de Amparo à Pesquisa do Estado de Alagoas (FAPEAL) for the travel grant offered to the authors through ERC – Fapeal/Confap/CNPq 2022 Call – Research opportunities in Europe for active PhD researchers from Brazil, which could enrich the work by presenting its bottom line and discussing its outcomes with researchers and peers from all over the world in seminars at Lund University, Sweden.

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

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