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Drought-Induced Alterations in Topsoil Characteristics and Acidification Risks in a Floodplain Ecosystem: A Case Study from Tam Nong District, Vietnam

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ABSTRACT

The Tam Nong district, a flood-prone, low-lying area within Dong Thap province, Vietnam, benefits from nutrient-rich sediments deposited by the upper Mekong River. Its soils, predominantly thionic Fluvisols with smaller areas of Gleyic Acrisols and Histic Fluvisols, are vital for regional agriculture. This study investigates the impact of severe drought events, specifically in 2016 and 2024, on the physicochemical properties of topsoil (0–25 cm). A comparative analysis between drought-affected (2024) conditions and pre-drought/less severe drought (2016 reference) conditions revealed significant, statistically supported detrimental alterations. Drought conditions promoted increased soil acidification, evidenced by reduced pHKCl values across all soil types ($p < 0.05$) and elevated total sulfur (SO_4^{2-}) concentrations. Conversely, organic matter (OM) content, overall fertility, and cation exchange capacity (CEC) generally declined, indicating acid sulfate-driven degradation and diminished fertility. Fine-textured thionic Fluvisols and Epi-prothothionic Histic Fluvisols exhibited greater vulnerability to drought-induced degradation compared to medium-textured Gleyic Acrisols. Thionic Fluvisols underwent the most severe acid sulfate degradation, transitioning from

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slightly acidic to increasingly acidic states, with pHKCl values frequently dropping below 4.0. Gleyic Acrisols were less affected, maintaining moderate OM and CEC. Histic Fluvisols displayed notable acidification despite their high OM content. These findings underscore the progressive nature of drought-induced soil degradation, posing increasing threats to agricultural sustainability and farmer livelihoods in this vulnerable floodplain ecosystem, and highlight the urgent need for tailored soil management strategies.

Keywords: Soil Acidification; Drought; Fluvisol; Vietnamese Mekong Delta; Degradation

1. Introduction

River deltas are cradles of civilization and global breadbaskets, but they are also environmental hotspots facing immense pressure from climate change [1,2]. Among these, the Vietnamese Mekong Delta (VMD) stands out as a region of extraordinary agricultural productivity, supporting the livelihoods of over 20 million people and ensuring regional and global food security [3,4]. The fertility of this vast floodplain is a direct product of complex biogeochemical processes, or "pedogenesis," driven by the annual monsoon floods of the Mekong River [5]. These floods deposit nutrient-laden sediments, creating and rejuvenating the topsoil—the biologically active uppermost layer of the Earth's crust. This topsoil is the foundation for a suite of critical "ecosystem services," including food and fiber production, water filtration and regulation, and carbon sequestration, which are essential for both human well-being and ecological stability [6,7].

However, the delicate hydrological balance that sustains the VMD is under threat. Climate change is altering precipitation patterns, leading to prolonged and more intense droughts, while upstream hydropower development modifies the river's natural flow regime [8,9]. These factors converge to create extended dry periods, which act as a primary driver of severe soil degradation [10]. In deltaic environments like the VMD, which are underlain by Holocene sediments rich in sulfidic materials, drought initiates a cascade of detrimental chemical reactions. The lowering of the water table exposes pyrite (FeS_2) and other metal sulfides to atmospheric oxygen. This triggers an oxidative process that generates large quantities of sulfuric acid (H_2SO_4), a phenomenon widely recognized as the formation of acid sulfate soils [11,12]. The resulting drop in soil pH can be extreme, creating hyper-acidic conditions that are toxic to most crops [13].

The consequences of such acidification are multifaceted. Firstly, low pH (<4.0) mobilizes potentially toxic concentrations of metal ions, particularly aluminum (Al^{3+}) and iron (Fe^{2+}), which inhibit root growth and nutrient uptake [14,15]. Secondly, it drastically reduces the availability of essential nutrients like phosphorus and molybdenum [16]. Thirdly, it degrades the soil's cation exchange capacity (CEC), a key measure of fertility representing the soil's ability to retain and supply essential cations like calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) [17]. Concurrently, the combination of high temperatures and increased soil aeration during droughts can accelerate the decomposition of soil organic matter (OM), further diminishing soil structure, water retention capacity, and overall fertility [18,19]. This confluence of degradation pathways poses a significant threat to agricultural productivity and the long-term sustainability of the VMD's agroecosystems [20].

The Tam Nong district in Dong Thap province, a low-lying floodplain area, is a microcosm of this regional vulnerability. Its landscape is dominated by thionic Fluvisols, soils that are inherently rich in OM but also contain significant sulfide deposits, making them highly susceptible to drought-induced acidification [21]. While the general principles of acid sulfate soil dynamics are well-established [11,13], there remains a critical gap in localized, quantitative assessments that compare soil health before and after the recent, historically severe drought events. Furthermore, understanding the differential responses among various local soil types—such as the dominant Fluvisols versus the less prevalent but distinct Gleyic Acrisols and Histic Fluvisols—is paramount for developing targeted, effective soil management and climate adaptation strategies [22,23].

This research, therefore, aims to: (1) comprehensively investigate the changes in key physicochemical properties (pH, sulfur content, OM, CEC, nutrients) of different topsoil types in the Tam Nong district by comparing a reference period (2016, pre-drought/less severe) with a recent severe drought year (2024); and (2) evaluate the extent of topsoil degradation, with a particular focus on acidification trends and fertility decline. Based on established soil science principles, we hypothesize that prolonged drought conditions will lead to a statistically significant decrease in soil pH and a corresponding increase in total sulfur (SO_4^{2-}) concentrations, particularly in the fine-textured thionic Fluvisols, resulting in a measurable decline in soil fertility indicators such as organic matter and cation exchange capacity.

2. Materials and Methods

2.1. Study Area

The Tam Nong district is located in Dong Thap province in the southwestern region of Vietnam, covering a flat deltaic landscape of 47,394.2 hectares [21]. It is geographically positioned between 10°38’–10°49′ North latitude and 105°31’–105°42’ East longitude. The topography is characterized by minimal variation, with an average elevation of approximately 2 meters above mean sea level [24]. The region has a tropical monsoon climate, with a distinct rainy season from May to November (receiving over 90% of the annual precipitation) and a dry season from December to April [25]. The mean annual temperature is 27.1°C, and the average annual rainfall is 1138 mm. During the dry season, high evaporation rates and scarce rainfall contribute to severe drought conditions [25,26]. The study area encompasses the core and buffer zones of the Tram Chim National Park, an internationally recognized Ramsar wetland site of significant ecological importance. The distribution of soil types and sampling locations is detailed in **Figure 1**. The primary soil groups, classified according to the World Reference Base for Soil Resources (WRB-FAO) [27], are Fluvisols (thionic) (81.97%), Acrisols (11.44%), and Humic Fluvisols (6.59%) [21,28].

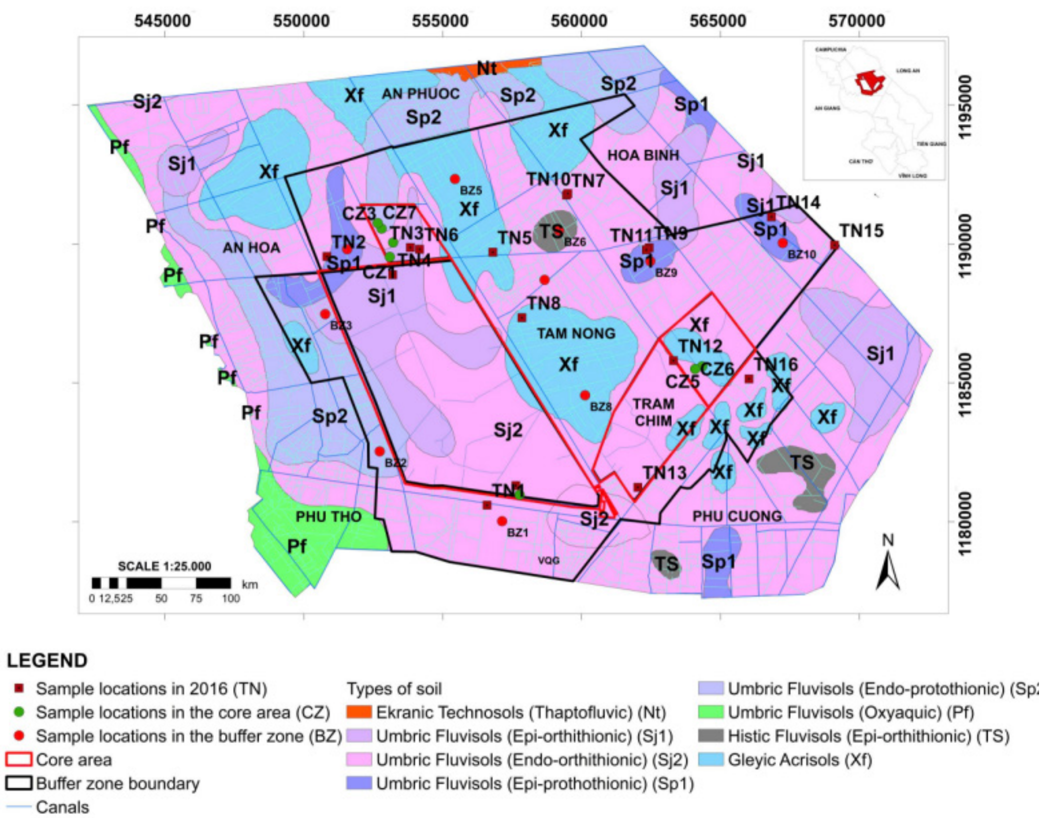

Figure 1. The map of the study area in Tam Nong District, Dong Thap Province, Vietnam. The map displays the distribution of soil types, sampling locations for 2016 (TN series) and 2024 (CZ and BZ series), and the boundaries of the Tram Chim National Park core and buffer zones. The inset map shows the location of Dong Thap Province within Vietnam.

2.2. Soil Sampling and Site Selection

This study employed a comparative temporal analysis design. Topsoil samples (0–25 cm depth) were collected during two key periods: a reference period in 2016 (representing less severe drought conditions) and a severe drought period in 2024. In 2024, a total of 17 boreholes were strategically drilled in both the core zone (CZ) and the surrounding buffer zone (BZ) of Tram Chim National Park.

These locations were selected to represent the main soil types and dominant land uses within the study area. For comparative analysis, data were utilized from 17 corresponding boreholes sampled in 2016 (designated as the TN series) within the same depth range and general locations. The geographical coordinates for both sampling campaigns are provided in **Tables 1** and **2**. Field surveys were also conducted in 2024 to document land-use changes and observe visible signs of soil degradation, such as cracking and surface salt accumulation.

Table 1. Borehole position in 2024.

Name	Soil Type	Borehole Position	
		Longitude (E)	Latitude (N)
CZ1	Umbric Fluvisols (Epi-orthithionic) (Sj$_1$)	105°29’15.00”	10°45’33.84”
CZ2	Umbric Fluvisols (Epi-orthithionic) (Sj$_1$)	105°29’18.96”	10°45’50.76”
CZ3	Umbric Fluvisols (Endo-orthithionic) (Sj$_2$)	105°29’5.28”	10°46’6.96”
CZ4	Umbric Fluvisols (Endo-protothionic) (Sp$_2$)	105°31’48.36”	10°40’54.84”
CZ5	Umbric Fluvisols (Endo-orthithionic) (Sj$_2$)	105°35’25.08”	10°43’24.96”
CZ6	Gleyic Acrisols (Xf)	105°35’16.66”	10°43’21.83”
CZ7	Gleyic Acrisols (Xf)	105°29’0.69”	10°46’13.42”
BZ1	Umbric Fluvisols (Endo-orthithionic) (Sj$_2$)	105°31’27.61”	10°40’23.91”
BZ2	Umbric Fluvisols (Endo-protothionic) (Sp$_2$)	105°29’2.73”	10°41’45.98”
BZ3	Umbric Fluvisols (Epi-orthithionic) (Sj$_1$)	105°27’58.30”	10°44’26.98”
BZ4	Umbric Fluvisols (Epi-prothothionic) (Sp$_1$)	105°28’24.41”	10°45’42.93”
BZ5	Gleyic Acrisols (Xf)	105°30’32.49”	10°47’5.00”
BZ6	Histic Fluvisols (Epi-prothothionic) (TS)	105°32’35.74”	10°46’4.50”
BZ7	Umbric Fluvisols (Endo-orthithionic) (Sj$_2$)	105°32’18.46”	10°45’6.68”
BZ8	Gleyic Acrisols (Xf)	105°33’6.24”	10°42’51.32”
BZ9	Umbric Fluvisols (Epi-prothothionic) (Sp$_1$)	105°34’23.88”	10°45’28.21”
BZ10	Umbric Fluvisols (Epi-prothothionic) (Sp$_1$)	105°37’0.89”	10°45’49.33”

Table 2. Borehole position in 2016.

Name	Soil Type	Borehole Position	
		Longitude (E)	Latitude (N)
TN1	Umbric Fluvisols (Endo-orthithionic) (Sj$_2$)	105°31’9.66”	10°40’42.73”
TN2	Umbric Fluvisols (Epi-prothothionic) (Sp$_1$)	105^0 28’0.20”	10^0 45’34.42”
TN3	Umbric Fluvisols (Epi-orthithionic) (Sj$_1$)	105°29’39.20”	10^0 45’44.78”
TN4	Umbric Fluvisols (Epi-orthithionic) (Sj$_1$)	105°29’18.20”	10°45’12.91”
TN5	Gleyic Acrisols (Xf)	105°31’17.01”	10°45’39.12”
TN6	Gleyic Acrisols (Xf)	105°29’50.09”	10°45’42.78”
TN7	Histic Fluvisols (Epi-prothothionic) (TS)	105°32’44.42”	10°46’45.78”
TN8	Gleyic Acrisols (Xf)	105°31’51.32”	10°44’22.36”
TN9	Umbric Fluvisols (Epi-prothothionic) (Sp$_1$)	105°34’22.33”	10°45’43.97”
TN10	Histic Fluvisols (Epi-prothothionic) (TS)	105°32’45.97”	10°46’47.76”
TN11	Umbric Fluvisols (Epi-prothothionic) (Sp$_1$)	105°34’19.03”	10°45’41.53”
TN12	Umbric Fluvisols (Endo-prototthionic) (Sp$_2$)	105°34’50.82”	10°43’31.73”
TN13	Umbric Fluvisols (Endo-protothionic) (Sp$_2$)	105°34’8.44”	10°41’3.32”
TN14	Umbric Fluvisols (Epi-prothothionic) (Sp$_1$)	105°36’47.37”	10°46’19.90”
TN15	Umbric Fluvisols (Endo-orthithionic) (Sj$_2$)	105°38’2.15”	10°45’46.67”
TN16	Umbric Fluvisols (Endo-orthithionic) (Sj$_2$)	105°36’20.39”	10°43’10.14”
TN17	Umbric Fluvisols (Endo-orthithionic) (Sj$_2$)	105°31’43.73”	10°41’5.59”

2.3. Laboratory Analysis

Collected soil samples from 2024 were analyzed for various physicochemical properties.

Soil Texture and Bulk Density: Determined using the hydrometer method and the core method, respectively [17,18].

Soil pH: Measured in a 1:5 soil-to-solution ratio using distilled water (pHH$_2$O) and 1M potassium chloride (pHKCl) [4].

Organic Matter (OM): Determined by the Walkley-Black wet oxidation method [19].

Total Sulfur (SO_4^{2-} as an indicator): Measured using Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) after appropriate extraction [20].

Cation Exchange Capacity (CEC) and Exchangeable Cations (Ca^{2+}, Mg^{2+}, K^+): Determined by the ammonium acetate (NH_4OAc) method at pH 7, with cations measured by ICP-OES [21].

Total Nitrogen (N): Determined by the Kjeldahl method [22].

Total Phosphorus (P_2O_5): Determined colorimetrically after acid digestion [23].

Total Potassium (K_2O): Determined by flame photometry after acid digestion [21].

Total Soluble Salts (TSS): Measured from the electrical conductivity of the soil solution.

All laboratory analyses followed standardized methods and were compared against standards specified by the Ministry of Natural Resources and Environment (MNRE), Vietnam [1,3].

2.4. Statistical Analysis

The physicochemical data from 2016 and 2024 were statistically compared to assess changes in topsoil properties. Descriptive statistics (mean, standard deviation) were calculated for all parameters. To determine the significance of observed changes between the two years, independent samples t-tests were performed for each soil type and parameter using SPSS software (Version 26.0). A p-value of less than 0.05 was considered statistically significant. The primary focus was to identify significant trends in soil acidification (pH, SO_4^{2-}), organic matter content, and overall fertility indicators under drought stress.

3. Results

3.1. General Soil Characteristics and Texture

The Tam Nong district is pedologically dominated by Fluvisols (thionic), which cover 81.97% of the area, followed by Acrisols (11.44%) and Humic Fluvisols (6.59%). The land area distribution of these soil types within the study zones is presented in **Table 3**. Analysis of grain size proportions from 2024 samples (**Table 4**) revealed distinct textural differences. The Fluvisols (thionic) generally exhibited a fine texture (clay loam to clay), with mean clay content ranging from 37.13% to 45.78%. In contrast, the Acrisols (represented by Gleyic Acrisols, Xf) had a coarser texture (sandy loam to sandy clay loam), with mean sand content from 35.04% to 40.99%. The Humic Fluvisols (represented by Histic Fluvisols, TS) were characterized by high clay content (42.22%) and a notably low bulk density (0.71 g/cm^3), indicative of their high organic matter content.

Table 3. Land area of soil types.

Soil Group	Soil Type	Core Zone (Ha)	Buffer Zone (Ha)
Fluvisols (thionic)	Umbric Fluvisols (Epi-orthithionic) (Sj1)	1837.3	403.1
	Umbric Fluvisols (Endo-orthithionic) (Sj2)	4484.8	8522.2
	Umbric Fluvisols (Epi-prothothionic) (Sp1)	71.2	902.8
	Umbric Fluvisols (Endo-protothionic) (Sp2)	340.4	953.2
	Total	**6733.7**	**10781.3**
Acrisols	Gleyic Acrisols (Xf)	569.7	3982.3
Humic Fluvisols	Histic Fluvisols (Epi-prothothionic) (TS)	-	180.1

Table 4. The grain size proportion of soil types. Values for Sand, Silt, and Clay are means from samples collected in 2024. Mean bulk density values are also from 2024 samples.

Soil Group	Sample Name	Soil Type	Soil Texture (%)			Mean Bulk Density (g/cm^3)
			Sand	Silt	Clay	
Fluvisols (thionic)	CZR1	Sj1	24.89	31.19	43.92	0.94
	CZR2	Sj1	22.96	34.06	42.98	1.00
	BZR3	Sj1	24.15	30.07	45.78	1.10
	CZR3	Sj2	25.72	34.70	39.58	1.09
	CZR5	Sj2	24.17	32.12	43.71	1.08
	BZR1	Sj2	25.52	33.80	40.68	1.07
	BZR7	Sj2	26.45	33.02	40.53	1.03
	BZR4	Sp1	27.73	33.64	38.64	1.15
	BZR9	Sp1	26.31	33.61	40.08	1.06
	BZR10	Sp1	28.34	34.07	37.59	1.08
	CZR4	Sp2	31.19	30.85	37.96	1.18
	BZR2	Sp2	31.05	31.83	37.13	1.09
Acrisols	CZR6	Xf	39.42	30.83	29.75	1.18
	CZR7	Xf	40.99	31.66	27.35	1.18
	BZR5	Xf	35.04	32.14	32.83	1.09
	BZR8	Xf	36.63	30.50	32.87	1.05
Humic Fluvisols	BZR6	TS	28.27	29.52	42.22	0.71

3.2. Impact of Drought on Soil Physicochemical Properties

The comparative analysis of soil chemical properties between the 2016 reference period and the 2024 severe drought period revealed significant, detrimental alterations across most soil types. Detailed results for dry and rainy seasons in 2024 are provided in **Tables 5** and **6**, respectively, while the critical comparison between 2016 and 2024 is summarized in **Table 7**.

Table 5. Results of the physical and chemical analyzed topsoil samples in dry season, 2024.

Soil Group	Sample Name	Soil Type	pH_{KCl}	OM (%)	SO_4^{2-} (%)	CEC (meq/100g)	N (%)	P_2O_5 (%)	K_2O (%)	TSS (%)
Fluvisols (thionic)	CZR1	Sj1	3.32	4.38	0.213	20.831	0.227	0.035	1.150	0.183
	CZR2	Sj1	3.26	4.79	0.203	20.896	0.245	0.044	1.250	0.135
	BZR3	Sj1	2.19	4.26	0.210	20.980	0.250	0.044	1.360	0.132
	CZR3	Sj2	3.31	6.50	0.212	17.850	0.175	0.051	1.410	0.160
	CZR5	Sj2	3.12	6.12	0.220	16.630	0.070	0.016	1.330	0.152
	BZR1	Sj2	2.86	3.97	0.093	15.880	0.206	0.021	1.190	0.086
	BZR7	Sj2	4.19	3.59	0.078	17.230	0.198	0.062	1.300	0.132
	BZR4	Sp1	3.03	4.41	0.084	19.850	0.201	0.041	1.000	0.123
	BZR9	Sp1	3.57	4.04	0.092	19.520	0.210	0.042	0.950	0.139
	BZR10	Sp1	3.25	5.36	0.120	18.350	0.350	0.038	1.190	0.126
	CZR4	Sp2	3.07	6.59	0.067	19.280	0.192	0.045	1.030	0.134
	BZR2	Sp2	2.68	3.19	0.074	18.840	0.232	0.048	1.100	0.156
Acrisols	CZR6	Xf	4.08	2.48	0.038	12.360	0.105	0.014	0.210	0.083
	CZR7	Xf	4.05	2.60	0.042	13.080	0.052	0.012	0.120	0.040
	BZR5	Xf	4.06	1.50	0.056	9.300	0.128	0.039	0.330	0.073
	BZR8	Xf	4.08	2.29	0.021	10.040	0.170	0.045	0.350	0.087
Humic Fluvisols	BZR6	TS	2.59	15.26	0.056	20.831	0.300	0.063	0.980	0.098

Table 6. Results of the physical and chemical analysed topsoil samples in rainy season, 2024.

Soil Group	Sample Name	Soil Type	pH_{KCl}	OM (%)	SO_4^{2-} (%)	CEC (meq/100g)	N (%)	P_2O_5 (%)	K_2O (%)	TSS (%)
Fluvisols (thionic)	CZR1	Sj1	4.23	6.4	0.062	23.150	0.31	0.045	1.230	0.153
	CZR2	Sj1	4.08	6.23	0.068	22.860	0.302	0.057	1.420	0.125
	BZR3	Sj1	3.95	6.15	0.070	22.150	0.29	0.056	1.450	0.125
	CZR3	Sj2	3.42	8.21	0.203	19.250	0.288	0.06	1.530	0.152
	CZR5	Sj2	3.39	8.01	0.210	18.790	0.156	0.032	1.410	0.115
	BZR1	Sj2	4.78	4.24	0.049	17.880	0.21	0.040	1.210	0.068
	BZR7	Sj2	4.36	4.45	0.065	19.250	0.24	0.080	1.380	0.115
	BZR4	Sp1	4.20	4.50	0.076	21.250	0.26	0.050	1.090	0.103
	BZR9	Sp1	4.09	4.28	0.065	20.130	0.242	0.052	1.009	0.128
	BZR10	Sp1	4.12	7.40	0.080	19.850	0.37	0.040	1.200	0.119
	CZR4	Sp2	3.38	7.42	0.060	22.550	0.279	0.059	1.040	0.124
	BZR2	Sp2	4.42	4.83	0.064	21.080	0.28	0.058	1.120	0.151
Acrisols	CZR6	Xf	4.5	2.89	0.019	14.570	0.198	0.045	0.470	0.062
	CZR7	Xf	4.25	2.97	0.020	15.280	0.179	0.052	0.390	0.037
	BZR5	Xf	4.40	1.55	0.012	9.750	0.15	0.047	0.352	0.067
	BZR8	Xf	4.60	2.35	0.019	10.560	0.19	0.053	0.370	0.084
Humic Fluvisols	BZR6	TS	3.81	19.05	0.042	27.830	0.34	0.078	1.018	0.070

Table 7. Variation in pHKCl, organic matter (OM), total sulfur content (SO42−); and cation exchange capacity of the topsoil between 2016 and 2024.

Soil Group	Soil Type	pH_{KCl}		OM (%)		SO_4^{2-} (%)		CEC (meq/100g)	
		2016 (Min-Max)	2024 (Min-Max)	2016 (Min-Max)	2024 (Min-Max)	2016 (Min-Max)	2024 (Min-Max)	2016 (Min-Max)	2024 (Min-Max)
Fluvisols (thionic)	Sj1	3.41–3.57	2.92–4.08	5.24–6.74	4.48–6.26	0.07–0.18	0.06–0.20	24.71–28.45	20.90–22.72
	Sj2	4.00–4.77	3.37–3.98	2.37–10.38	5.04–6.22	0.04–0.06	0.13–0.15	17.48–25.41	16.90–18.79
	Sp1	3.79–4.64	3.28–4.14	3.48–7.57	4.60–5.39	0.05–0.07	0.07–0.09	20.13–21.68	19.24–20.41
	Sp2)	4.08–4.65	2.86–3.90	2.09–7.29	4.89–6.12	0.05–0.06	0.06–0.07	16.05–21.05	19.06–21.82
Acrisols	Xf	4.54–4.82	4.07–4.44	1.16–2.96	2.17–2.44	0.01–0.02	0.01–0.03	9.65–15.58	11.19–12.54
Humic Fluvisols	TS	3.08–3.90	2.59–3.81	16.21–18.34	15.2–19.05	0.04–0.05	0.04–0.05	25.42–28.02	20.81–27.83

Soil Acidification (pHKCl and SO_4^{2-}):

A consistent and statistically significant ($p < 0.05$) decrease in pHKCl was observed across all Fluvisol and Histic Fluvisol sub-types. For thionic Fluvisols, pHKCl ranges shifted downwards dramatically. For instance, in Sj1 soils, the range dropped from 3.41–3.57 in 2016 to 2.92–4.08 in 2024. Many Fluvisol samples in 2024 exhibited pHKCl values well below 4.0, signifying the development of active acid sulfate conditions. Acrisols showed a slight but non-significant decrease in pHKCl. Histic Fluvisols, despite their high OM, also experienced a significant drop in pH.

Congruent with the decrease in pH, the total sulfur content (SO_4^{2-}) increased markedly in the thionic Fluvisols. For Sj2 soils, the SO_4^{2-} range increased from 0.04%–0.06% in 2016 to 0.13%–0.15% in 2024. Some dry season samples in 2024 exceeded 0.20% SO_4^{2-} (**Table 5**), confirming severe sulfate accumulation. Acrisols and Histic Fluvisols showed minimal change in SO_4^{2-} content.

Organic Matter (OM) and Cation Exchange Capacity (CEC):

Organic matter content displayed a general tendency to decrease in the thionic Fluvisols and Histic Fluvisols between 2016 and 2024 (**Table 7**). For example, Sj2 soils, which had a wide OM range of 2.37%–10.38% in 2016, narrowed to 5.04%–6.22% in 2024. Acrisols, however, showed a slight increase in OM content. Reflecting both the OM loss and increased acidification, CEC values generally decreased in the thionic Fluvisols and Histic Fluvisols. The CEC for Sj1 soils decreased from a range of 24.71–28.45 meq/100g in 2016 to 20.90–22.72 meq/100g in 2024. This trend indicates a significant decline in the soil's nutrient retention capacity. Counterintuitively, Acrisols and the Sp2 sub-type of Fluvisols showed a slight increase in CEC.

3.3. Seasonal Variations in 2024

A comparison between the dry season (**Table 5**) and rainy season (**Table 6**) data for 2024 highlights the dynamic nature of the soil properties. During the rainy season, pHKCl values were generally higher (less acidic), and SO_4^{2-} concentrations were lower, likely due to the leaching of soluble acids and sulfates by rainwater. Conversely, OM, CEC, and nutrient concentrations were often observed to be higher or more stable during the rainy season, reflecting partial recovery and reduced chemical stress.

3.4. Overall Soil Degradation Trends

The comprehensive data clearly indicates that severe drought is a potent driver of topsoil degradation in Tam Nong. The thionic Fluvisols were unequivocally the most severely affected, experiencing intense acidification and a significant decline in fertility indicators (OM, CEC). Histic Fluvisols, despite their high buffering capacity from OM, were also substantially acidified. In contrast, Gleyic Acrisols demonstrated greater resilience to these specific drought-induced chemical changes, showing only minor alterations (**Table 7**).

4. Discussion

The findings of this study reveal significant and concerning alterations in the physicochemical properties of topsoils in the Tam Nong district, directly attributable to severe drought conditions. These changes underscore the acute vulnerability of this floodplain agroecosystem, with distinct responses observed among the dominant soil types.

4.1. Drought-Induced Acidification: A Vicious Cycle

The widespread and statistically significant decrease in soil pHKCl is the most critical finding, confirming the intensification of acid sulfate soil conditions. This process aligns with studies from other sulfidic deltaic regions globally, where drainage and drought are known to trigger rapid acidification [11,13,29]. The high SO_4^{2-} concentrations observed in 2024, a direct product of pyrite oxidation, serve as chemical evidence of this process [12]. The pH values below 4.0 recorded in many Fluvisol samples are particularly alarming, as this is a critical threshold where aluminum toxicity becomes a major limiting factor for most crops, especially rice [14]. The fact that even the highly organic Histic Fluvisols experienced significant acidification demonstrates that high OM content alone cannot prevent severe degradation under prolonged drought stress, although it may buffer the pH decline to some extent. The relative stability of Acrisols is likely due to a lower initial sulfide content in their parent material and a coarser texture that may prevent the prolonged waterlogged, anoxic conditions necessary for extensive pyrite formation [22].

4.2. Organic Matter Depletion and Fertility Decline

The general decrease in OM and CEC in the most vulnerable soils (Fluvisols and Histic Fluvisols) represents a substantial loss of soil capital. The decline in OM can be attributed to a dual effect of drought: reduced biomass input from stressed or failed vegetation, and accelerated decomposition of existing OM due to higher soil temperatures and increased aeration from deep soil cracking [18,19]. The loss of OM has cascading negative effects, reducing water retention, degrading soil structure, and diminishing the soil's natural buffering capacity against acidification [10]. The observed decrease in CEC is a direct and predictable consequence of both OM loss and increased soil acidity. As H^+ and Al^{3+} ions flood the soil solution, they displace essential base cations (Ca^{2+}, Mg^{2+}, K^+) from the exchange sites, making them prone to leaching and depleting the soil's nutrient reservoir [17]. This combined degradation of OM and CEC signifies a fundamental decline in soil health and fertility, which will inevitably lead to lower crop yields and increased reliance on costly chemical fertilizers. The slight increase in CEC in Acrisols could be an artifact of sample variability or related to the weathering of primary minerals under changing pH, exposing new exchange sites, but this trend is an exception to the overall degradation pattern.

4.3. Differential Vulnerability and Tailored Management Implications

This study clearly demonstrates that not all soils are equally vulnerable. The fine-textured thionic Fluvisols are the most susceptible due to the "perfect storm" of their inherent properties: high sulfide content and a fine texture that promotes deep cracking upon drying, maximizing oxygen exposure. Histic Fluvisols are also highly vulnerable to acidification. The coarser Gleyic Acrisols are more resilient. This differential vulnerability is a crucial insight for land use planning and management. A "one-size-fits-all" approach is destined to fail. Management strategies must be tailored to specific soil types and their vulnerabilities [23]:

For highly vulnerable Fluvisols: The highest priority is water management. Maintaining a high water table through controlled irrigation, dikes, or weirs during the dry season is the most effective way to prevent pyrite oxidation [11]. Where acidification has already occurred, strategic liming based on soil testing is essential to neutralize acidity. However, this is a costly and temporary solution. Organic matter enhancement through the incorporation of rice straw, compost, or cover crops can improve buffering capacity and soil structure, but it cannot stop pyrite oxidation itself.

For resilient Acrisols: Management should focus on maintaining and building soil organic matter and preventing physical degradation. These soils may represent opportunities for crop diversification.

General Strategies: Across all soil types, adopting tolerant crop varieties (e.g., rice cultivars with higher aluminum tolerance) is a key adaptation strategy for farmers.

4.4. Socio-Economic and Policy Implications

The observed soil degradation has direct and severe socio-economic consequences. Declining soil fertility translates to lower crop yields, reduced farm income, and increased household expenditure on fertilizers and soil amendments [4]. This can trap farming communities in a cycle of poverty and food insecurity, potentially leading to land abandonment and rural-urban migration. The degradation of the Tram Chim National Park's buffer zone also threatens the integrity of this vital wetland ecosystem. Therefore, these findings carry important policy implications. Regional and national governments must move beyond reactive crisis management. Proactive policies are needed, including: (1) investing in smart irrigation and water management infrastructure; (2) providing financial support or subsidies for farmers to purchase lime and organic amendments; (3) strengthening agricultural extension services to disseminate knowledge on soil-specific management practices; and (4) integrating soil vulnerability maps into land-use planning to guide sustainable development.

4.5. Limitations of the Study and Future Research Directions

It is important to acknowledge the limitations of this study. The comparison relies on two discrete points, which provides a valuable "snapshot" but does not capture the continuous dynamics of degradation. Furthermore, inherent spatial variability in soil properties and unmonitored changes in land management practices (e.g., fertilizer use) between 2016 and 2024 could be confounding factors. Despite these limitations, the consistent, widespread, and statistically significant nature of the observed changes across multiple soil types provides robust evidence for the overriding impact of severe drought.

Future research should focus on establishing long-term monitoring sites to track the rate of soil degradation over time. Studies employing advanced techniques, such as microbial community analysis (to understand the impact on soil biology) and stable isotope analysis (to trace sulfur and carbon cycling), would provide deeper mechanistic insights. Crucially, participatory field trials are needed to co-develop and evaluate the efficacy and cost-effectiveness of various soil amelioration strategies in close collaboration with local farmers.

5. Conclusions

This study provides compelling and statistically robust evidence that severe drought acts as a critical driver of accelerated topsoil degradation in the floodplain ecosystem of Tam Nong district, Vietnam. By comparing a pre-drought reference year (2016) with a severe drought year (2024), we quantified a significant and detrimental shift towards more pronounced acid sulfate conditions. This was primarily characterized by a widespread reduction in soil pH and a corresponding increase in total sulfur concentrations, particularly within the dominant thionic Fluvisol group. This rampant acidification, coupled with a general decrease in organic matter content and cation exchange capacity in the most susceptible soils, signifies a rapid decline in overall topsoil quality and fertility.

Our results confirm the initial hypothesis and reveal a clear differential vulnerability among soil types, with fine-textured thionic Fluvisols and organic-rich Histic Fluvisols being the most severely impacted. The observed trends collectively point towards a progressive deterioration of soil health that threatens agricultural productivity, farmer livelihoods, and the ecological integrity of this vital region. If drought events persist or intensify as projected under future climate scenarios, these adverse impacts will undoubtedly be exacerbated. Therefore, the urgent development and implementation of adaptive, soil-specific land management strategies, robust soil conservation measures, and supportive governmental policies are imperative to mitigate these risks and safeguard the long-term sustainability of agriculture in the Vietnamese Mekong Delta and similar vulnerable deltaic regions worldwide.

Author Contributions

Data process and analysis, L.K.P., N.T.T.N., D.N.T., and N.V.T.; results interpretation and discussion, L.K.P., N.T.T.N., N.T.M.H.; manuscript design, L.K.P., N.T.T.N., D.N.T., and N.V.T.; manuscript revision, L.K.P., N.T.T.N., N.T.M.H. and D.T.A.; submission steps, D.T.A. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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