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Agropedoclimatic Characteristics and Suitability of Soils for Cocoa Cultivation in the Forest-Savanna Transition Zone of Séguéla, North-Western Côte d'Ivoire

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Abstract

The Séguéla region is a forest-savanna transition zone of north-western Côte d'Ivoire. This zone has traditionally been considered marginal for cocoa cultivation. Cashew, cotton and food crops are the main culture in this region. But more and more farmers diversified into cocoa in this area and report a satisfactory development of this culture. This reality raises the question of whether local soils and climate can truly sustain this crop. In this way, the present study characterised the morphological, physical and chemical properties of soils considering the main topographic position (summit, midslope, footslope) and the agroclimatic conditions of Séguéla region. The study also assessed the suitability for cocoa cultivation using established land-evaluation criteria. The results show that the soils are developed on metagabbro and greenstone. According to the World Reference Bases of soils, these soils are clay-dominated Cambisols with abundant coarse fragments. They are well drained at the summit but poorly drained to the downslope. Concerning Soil pH (5.6 - 6.5) and cation exchange capacity (26.5 - 41.2 cmol(+) kg^{-1}), they are highly favourable for cocoa. The topsoil organic matter is likewise adequate, but available phosphorus and exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}) are markedly deficient. The whole-profile C/N ratio is slightly elevated. On Climatic level, the mean of annual rainfall (1182.8 mm) is slightly below the recommended value. Yet the four-month humid season (June - October, ≈783 mm) meets cocoa's seasonal water

requirement despite an eight-month deficit period. The combination between soil and climate parameters indicates that all the three toposequence positions reach an overall suitability class of S2 (moderately suitable), each limited by different constraints. This study concludes that the soils and climate of the Séguéla area are moderately, though unevenly, suitable for cocoa cultivation, supporting the hypothesis that a cautious extension of cocoa production into this forest-savanna transition zone is agronomically plausible, but, it would be better to improve the levels of available phosphorus, exchangeable-base and think about supplying water during the dry season.

Keywords

Cocoa Cultivation, Land Suitability, Cambisols, Forest-Savanna Transition Zone, Séguéla, Côte d'Ivoire

1. Introduction

The cultivation of the cacao tree (*Theobroma cacao* L.), since its introduction to Ivory Coast in the 1890s [1], quickly spread in the humid forest zone of the southern half of the country, favoured by extensive forest reserves (about 16 million ha in 1960), rainfall above 1200 mm·year^{-1}, and generally suitable soils [2]. These natural potential lead Côte d'Ivoire to the first position of cocoa producer in the world since 1978 [3], with above of 40% of global supply; the crop supports more than one million farming households and around 40% of the country's export earnings [4]. Cocoa expansion has historically followed a pioneer-front, extensive and itinerant cropping pattern that progressively shifted the main production areas from east to west as forest reserves were depleted [5], raising concerns over the long-term sustainability of the sector [6] in the face of ageing orchards, declining soil fertility and climatic disturbance. But this dynamic is far from disappearing with the possible rise in global demand to satisfy the consumption needs of emerging countries like India [7] and especially with the rush of farmers towards high-income export crops like cocoa. This is the case in certain areas of Côte d'Ivoire, even those supposedly marginal to cocoa farming.

The Seguela region, located in the forest-savanna transition zone in northwestern Côte d'Ivoire [8], has traditionally been dominated by cashew, cotton, and food crop production, as its warmer, drier climate and even its soils were considered unsuitable for cocoa cultivation. However, some farmers who have diversified their crops [9] occasionally grow cocoa in this transition zone and report sometimes satisfactory tree development and productivity. It is therefore relevant, from both an agronomic and strategic perspective, to assess whether the soils and climate of this area allow for sustainable cocoa cultivation. Indeed, this could contribute to environmental protection in a context where rural populations in this region, seeking higher incomes, do not hesitate to engage in gold panning.

This study addresses this question for the Séguéla region through two comple-

mentary objectives: 1) to characterize the morphological, physical and chemical properties of soils along a representative toposequence and 2) to characterize the agroclimatic parameters of the area.

2. Materials and Methods

2.1. Study Area

The Séguéla department lies in north-western Côte d'Ivoire (roughly 7˚45'W-6˚44'W, 7˚73'N-8˚66'N; mean elevation 350 m), 270 km from Yamoussoukro and 502 km from Abidjan, respectively the administrative and political capital of the country (Figure 1).

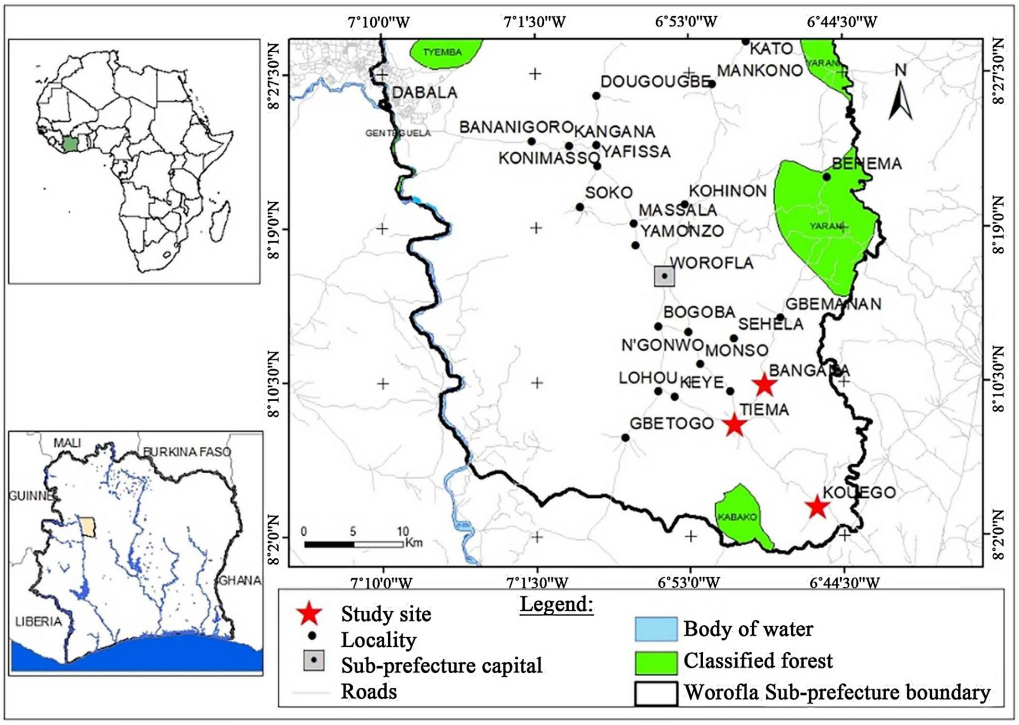


Figure 1. Location of the study area in Côte-d'Ivoire.

The area has a savanna climate with a dry winter (Sudanian-type), with a markedly wetter season from July to October and a dry season from November to June; mean annual rainfall is about 1182.8 mm and mean annual temperature about 26 ˚C [8]. The area lies in the forest-savanna transition zone, with vegetation grading from gallery forest and forest islands to increasingly open savanna. The relief consists mainly of plateaus and granitic hills (mean elevation 260 m) [10], drained by the Sassandra and Yani rivers and their tributaries. The geology is of Middle to Lower Proterozoic age, comprising Eburnean granitic complexes and Birimian volcano-sedimentary (greenstone) formations [10]. Gold mining and artisanal mining are the dominant activities in this area. This is proving restrictive for agriculture, particularly cocoa cultivation, which is increasingly expanding onto marginal lands.

2.2. Soil Characterisation

Three soil pits (100 × 80 × 120 cm) were opened along a toposequence (N235˚ orientation), starting to summit to footslope, under existing cocoa plots. The existing cacao plantations were between 8 and 10 years old, with a ground cover rate of approximately 80% thanks to associated crops such as the cashew tree.

Soil profile P1 was established at the summit, on a flat area with a slope of approximately 1%; P2 at the midslope, 230 m from P1, with an average gradient of approximately 3% and P3 at the footslope, 210 m from P2, with an average gradient of approximately 2%. This toposequence was representative of the geomorphology and soils of the study area. The soil profileswere described in the field horizon by horizon based on colour (with a Munsell code), texture, structure, coarse-fragment content, porosity, drainage class and rooting. In each profile, soil samples were collected at 20 cm intervals, resulting in five composite soil samples per profile (0 - 20, 20 - 40, 40 - 60, 60 - 80, and 80 - 100 cm). Thus, the study was conducted on a total of 15 soil samples, collected for laboratory analysis of pHwater and pHKCl, organic carbon, total nitrogen (from which the C/N ratio and organic matter content were derived), cation exchange capacity (CEC), exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) and available phosphorus. For these analyses, the samples were air-dried in the shade within the laboratory. Then, they were passed through a 2 cm mesh sieve. The material retained on the sieve was weighed to determine the coarse-fragment content, and the analyses were performed on the fine soil fragment obtained from the sieving process.

The soil pH measurements were carried out by the electrometric method, in a sol/water ratio of 1:2.5 [11]. Total organic carbon was determined according to the Walkley-Black method [12]. The total nitrogen content was obtained by the Kjeldahl method [13]. The exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}) were determined by extraction with ammonium acetate buffered to pH 7, followed by saturation with NaCl for the determination of the cation exchange capacity (CEC). For the determination of assimilable phosphorus, the Olsen method, as modified by Dabin [14], was used.

Soils were classified according to the World Reference Base (WRB) system.

2.3. Agroclimatic Characterisation

The climate data were derived from observations made by the Regional Directorate of Agriculture in Séguéla, with missing values supplemented by CHIRPS data (rainfall data) and AgERA5 (temperature data) for the same area over a 30-year period (1990 to 2020).

Mean monthly rainfall and temperature for the study area were compiled to construct a Gaussen ombrothermal diagram. Monthly potential evapotranspiration (PET) was estimated using the Thornthwaite method from mean monthly temperature and a latitude correction factor.

Cocoa water requirements were derived from PET using a crop coefficient (Kc = 1.05). The monthly water balance (deficit or surplus) was obtained by compar-

ing rainfall to crop water requirements, allowing identification of dry, pre-humid, humid and post-humid periods over the year.

2.3.1. Potential Evapotranspiration

It was calculated using the Thornthwaite method, according to the formula (1)

$$PET_m = 16\left(\frac{10T_m}{I}\right)^{\alpha} F(m,\varphi) \quad (1)$$

where,

PET_m : monthly potential evapotranspiration for month m (m = 1 to 12), in mm;

T_m : mean monthly temperature (˚C);

I : monthly thermal index $I = \sum_{m=1}^{12}(T_m/5)$ 1.514;

α = 0.000000675 * I3 − 0.0000771 * I2 + 0.0179 * I + 0.49;

$F(m,\varphi)$: Thornthwaite's latitude-dependent correction factor, which latitude is 8.05˚ in the Séguéla area.

2.3.2. Water Requirement of the Cocoa Tree

The cocoa water requirement (ETc) was equated with the potential evapotranspiration (PETm) and the cocoa tree's crop coefficient (Kc), which is 1.05 according to N'Douba (2016), through the formula (2):

$$(ET_c) = Kc \times ETP \quad (2)$$

Combining rainfall with cocoa water requirements identifies climatic periods over the year.

2.4. Land Suitability Classification for Cocoa

Land suitability for cocoa was assessed using a parametric matching procedure adapted from the FAO Framework for Land Evaluation, in which each measured soil or climatic parameter is compared against a reference threshold or optimal range reported in the cocoa agronomy literature, and rated on a simplified four-class ordinal scale: S1 (highly suitable, parameter within or above the optimal range), S2 (moderately suitable, parameter departing moderately from the optimum), S3 (marginally suitable, parameter markedly below or above the recommended range, but not prohibitive), and N (not suitable, unless the limitation is specifically corrected) (Table 1).

Twelve parameters were rated on this scale, covering both the edaphic dimension

Table 1. Suitability class scale used in the parametric matching procedure.

Class	Designation	Meaning
S1	Highly suitable	Parameter within the optimal range, or above it
S2	Moderately suitable	Moderate departure from the optimum
S3	Marginally suitable	Marked departure from the optimum, but not prohibitive
N	Not suitable	Prohibitive limitation, unless specifically corrected

(eight parameters, from the soil characterisation) and the climatic dimension (four parameters, from the agroclimatic characterisation of the study area) (Table 2).

Table 2. Edaphicand climaic parameters used for the suitability assessment.

Parameter	Reference threshold for cocoa	Source
Soil pHwater	5.0 - 7.0 (optimal range)	[15]
Topsoil organic matter (0 - 20 cm)	>30 g·kg^{-1} (3%)	[16] [17]
Total nitrogen	>9 g·kg^{-1} (0.9%)	[17]
C/N ratio	9 - 12	[15]
Coarse-fragment content	Low stoniness preferred	[2]
Drainage class	Well-drained preferred	[2]
Available phosphorus	10 mg/kg (critical level) to 100 mg/kg (optimum level) Olsen-Dabin method	[17] [18]
Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+})	Ca: ≥11 cmol(+) kg^{-1}; Mg: ≥0.8 cmol(+) kg^{-1}; K: ≥0.03 cmol(+) kg^{-1}	[17] [19]
Cation exchange capacity (CEC)	≥21 cmol(+) kg^{-1}	[19]
Mean annual rainfall	≥1200 - 1250 mm	[20] [21]
Humid-season rainfall (Jun - Sep)	≥700 mm	[21]
Continuous dry season length	Shorter dry seasons preferred	[21]
Water deficit period	Minimal deficit preferred	[21]

2.5. Statistical Analysis

Differences in soil physical and chemical parameters, and in chemical element ratios, between the three topographic positions were tested by analysis of variance (ANOVA), through XLSAT Software, followed by mean-comparison procedures, with significance assessed at the 5% threshold (Pr > F); means sharing a letter within a parameter are not significantly different.

3. Results

3.1. Geological Setting and Soil Morphology

The study area is dominated by metamorphic formations: the summit soil (P1) has developed on metagabbro, while the midslope (P2) and footslope (P3) soils have developed on greenstone (schiste vert). Along the toposequence, soils are clay-dominated (50% - 60% clay on average), carry a high load of coarse fragments (about 80% on average, mainly earthy concretions and nodules rather than quartz), are abundantly rooted, and are dark brown in colour throughout, consistent with a brunification process superimposed on profile reworking (remaniement). Drainage is good at the summit (drainage index 1.7 - 1.9) but poor to very poor at the midslope and footslope (drainage index 3 - 5), reflecting in-

creasing hydromorphy downslope. Based on these morphological criteria, the summit soil is classified as a Haplic Clayic Cambisol, the midslope soil as an Amphistagnic Clayic Pisoplinthic Cambisol (Manganiferric), and the footslope soil as an Endogleyic Plinthic Cambisol (Figure 2).

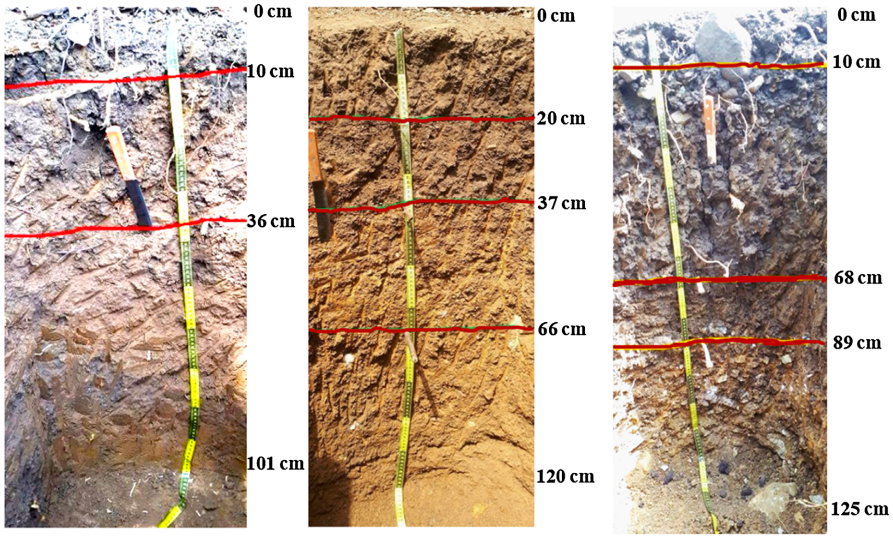


Figure 2. Different soils in the study area.

3.2. Chemical Soil Properties

3.2.1. Acidity and Organic Matter of Soil

Table 3 presents the acidity and organic status of soil measured by horizon for the three profiles. Across all three profiles, the topsoil layer (0 - 20 cm) is slightly more acidic than the underlying layers, and the difference between pHwater and pHKCl exceeds 1 pH unit in nearly all horizons (except the 40 - 60 cm layer of the midslope profile, where it is 0.7), indicating a fairly strong potential (reserve) acidity. Organic carbon is highest in the summit topsoil (2.54%) and declines with depth in all three profiles (Figure 3); total nitrogen follows a broadly similar pattern, being relatively lower in the midslope topsoil, which also shows the highest C/N ratio of the surface layers (14).

Table 3. Acidity and organic status of soil of soils by profile and depth along the Seguéla toposequence (P1: summit; P2: midslope; P3: footslope).

Profile (landscape position)	Depth (cm)	pH water	PH KCl	ΔpH	C (%)	OM (%)	N (%)	C/N
Summit	0 - 20	6.0	4.8	1.2	2.54	4.37	0.21	12
Summit	20 - 40	6.3	4.8	1.6	1.21	2.08	0.13	9
Summit	40 - 60	6.5	5.0	1.5	1.08	1.86	0.10	11
Summit	60 - 80	6.5	5.0	1.5	1.08	1.86	0.10	11
Summit	80 - 100	6.5	5.0	1.5	1.08	1.86	0.10	11

Continued

Midslope	0 - 20	5.7	4.6	1.1	2.42	4.16	0.17	14
Midslope	20 - 40	5.6	4.1	1.5	1.32	2.27	0.12	11
Midslope	40 - 60	6.1	5.4	0.7	1.04	1.79	0.13	8
Midslope	60 - 80	6.0	4.8	1.2	0.73	1.26	0.09	8
Midslope	80 - 100	5.9	4.5	1.4	0.60	1.03	0.07	9
Footslope	0 - 20	6.0	4.4	1.6	2.31	3.97	0.21	10
Footslope	20 - 40	6.1	4.5	1.6	0.97	1.67	0.12	8
Footslope	40 - 60	6.1	4.5	1.6	0.97	1.67	0.12	8
Footslope	60 - 80	6.0	4.6	1.4	0.74	1.27	0.08	10
Footslope	80 - 100	6.0	4.8	1.2	0.55	0.95	0.06	9

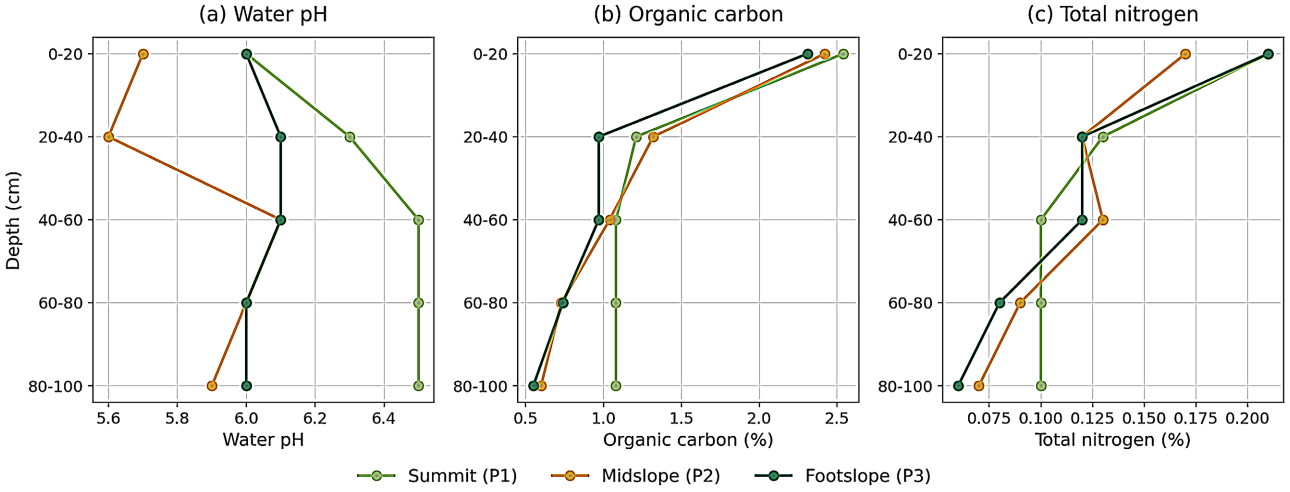


Figure 3. Depth distribution of (a) soil water pH, (b) organic carbon content and (c) total nitrogen content along the summit (P1), midslope (P2) and footslope (P3) profiles of the Kouégo toposequence.

3.2.2. Available Phosphorus, Cations and Cation Exchange Capacity of the Soil

Figure 4 illustrates the distribution of chemical parameters with depth. Available phosphorus is concentrated in the topsoil layer and decreases only slightly with depth at the other two levels. Cation exchange capacity (CEC) generally increases with depth at mid-slope and footslope but stays comparatively flat at the summit, with a value around 25 to 27 cmol(+)kg^{-1}. Ca^{2+} and Mg^{2+} both increase in the deepest horizons of the footslope profile, while K^{+} decreases sharply with depth at the summit and remains low and stable at the other two positions; Na^{+} shows no consistent depth trend at any position.

3.2.3. Comparison of Soil Parameters between the Three Topographic Positions

Table 4 summarises the statistical comparison of soil parameters between the three topographic positions, derived from the horizon-level values. pHwater differs significantly among positions (Pr = 0.003), being highest at the summit (6.4)

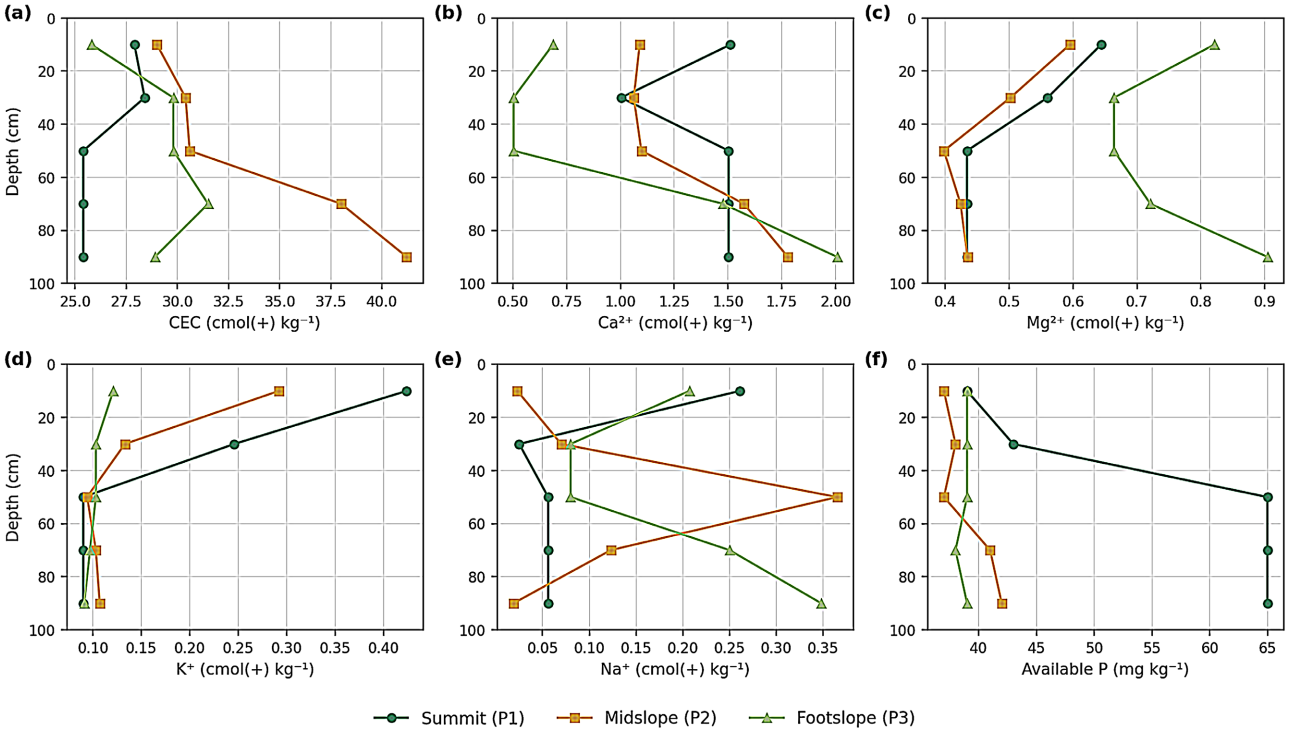


Figure 4. Depth distribution of (a) CEC, (b) Ca^{2+}, (c) Mg^{2+}, (d) K^{+}, (e) Na^{+} and (f) available phosphorus along the summit (P1), midslope (P2) and footslope (P3) profiles of the Kouégo toposequence.

Table 4. Comparison of soil physical, chemical and chemical-balance parameters between topographic positions (mean values; means followed by the same letter within a row are not significantly different at $p < 0.05$).

Parameter	Summit	Midslope	Footslope	Mean	Pr > F	Sig.
PHwater	6.4[a]	5.9[b]	6.0[b]	6.09	0.003	*
PHKCl	4.92[a]	4.68[a]	4.56[a]	4.72	0.189	ns
C (%)	1.398[a]	1.222[a]	1.108[a]	1.243	0.801	ns
N (%)	0.128[a]	0.116[a]	0.118[a]	0.121	0.917	ns
C/N	10.80[a]	10.00[a]	9.00[a]	9.93	0.284	ns
OM (%)	2.40[a]	2.10[a]	1.90[a]	2.14	0.804	ns
CEC (cmol(+) kg^{-1})	26.5[b]	33.8[a]	29.2[ab]	29.8	0.018	*
Ca^{2+} (cmol(+) kg^{-1})	1.405[a]	1.320[a]	1.035[a]	1.253	0.429	ns
Mg^{2+} (cmol(+) kg^{-1})	0.501[b]	0.471[b]	0.755[a]	0.576	0.001	*
K^{+} (cmol(+) kg^{-1})	0.188[a]	0.146[a]	0.103[a]	0.146	0.419	ns
Na^{+} (cmol(+) kg^{-1})	0.091[a]	0.120[a]	0.193[a]	0.135	0.408	ns
Available P (mg kg^{-1})	55[a]	39[b]	39[b]	44.4	0.008	*
Ca/Mg	2.904[a]	2.902[a]	1.326[b]	2.377	0.017	*
Mg/K	3.652[b]	3.646[b]	7.410[a]	4.903	0.001	*
(Ca + Mg)/K	15.20[a]	14.70[a]	17.95[a]	15.95	0.795	ns

and statistically similar, and lower, at the midslope (5.9) and footslope (6.0). For CEC, Mg^{2+} and available phosphorus there are a significant difference between positions: CEC is highest at the midslope (33.8 cmol(+) kg^{-1}) and lowest at the summit (26.5 cmol(+) kg^{-1}); Mg^{2+} is highest at the footslope (0.755 cmol(+) kg^{-1}) and lowest at the midslope (0.471 cmol(+) kg^{-1}); and available phosphorus is highest at the summit (55 mg kg^{-1}) and statistically similar and lower at both other positions (39 mg kg^{-1}). Among element ratios, Ca/Mg and Mg/K differ significantly between positions, both driven by the footslope, which combines the lowest Ca/Mg ratio (1.326) and the highest Mg/K ratio (7.410).

Apart from these parameters, there are no significant differences between the soils of the topographic positions.

3.3. Climatic Characteristics

The ombrothermal diagram (Figure 5) shows a unimodal rainfall regime, with mean monthly rainfall ranging from 16 mm in January to a peak of 215.8 mm in August, and mean monthly temperature ranging from 23.7˚C in December to 26.6˚C in March.

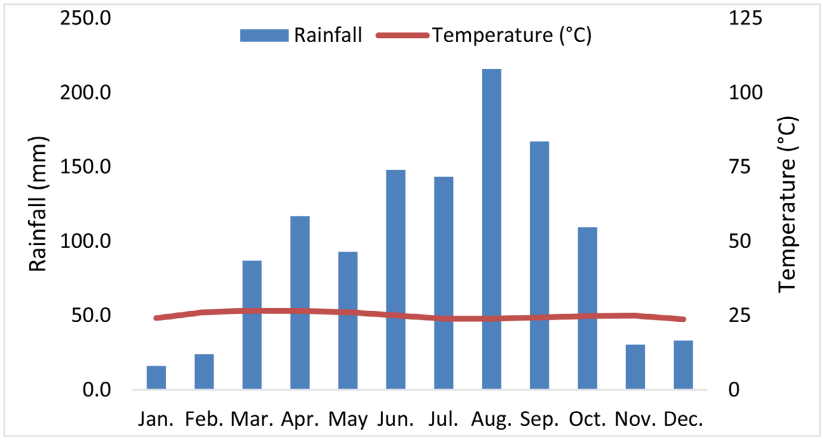


Figure 5. Ombrothermal (Gaussen) diagram for the Séguéla area, showing mean monthly rainfall and temperature.

The monthly water balance (Figure 6) shows an eight-month continuous deficit period from October to May, with the largest monthly deficit in February (100 mm) and the smallest in October (8.2 mm); the four months of June to September show a water surplus, the largest occurring in August (108.7 mm).

Potential evapotranspiration, estimated by the Thornthwaite method, is highest in March (141 mm) and lowest in December (95 mm), closely tracking the temperature cycle.

Combining rainfall with cocoa water requirements identifies four climatic periods over the year (Figure 7): a dry period of about four months (mid-November to early March), a pre-humid period of about three months (early March to early June), a humid period of about four months (early June to mid-October) with no water deficit, and a short post-humid period of under a month (mid-October to

early November).

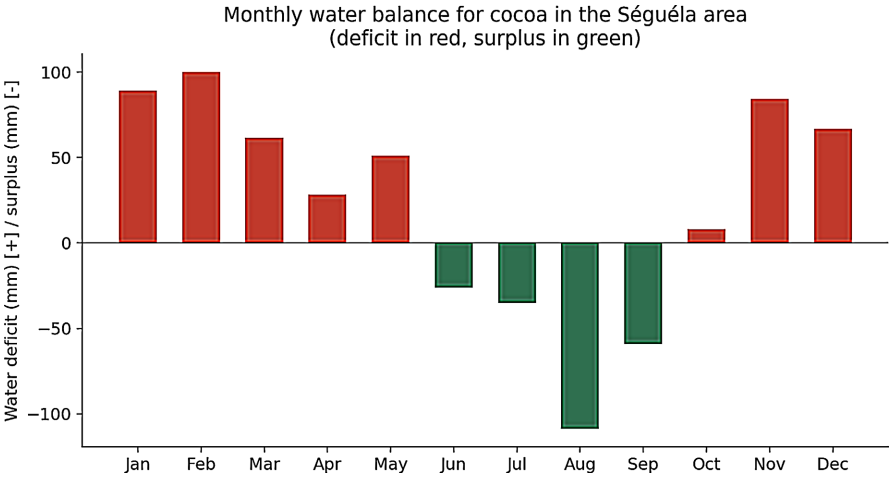
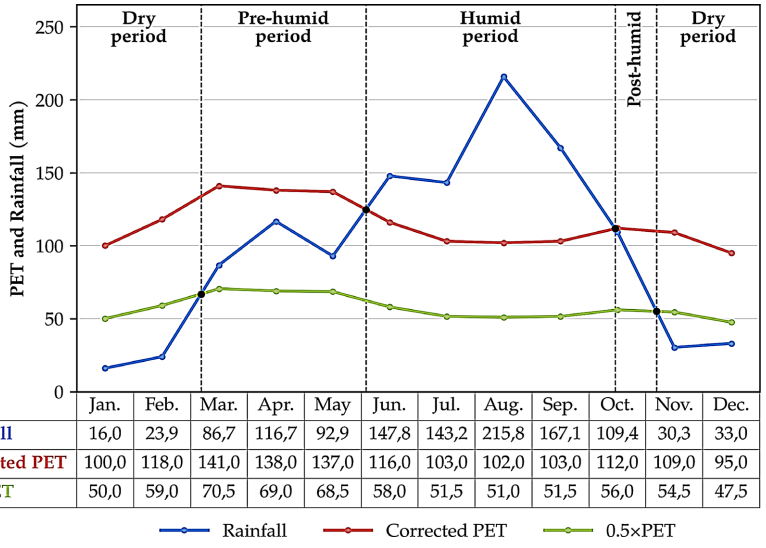


Figure 6. Monthly water balance for cocoa in the Séguéla area (positive values: deficit; negative values: surplus).



	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Rainfall	16,0	23,9	86,7	116,7	92,9	147,8	143,2	215,8	167,1	109,4	30,3	33,0
Corrected PET	100,0	118,0	141,0	138,0	137,0	116,0	103,0	102,0	103,0	112,0	109,0	95,0
0.5×PET	50,0	59,0	70,5	69,0	68,5	58,0	51,5	51,0	51,5	56,0	54,5	47,5

Figure 7. Climatic periods for cocoa in Seguela area.

3.4. Soil Suitability for Cocoa Cultivation

3.4.1. Suitability for Cocoa Cultivation According to Soil Morphological and Chemical Parameters

Table 5 shows that the cumulative rainfall during the wet season, the pH and CEC values of all soil profiles, and the organic matter content of the topsoil (0 - 20 cm) are highly favorable for cocoa cultivation and constitute the major advantages of the Séguéla region. However, suitability is reduced to a moderate level by the C/N ratio, the length of the dry season, the resulting period of water deficit, and annual rainfall slightly below the recommended optimum. The main limiting factors, which render certain criteria marginal or unsuitable, are the high content of coarse fragments and poor drainage, the low content of available phosphorus, and the marked deficiency of exchangeable bases.

Table 5. Synthesis of land suitability for cocoa cultivation in the Séguéla area, based on soil and climatic criteria.

Criterion	Observed value (Séguéla)	Suitability rating
Soil pHwater	5.6 - 6.5	S1 - Highly suitable
Cation exchange capacity (CEC)	26.5 - 41.2 cmol(+) kg^{-1}	S1 - Highly suitable
Topsoil organic matter (0 - 20 cm)	39.7 - 43.7 g kg^{-1}	S1 - Highly suitable
C/N ratio	9 - 14 (whole profile)	S2 - Moderately suitable
Coarse-fragment content	~80% (mean)	S2/S3 - Moderately to marginally suitable
Drainage class	Good at summit; poor at midslope/footslope	S1 (summit)/S3 (midslope, footslope)
Available phosphorus	39 - 55 mg kg^{-1}	S3 - Marginally suitable
Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+})	5-10× below recommended levels	S3/N - Marginally suitable to unsuitable
Mean annual rainfall	1182.8 mm	S2 - Moderately suitable
Humid-season rainfall (Jun - Oct)	≈783 mm	S1 - Highly suitable
Continuous dry season length	≈4 months	S2 - Moderately suitable
Water deficit period	8 months (max. 100 mm in February)	S2 - Moderately suitable

3.4.2. Soil Suitability for Cocoa Cultivation According to Toposequence Positions

Because the ANOVA comparison shows that soil properties differ significantly between topographic positions for several parameters (pHwater, CEC, Mg^{2+}, available P, Ca/Mg, Mg/K), it is useful to break the soil-based suitability assessment down by position along the toposequence (Table 6), independently of the climatic criteria, which apply uniformly across the site.

Combining the soil- and climate-based ratings, the overall land suitability class for cocoa in the Séguéla area is best described as S2 (moderately suitable), with the midslope and footslope positions constrained mainly by drainage and nutrient limitations, and the summit constrained mainly by water availability.

Correcting the phosphorus and exchangeable base deficiencies would be the most effective way to improve the fertility of these soils.

Table 6. Soil-based land suitability for cocoa cultivation by toposequence position (summit, midslope, footslope).

Position (WRB soil type)	Favourable soil traits	Limiting soil traits	Soil-based suitability class
Summit (Haplic Clayic Cambisol)	Highest pHwater (6.4, near neutral); highest available P (55 mg kg^{-1}); good drainage (index 1.7 - 1.9)	Lowest CEC (26.5 cmol(+) kg^{-1}, though still adequate); high coarse-fragment content restricting rooting depth	S2 - Moderately suitable
Midslope (Amphistagnic Clayic Pisoplinthic Cambisol)	Highest CEC (33.8 cmol(+) kg^{-1}); comparatively balanced Ca/Mg ratio (2.90)	Most acidic pHwater (5.9); lowest available P (39 mg kg^{-1}) and Mg^{2+} (0.471 cmol(+) kg^{-1}); poor drainage in deep horizons (index 3 - 5)	S2 - Moderately suitable
Footslope (Endogleyic Plinthic Cambisol)	Near-neutral pH (6.0); highest Mg^{2+} (0.755 cmol(+) kg^{-1}); intermediate CEC (29.2 cmol(+) kg^{-1})	Lowest Ca/Mg (1.33) and highest Mg/K (7.41) ratios (nutrient imbalance); poor to very poor drainage (index 3 - 5); low available P (39 mg kg^{-1})	S2 - Moderately suitable

4. Discussion

The morphological traits identified along the toposequence—high coarse-fragment content, clay-dominated texture, abundant rooting, good drainage at the summit versus poor drainage downslope, and a generally dark brown colour—point to reworking (remaniement) and brunification as the dominant pedogenetic processes at the study area. While the high coarse-fragment content can constrain root penetration and nutrient uptake, as reported elsewhere for cocoa soils, earthy coarse fragments of the kind observed here may also assist water storage.

Soil pH (5.6 - 6.5) places these soils within the 5 - 7 range generally considered optimal for cocoa [22], consistent with the moderately acidic conditions reported by [23] for cocoa soils in the forest-savanna transition zone further south of Côte d'Ivoire (M'Brimbo area). The consistently high CEC (all values above the 12 cmol(+)·kg^{-1} threshold considered adequate for cocoa) and the organic matter content of topsoil horizons (above the 30 g·kg^{-1} threshold defined by [19]) are both favourable, even though the whole-profile C/N ratio is somewhat above the 9 - 12 range typically recommended, but acceptable according to [16]. Against these favourable indicators, however, available phosphorus is only about half of the level generally recommended for cocoa, and exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}) are five to ten times lower than recommended values. The practical impact of these deficiencies is likely mitigated to some extent by comparatively balanced Ca/Mg, Mg/K and (Ca+Mg)/K ratios according to [18].

Climatically, mean annual rainfall (1182.8 mm) falls short of the 1250 mm or 1300 mm minimum proposed for cocoa respectively by [21] and [24] implying an annual water deficit of under 100 mm or 150 mm. However, alongside this relatively small annual rainfall deficit, the water deficit for cocoa trees reaches approximately 100 mm for the single month of February (the driest month). Nonetheless, the June-October humid period totals about 783 mm, above the 700 mm seasonal minimum some authors consider necessary for cocoa, provided the number of dry days within that period remains limited [24].

This rainfall pattern has led some authors to classify certain neighboring areas as having poor suitability for cacao cultivation. However, similar rainfall patterns have been observed in at least one area of the traditional cocoa production loop in Côte d'Ivoire. This suggests that the climate of Séguéla is not necessarily incompatible with cocoa production.

On purely chemical and morphological grounds, the three positions are broadly equivalent, each reaching a soil-based suitability class of S2 (moderately suitable) but for different reasons: the summit is held back mainly by its comparatively low CEC and a high coarse-fragment content that restricts effective rooting depth, despite favourable pH and available phosphorus; the midslope combines the best CEC of the toposequence with the most acidic pH, the lowest available phosphorus and Mg^{2+}, and a deep-horizon drainage impediment; and the footslope combines a near-neutral pH and the highest Mg^{2+} content with a pronounced Ca/Mg

and Mg/K imbalance and the poorest drainage of the three positions.

This formal equivalence in terms of soil suitability class could contrast with observations of cocoa tree vigour and production. This is because certain parameters could mitigate the impact of other parameters that would be unfavorable, such as coarse elements that could improve the soil's water retention capacity and mitigate the effect of water stress in the Séguéla area.

5. Conclusions

This study provides an outline of the soil and climate characteristics of the Séguéla forest-savanna transition zone, an area historically considered unsuited to cocoa. The soils are Cambisols with a generally favourable pH range and cation exchange capacity for cocoa, moderated by pronounced deficiencies in available phosphorus and exchangeable bases; all three toposequence positions reach the same soil-based suitability class (S2), though for different reasons (lower CEC and coarse fragments at the summit, acidity and phosphorus at the midslope, base imbalance and drainage at the footslope), while observed vegetative development and pod load are nonetheless best at the footslope and midslope and weakest at the summit. Climatically, annual rainfall is slightly below the recommended threshold for cocoa, but the four-month humid season meets the crop's seasonal water requirement, and the resulting eight-month deficit period, while a constraint, does not appear prohibitive.

Under the conditions in which this study was conducted, the overall results indicate that the soils and climate of the Séguéla area are moderately, though unevenly, suitable for cocoa cultivation (overall suitability class S2), supporting the hypothesis that a cautious extension of cocoa production toward this forest-savanna transition zone is agronomically plausible. Correcting phosphorus and exchangeable-base deficiencies would likely be needed to close the yield gap with more traditional cocoa-growing regions. Future work should evaluate the yield response to targeted phosphorus and base-cation amendments, and assess the potential for supplemental irrigation during the dry season, particularly in the context of ongoing climatic change.

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Author Contributions

This study is a team effort, involving four scientists. The initiative and scientific direction including final redaction, were led by GALA Bi Trazié Jérémie. Field data were collected by ALLA Kouadio Sylvestre and ELETE Koutoua Arthur Johnson. Data analysis was conducted by ALLA Kouadio Sylvestre and GOLE Bi Teddy Charles, while the process of locating the study area was developed by AMANI Sostène Franck Sylva.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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