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The nature and spatial variability of lowland savanna soils: improving the resolution of soil properties to support land management policy

Donoghue, S. [1*] **Furley, P.A.** [1] **Stuart, N.** [1] **Haggis, R.** [1] **Trevaskis, A.** [2] **and Lopez, G.** [3]

[1]School of Geosciences, University of Edinburgh;

[2]University of Oxford;

[3]Government of Belize, Forest Department, Forest Drive Belmopan, Belize.

***Corresponding author:** email: s.l.donoghue@sms.ed.ac.uk

Running title: Spatial variability of lowland savanna soils

Abstract

A fresh approach is presented to address the increasingly urgent need for alternative land management strategies in savannas. We illustrate how fine-scale information of soil characteristics can be used to enable a more precise delimitation of sites suitable for different forms of land stewardship, including agro-pastoral activities, forestry, biodiversity and tourism. By collating data from previous soil surveys, and augmenting this with targeted new surveys, we produce the first national data set of soil properties for the lowland savannas of Belize. Most of these soils are typical of savanna soils worldwide, i.e. acidic (mean surface pH = 5.7), nutrient-poor (mean surface TEB = 3.4 cmol/kg), and coarse textured (mean surface clay = 13.0%). Nevertheless, there is a marked spatial variability across the country in these soil properties. Some soils exhibit unusually high subsurface clay fractions (max = 73%), whilst other sites have exceptionally high pH in lower horizons (max = 8.4). Cluster analysis is used to group sites with similar soil properties. Across 79 sites there is a clear division between soils with high clay percentages and those with coarser textures. These are sub-divided into five groups based on further differences in parent material, chemical properties, and site characteristics. Mapping the locations of these groups enables more specific land use recommendations to be made. This ability to make targeted land use recommendations from fine scale soil information represents an advance over the previous national land use policy, where all savanna lands were considered unsuitable for any form of agriculture. This approach could be applied to marginal savannas worldwide.

Key words: savanna soils, cluster analysis, land management, Belize

1. Introduction

Throughout the world inappropriate management practises in savannas have led to soil degradation, with a major loss of organic matter (OM) that has contributed to global carbon emissions (Grace *et al.,* 2006). These impacts are well documented in savanna regions such as the Brazilian *cerrados*, where degradation is predominantly due to clearance for large-scale agriculture (Klink and Machado, 1995). However, as a result of increasing population pressures, other savanna areas within the moist tropics and across drier parts of Africa are likely to be utilised for more intensive agriculture in the near future (Ngumbi and Dindi, 2017). It has been estimated that already one fifth of the world's population live in or around savannas, and many of these areas are witnessing rapid increases in population growth (Furley, 2016).

Whilst some savanna soils may be amenable for conversion to agriculture, many tropical savanna soils have severe limitations. Unless these are overcome conversion to agriculture may not be sustainable, and could cause augmented desiccation, erosion, and nutrient loss. Even savanna soils that can support cultivation and livestock grazing are likely to experience loss of OM content, weakened nutrient cycling, and increasing CO_2 emissions, if converted. Savanna soils are also known to exhibit local variability, as exemplified by research in African savannas (Obalum *et al.,* 2017). Although scientists understand the variable land use potential of savanna lands, many national land use planners consider savanna lands as uniform in their use and value. For example, while analysing the potential of the Brazilian *cerrado* soils for land use conversion, Brannstrom *et al.,* (2008) amalgamate a wide range of savanna formations, summarising that the predominant soils are highly weathered and acidic Oxisols, whose high aluminium concentrations require fertilizers and lime for livestock and crop production. While accurate this fails to distinguish the significant local variation in the soils, such as the non-uniform textural profiles giving rise to Ultisols, deeper coarse-textured profiles developing Alfisols, or less developed Entisols on eroded rocky outcrops. Differences in topography and drainage also generate distinctive catena patterns (Furley 2000; 1996). Hence there is a considerable diversity of land use possibilities existing within *cerrado* soils. This emphasises the importance of understanding the nature and the variations in soil properties of savanna woodlands and grasslands, particularly for smallholder farmers with limited resources.

Savannas cover around 10% of the total land area in Belize and are therefore an important national ecosystem (Meerman, 2011). Similar small patches of savanna can be found throughout much of Central America and the Caribbean. Although Belizean savannas represent a small proportion of the biome they illustrate how a fine-scale approach can address some of the global issues concerning development of savanna lands.

2. Case study: savannas of Belize

The savannas are an important but frequently disregarded natural resource. The land is viewed as being largely unsuited to farming other than low-density pastoralism and softwood extraction (King *et al.,* 1992; Haggis, 2013). Furthermore, although settlements and roads have been preferentially constructed on savanna land, most has remained commercially unused until recently. Whilst some tracts of savanna are designated as pine-forest reserves or are managed as nature reserves, the lack of a definite management policy in national land use legislation (Meerman, 2011) and a perception among local people that savannas are 'waste ground', has contributed to practices such as dumping, opportunistic harvesting and a lack of control of wildfires, resulting in widespread deterioration. In the last decade shrimp farming has encroached into savanna areas near the coast. As the population of Belize rises, marginal lands including the savannas are now starting to be developed for agriculture. Meerman and Cherrington (2005) warned in their general assessment of risks to land degradation in Belize that savanna soils were generally too acidic for conversion to agriculture. A later report by the Government of Belize’s Department of Environment (2014) concluded that almost a third of the roughly 1 million acres of agricultural land in Belize now occurs on land classified as marginal or unsuitable for agriculture, and one third of all agricultural land occurred on acidic soils sensitive to land degradation. A nationwide GIS analysis of land use change by Cameron *et al.,* (2011) showed that more than 10% of the remaining savanna lands had been converted to other land uses in the past 20 years of which agro-pasture and shrimp farming were the most frequent.

There are two principal savanna domains in Belize, which may be generalised as upland and lowland. The lowland savannas, which form the focus of this paper, are mostly located closer to sea level, with varied parent materials and some coastal influences such as saline spray and marine ingressions in low lying areas. The coastal plains are relatively flat and poorly drained, comprised of parent materials made up from siliceous alluvium of various ages derived from the Maya Mountains and from Quaternary coastal marine deposits. The marked seasonality of the climate influences soil properties through wetting (temporary inundation) and drying (often intense) resulting in infertile soils that typically support savanna landscapes.

Despite the generally infertile nature of the soils, there are considerable variations in savanna soil properties, implying local differences in potential for agriculture and also possibilities for other types of land use being sustainable. Until now however, soil variability within savannas areas has been poorly understood. Assessments of savanna soils are now urgently required so that plans can be formulated before the pressure from the growing population results in unplanned and unsustainable development.

There have been very few studies dealing with savanna soils in Belize and none specifically concentrating on lowland formations. Further, the objectives of the present study differ from the comprehensive but broad scale national surveys conducted previously by the Land Resources Division of the ODA (King *et al.,* 1992). This study seeks to create a larger data set focused solely on the savanna soils and to use this information to assess whether there is any spatial variation in soil properties. It aims to establish if there are spatial soil groupings that could be used to make national land management policies more locally applicable.

3. Methods

3.1. Data assemblage

To create a national savanna soils data set for Belize we sought an approach applicable internationally in other countries which also have limited resources for conducting extensive soil surveys. Firstly savanna data from pre-existing surveys were collated (Jenkin *et al.,* 1976; King *et al.,* 1986; Furley and Ratter, 1989; King *et al.,* 1989; King *et al.,* 1992; Furley *et al.,* 2001). This dataset was reduced and simplified to establish a subset of soil properties that were comparable across all the sites. New surveys and laboratory analysis of soil samples were conducted to increase coverage in areas where the existing data were sparse or non-existent (Stuart *et al.,* 2012). Combining the historical data with the new surveys produced a total of 79 sites spread across the country (Figure 1). The full dataset may be accessed at https://datashare.is.ed.ac.uk/handle/10283/3132.

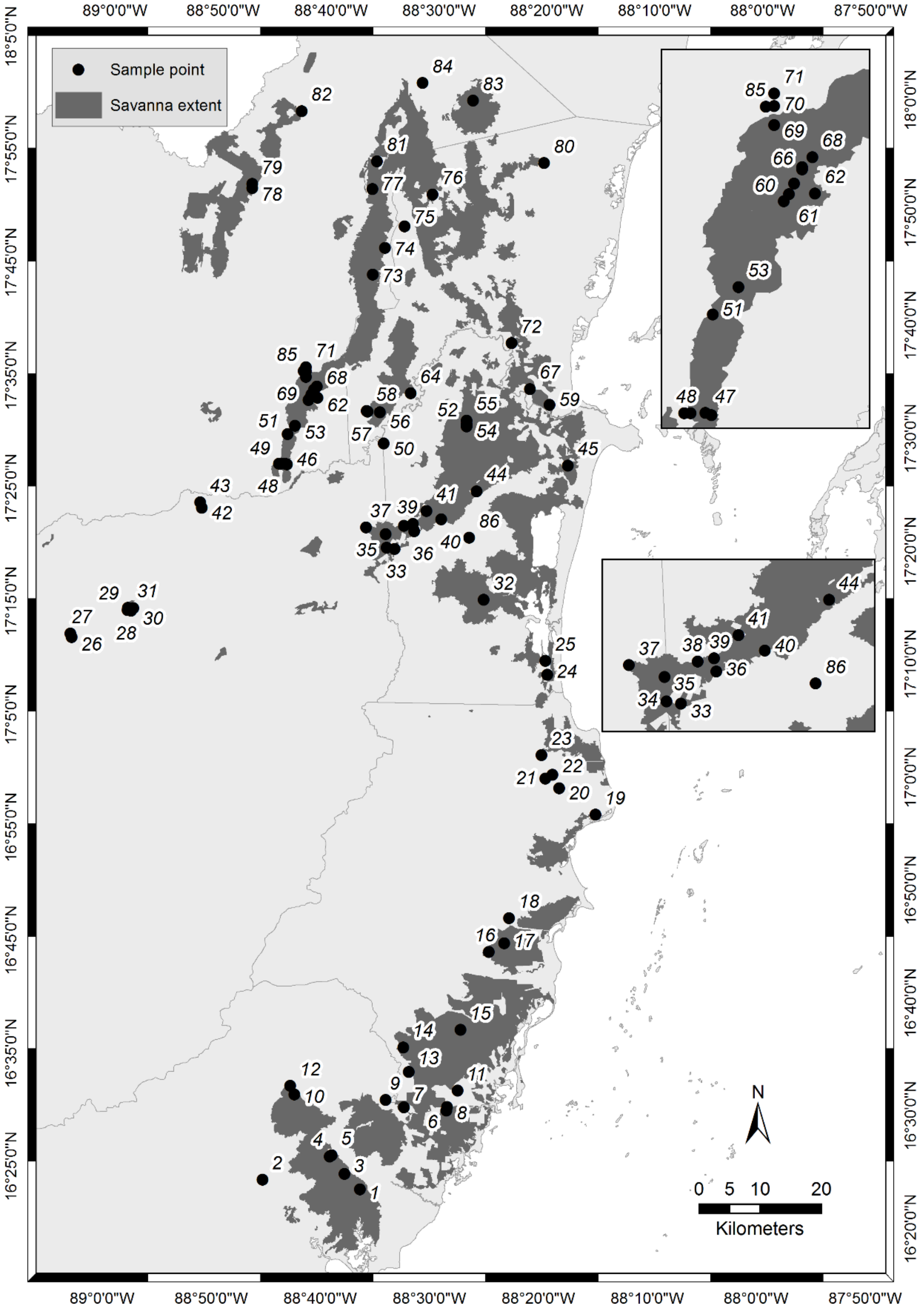

Figure 1: the distribution of soil sample sites used in this study (with site ID for reference and insets to magnify areas with high point density). Savanna extent is based on Meerman et al's. (2011) ecosystem survey and Cameron et al's (2011) remotely sensed data. Some sample locations predate the ecosystem surveys, therefore no longer occur on savanna vegetation.

3.2. Soil analyses and field data collection

All field samples were air-dried and then sieved (<2mm). The analyses followed standard procedures so the data has international comparability. Field and laboratory methodology from the earlier surveys i.e. ODA/NRI, are reported in King *et al.* (1992, Vol. II p289). Where possible identical methods of analyses were used for the newly surveyed soils (Stuart *et al.,* 2012, Appendix 2), except that pH measurements were only conducted in H_2O, and a simplified particle size analysis was employed (Kettler *et al.,* 2001). Profile descriptions included in the database provide further information about all the sites.

Property	Weighting	Justification
Surface OM	5	Highest weight reflecting the importance of OM influencing soil fertility and moisture retention; most important in the top soil.
Subsurface Clay	4	Impedes drainage and limits rooting depth.
Surface Total N	4	Essential nutrient related to OM and indicator of surface conditions.
Surface pH	3	Influencing nutrient and cation availability.
Surface Clay	3	Influencing drainage, leaching and soil structure.
Surface Available P	3	Major limiting plant nutrient related to OM and particularly important at the surface and rooting zone.
Surface TEB	2	Influences pH and nutrient availability. Secondary impact on plant growth.
Subsurface pH	1.75	Influences nutrient availability and can reflect subsurface variations in parent material.
Subsurface Total N	1.25	Less of an influence on soil fertility and occurring in low concentrations in savanna soils.
Subsurface TEB	1.25	Less significant as there are lower nutrient concentrations.
Subsurface OM	1	Very low levels and limited impact.
Subsurface Available P	0.75	Generally very low concentrations.

Table 1: weights applied to each soil property in descending order, with justifications

3.3. Cluster analysis

Cluster analysis is a powerful data-mining tool as it classifies multivariate data into groups with similar properties, thereby reducing data complexity and aiding interpretation. In the present study cluster analysis was used to identify if there were any groupings of sites within the national dataset. These were then mapped to examine if groups of soils with certain properties occurred in specific parts of the country, and if this could be used to inform land assessment and management decisions.

Before analysis the soil dataset was reduced in complexity by selecting variables considered to be the most significant when assessing land use and management. These were; clay percentage, pH, TEB, OM, total nitrogen, and available phosphorus, for both surface and subsurface horizons. As is usual with many clustering methods these soil properties were weighted to represent their relative importance in determining land suitability (Table 1). To allow comparison between soil properties measured on different scales, data for all properties were normalized into a 0-1 range using min-max normalization.

SPSS software (version 21) was used to perform cluster analysis in order to identify groups of sites that were similar in terms of these soil properties. Of the various alternative approaches to cluster analysis, such as hierarchical and model-based clustering, *k*-means clustering was selected as it permits individual sites to move between clusters during the iterations until an optimal result is achieved (Romesburg, 2004). As *k*-means clustering (MacQueen, 1967) partitions multivariate data into *k* clusters, an important parameter is the value of *k* (the number of groups generated). Different *k* values were tested and evaluated using the variance ratio criterion (VRC) (Calinski and Harabasz, 1974). Partitioning into 3, 5, 8 or 10 groups generated acceptable VRC statistics. $k = 5$ groups were retained as this provided the best compromise between producing groups with statistically different properties and with some spatial pattern. For higher *k* values between-group differences were less clear and the spatial patterning less evident. A second key parameter are the sample sites chosen as the initial cluster centres around which the clusters are built. This choice can be influenced by the ordering of the input data. Therefore, to avoid the selection of less suitable initial cluster centres, the algorithm was re-run multiple times, each time with a random sorting of the input data. Results were evaluated using a one-way ANOVA in SPSS to generate the greatest difference between clusters. The final cluster analysis results were then validated using the C-Index internal validation method (Hubert and Schultz, 1976) using R software. For $k = 5$ the C-Index was 0.61, which we take to indicate an acceptable degree of intra-cluster similarity and inter-cluster difference for the purposes of an applied study such as this. For each of the 5 groups the mean and standard error for each soil property were extracted and plotted and the overall mean shown for comparison.

4. Results and discussion

4.1. Soil properties and spatial variations

The newly created database (n = 79) confirms that the properties of the Belizean soils (Table 2) are generally consistent with the global ranges for savanna soils, particularly those of moist neotropical savannas. They are typically acidic, nutrient-poor, and generally coarse-textured at the surface, with varying amounts of OM depending on drainage and vegetation cover. Most of the soils fall within the tropical categories of the USDA Ultisol and Entisol orders (Tropaquult and Tropofluvent), but some of the deeper sandy profiles are likely to be Spodosols (Tropohumod), or Alfisols (Albaqualf) developing in stretches with siliceous alluvium overlying calcareous parent materials (USDA, 2017). Inceptisols (Tropaquept) are found in seasonally waterlogged areas (Baillie *et al.,* 1993). However there are numerous transitions that reflect variations in the underlying parent materials and water balance, and many of the soil samples have compound profiles. These variants occur over heterogeneous scattered patches of savanna and examination of the site locations revealed how the soil properties sometimes changed markedly across relatively small distances.

	Property	Mean	S.E.	Range	Comment
Surface	Clay %	12.95	1.24	0 – 49	16% classed as type of clay soil[1]
	pH	5.45	0.07	4 - 7.1	84% are strongly or moderately acidic (i.e. ≤6)[1]
	TEB(cmol/kg)	3.40	0.58	0 - 27.1	65% low i.e. ≤2cmol/kg[2]
	OM %	6.14	0.48	0.29 - 21.92	85% fall in very low–low range, with 56% in very low[2]
	Total N %	0.12	0.012	0 - 0.55	80% fall in low range (≤0.2%)[2]
	Avail P(ppm)	2.59	0.23	0 - 8.4	Only 14% above the critical level of 4ppm[2]
Subsurface	Clay %	34.05	2.2	0 – 73	67% type of clay soil, with 35% pure clay soils[1]
	pH	5.69	0.1	4.2 - 8.4	77% are strongly or moderately acidic (i.e. ≤6)[1]
	TEB(cmol/kg)	6.67	1.4	0 - 65.1	62% low i.e. ≤2cmol/kg[2]
	OM %	0.97	0.16	0.3 - 7.98	97% fall in very low range[2]
	Total N %	0.029	0.003	0 - 0.1	All fall in low range (≤0.2%)[2]
	Avail P(ppm)	1.81	0.18	0 - 5.7	Only 9% above the critical level of 4ppm[2]

Table 2: key parameters of lowland Belizean savanna soils from this study. Reference sources are 1 - USDA (2017) and 2 - Landon (1984).

One unusual feature observed in many lowland sites in Belize is a low surface but high subsurface clay fraction with high bulk density. The mean surface clay content is 13% whereas the figure for the subsurface is 34% and over a third of the sites have high clay percentages (>40-50%). Where clay-rich subsoils are found over widespread areas of the lowland plain it has been suggested that eluviation of fine materials from upper soil horizons could account for the translocation and accumulation of clay sized particles in the B horizon (King *et al.,* 1992). However this is not a consistent pattern throughout the lowlands. Clay-rich soils also tend to occur in low-lying sections of nearly level or gently undulating landscapes where fine soil fractions have been washed laterally into depressions and shallow valleys, and dampness is often signalled by palmetto palm (*Acoellorraphe wrightii*). An alternative explanation is that the argillaceous substrate results partly from finer sediments of different geological provenance, overlain by more recent coarse alluvial deposits from the adjacent Maya Mountains or marine deposits. Consequently the parent materials can be multi-banded as recognised by King *et al.,* (1992). This proposal fits with the observed data, particularly along the southern coastal plains of Stann Creek and the Toldeo districts. In the future a more detailed analysis of clay minerals would help determine which process is dominant.

Soil pH is consistently acidic in both surface and subsurface horizons (mean = 5.4 and 5.7 respectively). Nevertheless there are large variations with surface levels falling as low as 4 (Table 2). Lower soil pH is slightly more common in the south, which could occur because southern Belize receives higher rainfall than other parts of the country (Figure 2), and is therefore likely to experience greater leaching. Conversely in central and northern regions some subsurface soils have elevated pH with levels >8. A number of these sites appear to have been influenced by the proximity to the coast even where they are clearly located within broadly-defined savanna. For example, site 25 has a surface pH of nearly 5 but a TEB of 14 cmol/kg with nearly half contributed by exchangeable Na. More neutral or alkaline sites are also found where the weathered limestone bedrock (locally known as *sascab*) is closer to the surface and covered by only a thin layer of alluvial/palaeo-alluvial sands and gravels. At these sites the Ca, Mg and TEB levels are also elevated, as demonstrated by sites 37

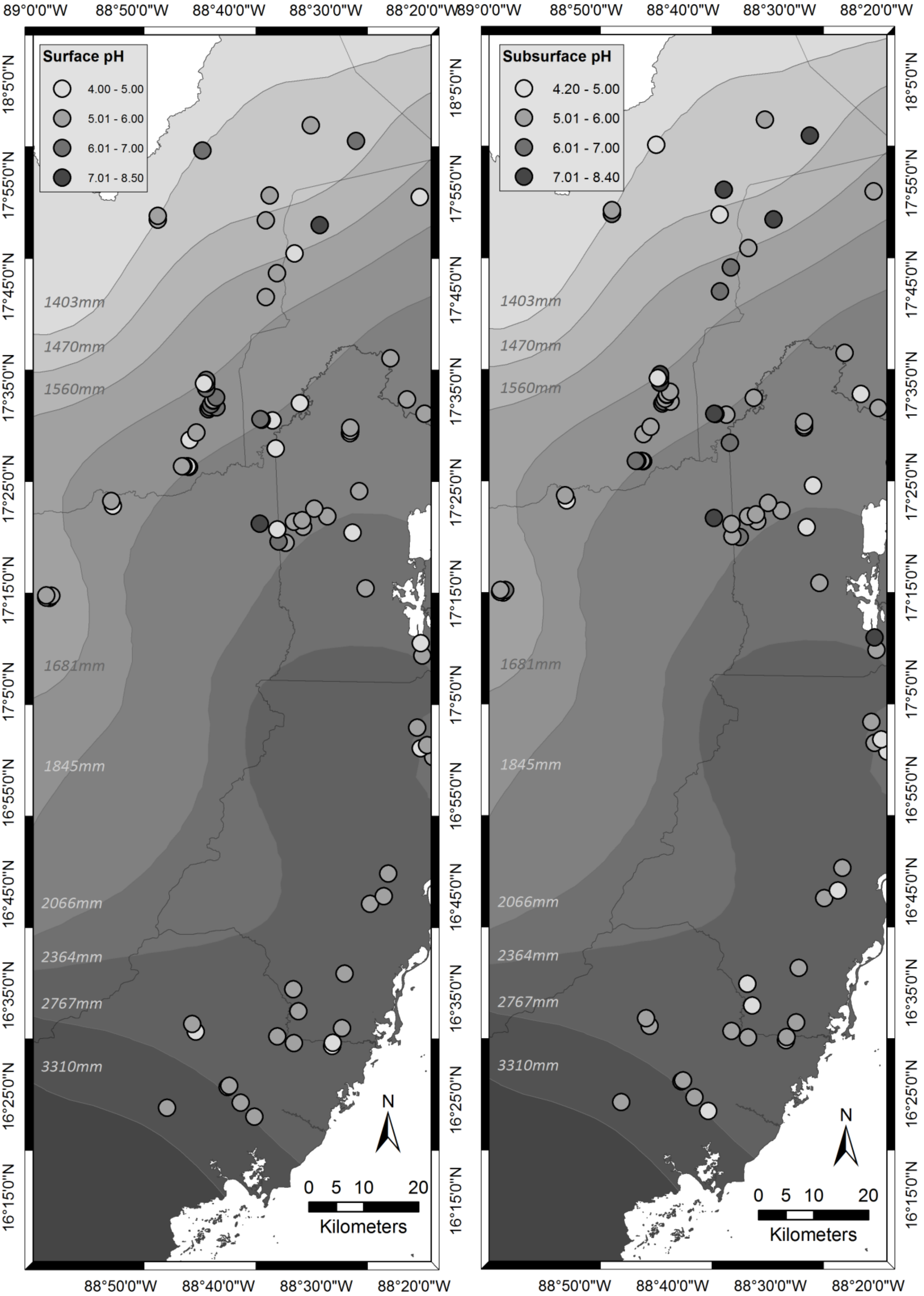

Figure 2: surface and subsurface pH of sample sites, with rainfall isohyets interpolated from 2013 annual rainfall data from Hyrdomet.gov.bz.

and 76 and possibly 83 (Figure 1). These sites have a subsurface pH levels of 8, 7.9 and 8.4 respectively with subsurface TEB levels of 50, 27 and 30 cmol/kg. Furthermore Ca accounts for over 90% of the TEB in these sites, specifically 99% at site 37, 93% at site 76, and 94% at site 83.

The OM, total N, and available P levels are as expected, i.e. higher in surface than subsurface soils and are generally low or very low (mean topsoil levels of 6.1%, 0.1% and 2.6% respectively). These low levels have possibly resulted from eluviation and leaching coupled with rapid decomposition (Ngatia *et al.,* 2014), and dehydration at different times of the year. Patches of more fertile surface soil with higher organic levels tend to be associated with the presence of denser vegetation, such as mixed savanna woodland. At these sites vegetation physically protects the soil and provides a constant input of organic material which retains moisture and mineralises nutrients. Additionally, high OM can occur in soils where the clay-rich subsurface has caused significant seasonal waterlogging, thereby reducing rates of decomposition. This is the case in site 62 where poor drainage from high subsurface clay (>60%) within a topographic depression, resulted in a dense growth of palmetto which contributed to the elevated topsoil organic content (8%) and slightly acidic pH value (6.0).

4.2. Soil groupings

The cluster analysis of soil properties was used to produce 5 statistically distinct groups (Figures 3 and 4). Comparison of inter-group soil properties and divergence from overall mean value for all the 79 samples reveals a clear top-level split according to clay levels (Table 3). This divide possibly arises from differences in topography, geology and rainfall, as previously outlined.

The high clay groups (1, 2 and 5) have mostly developed on Pleistocene coastal deposits comprised of mudstones and other marine sediments, or older Tertiary (Toledo) beds over which there are varied layers of more recent alluvial or coastal deposits (Wright *et al.,* 1959). The differences between the groups reflect the proportions of fine fractions throughout the profile. Clay-rich subsoils are predominantly found in group 1 (n = 19), which is located in the central Belize river valley (e.g. sites 56, 59, 40), and along the rivers of the southern coastal plains (e.g. sites 8, 11, 15) (Figure 3). This

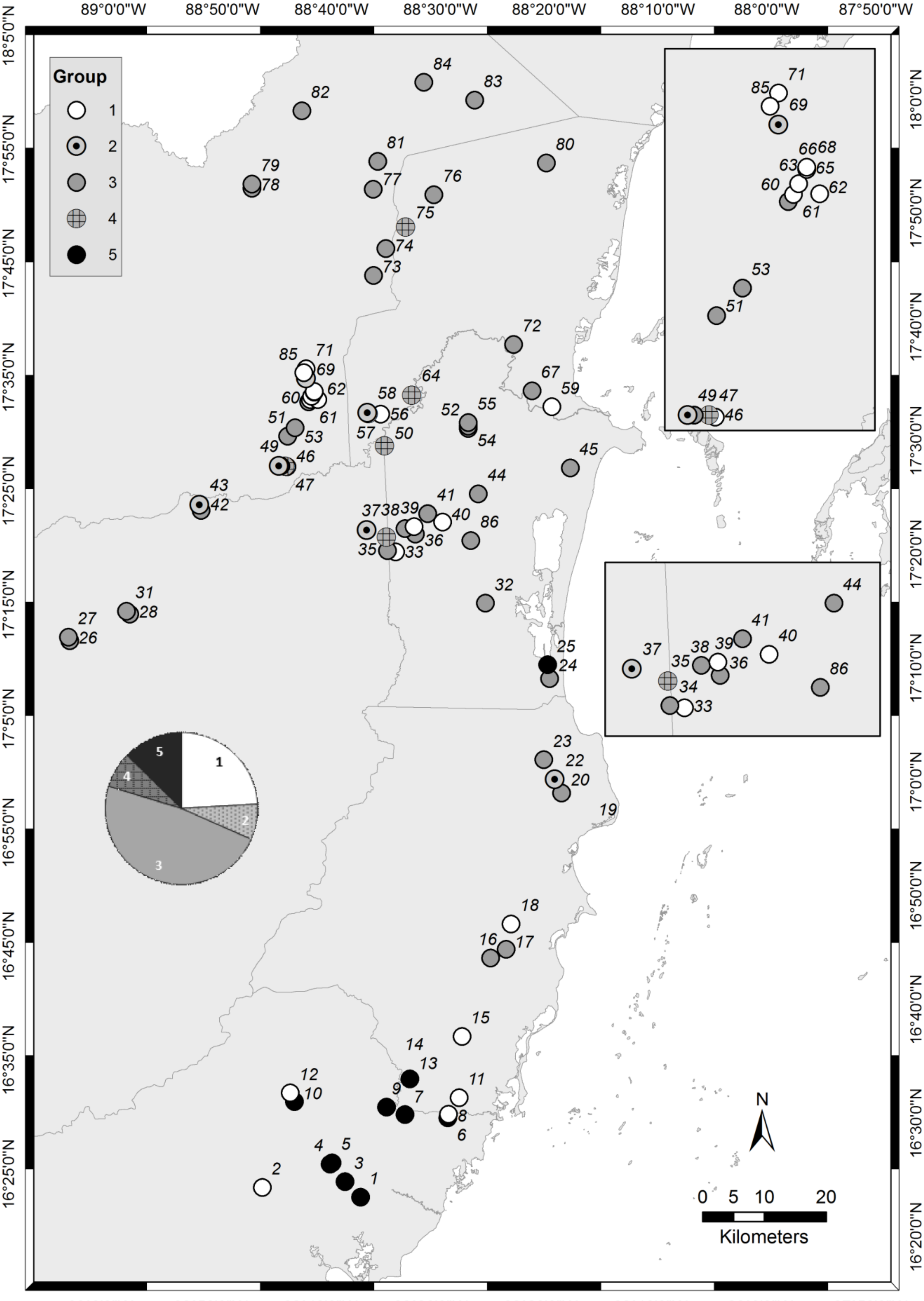

Figure 3: groups resulting from cluster analysis. The pie chart illustrates the proportion of sample points in each group.

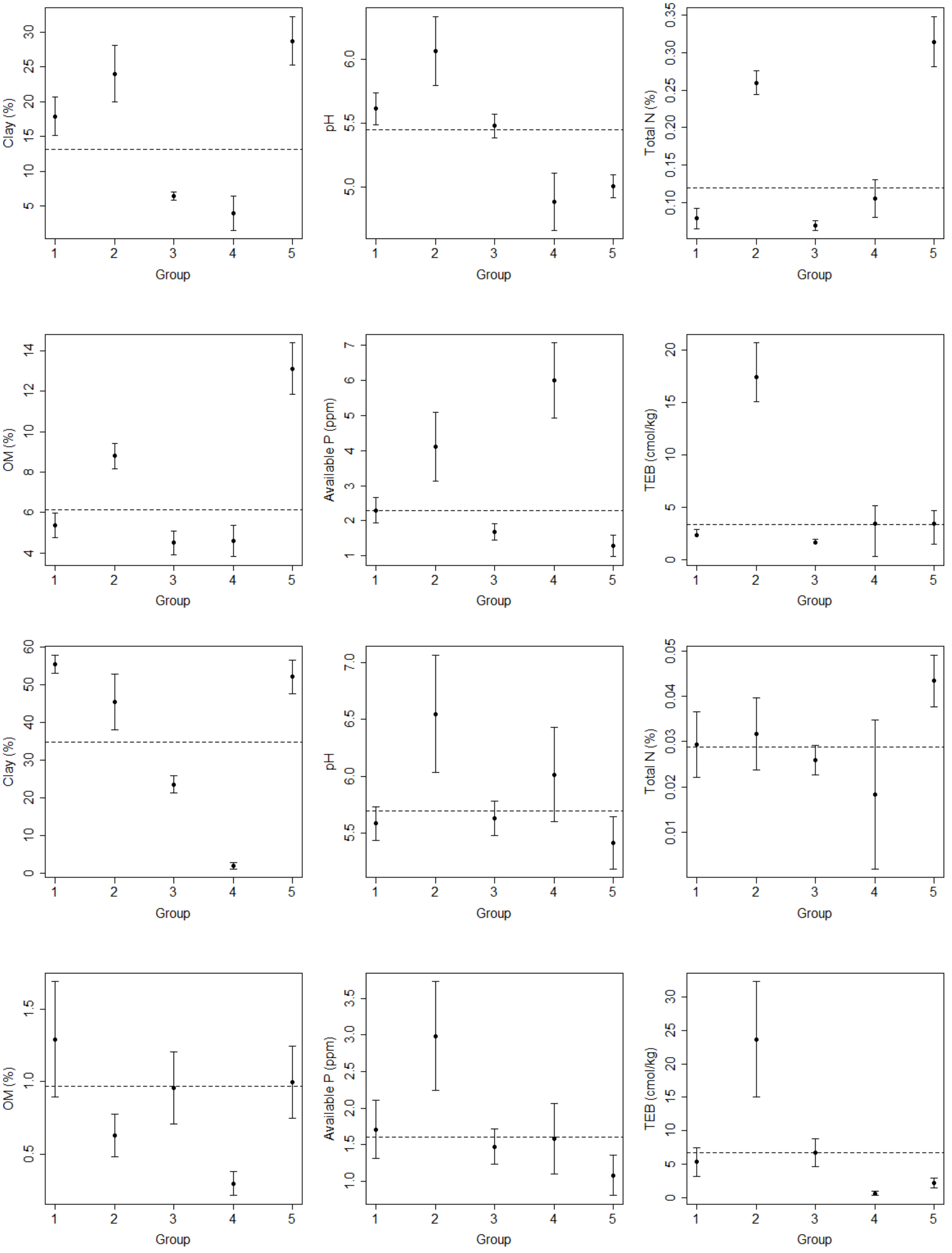

Figure 4: soil properties of each clustered group in the surface and subsurface horizons. Black dots represent the mean, and error bars are 1 standard error above and below the mean. The dashed line represents the mean value of the property for all sites.

group occurs predominantly within the Puletan Suite (King *et al.,* 1992, Table 4), with pale, coarse-textured, acidic, nutrient-poor, and well weathered surface horizons. However in places it is transitional to the Melinda Suite (ibid) where the soils are found in alluvial terraces and colluvial sites of river valleys (e.g. site 40). Subsequent soil evolution has resulted in impermeable clay-rich substrates (mean clay = 56%) beneath a coarser surface horizon (mean clay = 18%). The upper horizons are similar to the other savanna soils (such as the widespread group 3), being acidic with low nutrient levels and weakly organic. Group 2 is less typical of savanna soils due to its almost neutral pH (Figure 4). This small group of soils (n = 6) is concentrated in the central river valleys (Figure 3) and is derived from a thin cover of siliceous sands and gravels (alluvium) overlying calcareous parent materials. Where weathered limestone lies near the plant rooting zone the availability of cations (notably exchangeable Ca) supports a mixed vegetation (e.g. sites 37, 49, 58 and 69). In these areas a frequently sharp boundary occurs, and is represented at the surface by a clear transition between savanna vegetation above alluvial material and broad leafed or semi-deciduous forest overlying adjacent limestone parent material (Figure 5a). Unlike the other groups, group 5 is almost exclusively found in the southern coastal plains where it is intermixed with group 1 (Figure 3). Group 5 contains high surface clay levels (Figure 4), possibly a consequence of a layer of fan-like alluvium overlying the marine Toledo beds. Furthermore, group 5 has a more acidic pH than average, likely resulting from intensive leaching of base cations from the more prolonged rainfall in Southern Belize (Figure 2).

The groups with lower proportions of clay (3 and 4) are located in the central river valleys and northern Belizean plains where there is a variable cover of coarse-textured deposits. The parent materials represent various phases of siliceous alluvium eroded from igneous crystalline and sedimentary rocks of the Maya Mountains, possibly Late Tertiary-Pleistocene in age (King *et al.,* 1992; Wright *et al.,* 1959). This ancient detritus is believed to have been deposited as outwash over the undulating northern and central plains (Figure 5b) and is coincident with areas of characteristic savanna vegetation (Goodwin *et al.,* 2013). The deposits overlie weathered limestone at extremely variable depths giving a range of soils supporting typical savanna to semi-evergreen forest, depending upon the proximity of the calcareous parent materials to the surface (Figure 5a). Most of these soils belong to the Puletan Suite (King *et al.,* 1992), which corresponds well with group 3 soils which have the most widespread distribution (n = 38; locations and properties shown in Figures 3 and 4). The occurrence of fine fractions in the subsurface with characteristic mottling is likely due to illuvial accumulation. Group 3 sites are also found on some hillwash, residual and colluvial soils predominantly derived from granitic parent materials, assigned by King *et al.,* (1992) as Stopper Suite soils (e.g. sites 26-27 and 28-31). Group 4 comprises a smaller range of sites (n = 6), and are found mainly within the Belize river valley or well-watered stream and lagoonal sites (i.e. at Crooked Tree, site 75) (Figure 3). Group 4 profiles are found over older and recent alluvial sites in damp locations often with palmetto as a co-dominant vegetation. Specifically, group 4 lacks the fine textured substrate that is present in group 3 (Figure 4), but the sampling points are spread over a variety of sites and it is difficult to pinpoint a consistent explanation. Another characteristic of group 4 is the slightly higher surface P (Figure 4), which may be associated with a grassland vegetation cover and in one instance (site 35) on herbaceous marsh. However few group 4 sites remain undisturbed, as their more favourable soil properties means they have often already been exploited for agriculture (e.g. sites 50 and 64). In contrast group 3 is more widespread and appears to be representative of clay-poor and arguably more characteristic savanna soils. Since group 4 comprises a few scattered and varied sites the two groups (3 and 4) are probably better considered together.

	Clay divide	Chemical divide	Group
Higher clay %	Very high in subsurface, medium in surface.	Average-low concentrations (both horizons)	1
	High in surface, medium in subsurface.	High pH, TEB & N/P; average-low OM (both horizons)	2
	Very high in both horizons	Low pH, TEB & P; average-high N & OM (both horizons)	5
Lower clay %	Average-low in both horizons	Average concentrations but slightly lower in surface compared with subsurface	3
	Very low in both horizons	Surface = low pH, high P, average OM, N, TEB; Subsurface = high pH, average P, low OM, N & TEB	4

Table 3: key soil property differences between the resulting groups from cluster analysis. Note the comparison between soil properties are relative, for actual values see figure 4.

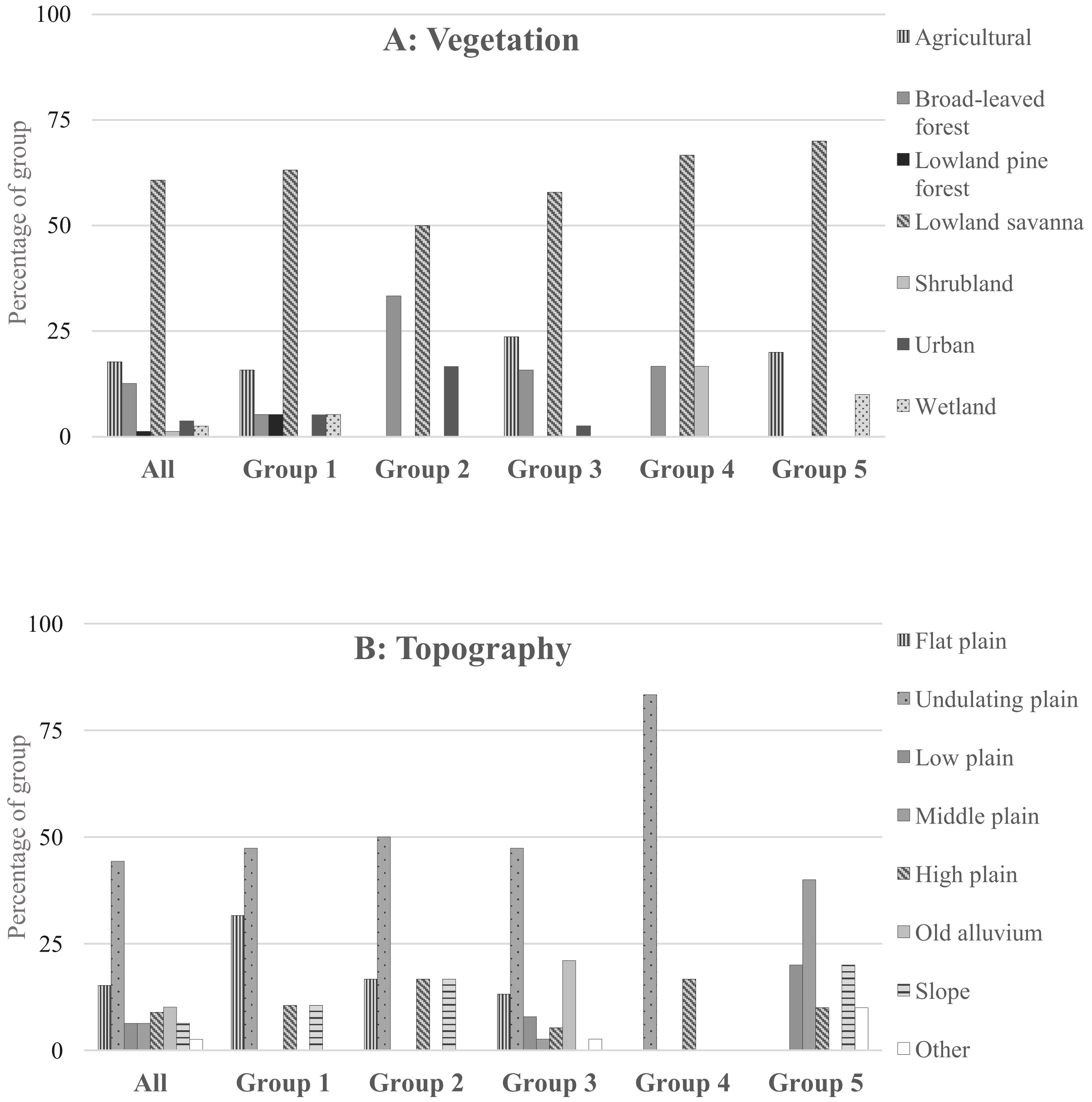

Figure 5: vegetation (A) and topography (B) characteristics for each group and all groups for comparison. The bars represent the percentage occurrence of the site characteristic in each group. Vegetation types were simplified from field notes, and topography descriptions were extracted from land system maps (King et al. 1992).

5. Implications for management

The groups identified by cluster analysis help simplify the complex variety of soils found over the savanna lowlands. Specifically, cluster analysis illustrates that some savanna soils may be suitable for agriculture in their present state, but these are scattered and of limited extent within the overall savanna mosaic. While most of the savanna soils are characterised by their acidic, infertile and coarse-textured surface horizons, there are several sites with more favourable properties that might sustain cultivation, particularly small-scale agriculture, or at least more intensive pastoralism. This inherent variety in the potential of savanna soils was recognised in the work of the land resources assessment teams such as the Land Resource Development Centre, who indicated the need for detailed local and site investigation.

The most favourable group for agricultural development (group 4) is of limited extent within the present day distribution of savanna. It appears to be related to relatively recent alluvial and colluvial parent materials, along river valleys, seasonal streams, lacustrine margins or sites derived from granitic parent materials. The properties of group 4 fulfil the requirements for the best agricultural soils proposed by King *et al.,* (1993) in that they have developed in alluvium or colluvium similar to those classified as Melinda Suite, and are covered by grass-dominant savanna. Such soils provide a good rooting depth with adequate nutrient and water resources. Since these sites are amongst the most favourable and accessible locations in the country (Jenkin *et al.,* 1976; King *et al.,* 1993) many of these former savanna tracts (e.g. those in the Belize river valley) have been exploited.

By contrast, the sandy soils of the northern and central coastal plains are described as the ‘worst soils in the country’ for agricultural development (King *et al.,* 1993). Most of the soils classified as Puletan Suite fall into this category and are coincident with the group 3 soils which are found extensively. King *et al.,* (1993) suggest that the best and deepest of these soils could support tree crops like cashew, and where they are relatively freely drained could be utilised for the traditional uses of pine production and pasture. Nevertheless, any such land use would require nutrient supplements together with measures to counteract acidity and moisture variations, especially low soil moisture in the dry season. In this way chemical limitations in some of the group 3 soils could conceivably be ameliorated, as was achieved in the analogous *cerrado* and *llanos* soils in South America. Furthermore, the better drained soils of Group 3 in the southern coastal plains might support localised crops such as pineapple, cashew and coconut production, although sites with high subsurface clay will be least amenable to exploitation. The deeper soils characteristic of the transition to the Revenge Suite (mostly in the Northern coastal plains and defined as developing over mixed siliceous and calcareous parent materials) may also support coconut and pineapple production along with livestock, but much

Suite	Description	USDA equivalent[1]
Major suites:		
Puletan	The most widespread savanna group (>2/3 of land area). Developed over deposits of old (possibly Tertiary to mid-Pleistocene) siliceous alluvium. Derived from crystalline or meta-sedimentary rocks eroded from the Maya Mountains. Pale coarse-textured surface soils grading to mottled subsurface horizons which are frequently compact and impermeable. Variable depths and seasonally very wet (often flooded) or very dry (liable to drought). Leached, acidic and base-deficient soils with low levels of P and N.	- Ultisols *(Tropodult; Tropaquult, Albaquult, Paleaquult)* - Spodosols *(Tropohumod)* if deeper sandy soil
Melinda	Derived from well to poorly drained river and floodplain alluvium, especially recent river basins draining to the coast from the southern Maya Mountains. Soil horizons exhibit banding reflecting their riverine history, frequently overlying old coastal deposits or alluvium. Significant nutrient deficiencies, but the better drained sites on more recent alluvium are capable of utilization for tree crops, pasture or (traditionally) milpa (shifting cultivation).	- Ultisols *(Tropaquult)* - Entisols *(Tropofluvent)*
Stopper	Transitional soils developed in colluvial hillwash, and some residual soils derived from granitic parent materials. The latter have been largely cleared and typically utilised for citrus.	- Inceptisols *(Dystropept)* - Ultisols *(Hapladult)*
Revenge	Moderately thick but variable depth of acidic siliceous surface soils overlying limestone. Marked vertical differences in soil properties reflecting the different provenances of the parent materials.	- Alfisols *(Albaqualf)* at the sandier end of the textural spectrum
Transitional Suites (occupying minor savanna areas):		
Yaxa	Well to imperfectly drained clay-rich soils developed over calcareous parent materials. Neutral to alkaline with sufficient base nutrients to support lowland forest and agriculture.	- Inceptisols *(Eutropept, Tropaquept)* - Alfisols *(Rhodudalf)* if deeper soils - Mollisols *(Rendoll)* at shallower sites
Jacinto	Mixture of Pleistocene coastal deposits, later alluvium over mudstones, calcareous sandstones, plus some conglomerates (Toledo Beds). Dark calcareous soils containing significant amounts of sand in the surface horizons with increasing levels of clay with depth. The soils have the greatest agricultural potential so have mostly been cleared of vegetation.	- Inceptisols *(Eutropept)* - Afisols *(Hapludalf)*
Tintal	Seasonally very poorly drained soils with varied textures and nutrient status; gleyed and often brackish.	- Inceptisols *(Topaquept)* - Entisols *(Fluvaquent)* - grading to Histosols with increasing OM content
Guinea Grass	Dark calcareous soils with significant amounts of sand in the surface horizons becoming increasingly argillaceous with depth. Confined to northern Belize with very limited areas under savanna.	- Alfisols *(Hapludalf)* - Inceptisols *(Eutropept)*
Ossory	Residual and hillwash soils derived from very varied metasediments from the Maya Mountain.	- Inceptisols *(Dystropepts)* - Ultisols *(Hapladult)* if deeper soils
Altun Ha	Medium and coarse-textured siliceous soils overlying limestones on the Northern Coastal Plain. Characteristically flinty with a neutral to slightly acidic pH.	- Inceptisols *(Eutropept)* - Alfisols *(Hapludalf)*

Table 4: summary properties of the principal soil suites discussed in this paper with USDA equivalents (1 - USDA, 2017).

depends upon the compaction of the lower soil horizons and the degree of impermeability.

Many of the soils in groups 1, 2 and 5 have the potential for agriculture but are limited by the high clay levels in the B-horizon. The impermeable clay-rich substrate not only limits rooting depth but also impedes drainage causing perched water tables, seasonal or semi-permanent saturation, and a lack of aeration in the rooting zone. Where such soils are above the level of ground water the land would require a major engineering investment to reduce seasonal flooding in the wet season, and conversely in places to irrigate in the dry season. Therefore, capital intensive management techniques would be required to make these soils viable for agriculture, which is unlikely in the foreseeable future. However, although these solutions are uneconomic today future advances in technology may alter the economic balance meaning that these options for land management should be explored. If this occurred initial resources might best be focused on group 2 soils, which are clustered in the Belize River Valley and have slightly more favourable conditions (i.e. a neutral pH, less clay at depth, and higher TEB and N levels).

The savannas are under continuous and accelerating threat of development without a clear government policy towards their conservation or utilisation (Meerman, 2011). The scattered nature of the better savanna soils for agriculture may favour traditional smallholder farming in view of their small size and widespread distribution. The best soils offering possibilities for more commercial farming have mostly been utilised already. Management alternatives could be helped by information on the nature and potential development of soil resources along with consideration of their non-agricultural, forestry and biodiversity value. Several other potential uses for the lowland savannas have been investigated over the past decade. For instance, the conservation and tourism prospects are limited but significant. A number of plant species are specialists of pine savannas, including 17 of the 41 country endemics (Goodwin *et al.,* 2013). Some animal species rely on savanna areas such as the critically endangered yellow headed parrot, whilst others such as the jaguar also utilise these more open landscapes. In addition, the savannas offer space that is welcomed by local inhabitants for recreation and as a community resource (Wells *et al.,* 2018). The Programme for Belize, a well-known conservation NGO, occupies a major savanna area in the Northern plains and in the southern Toledo District, the Paynes Creek National Park is a significant biodiversity refuge, providing environmental regulation and forest resources in an area of limited agro-pastoral value.

6. Conclusions

The creation of this new data set confirms that the soil properties of the lowland savannas of Belize fall within the typical ranges of similar savannas worldwide, i.e. 84% of the samples are acidic, coarse-grained soils with low OM. However, a large number of sites have high proportions of impermeable subsurface clay. These are found in areas of level or gently undulating topography that result in seasonal or semi-permanently wet surface conditions. Another unusual aspect of this data set is the number of sites with high pH and TEB levels in the subsurface, which are located where more alkaline parent materials are found within the plant rooting zone.

The diversity of soil properties has been simplified by a cluster analysis, generating 5 soil groups that could support different future land management strategies. The most fertile soils are those of group 4, which develop in relatively recent alluvium or colluvial parent materials, and will require careful nutrient management to maintain their productivity. The most widespread group (group 3) contains infertile soils, coarse-textured surface horizons, and is associated with more characteristic savanna vegetation. These soils could possibly be developed for agriculture with intensive fertilisation, as witnessed in the Brazilian *cerrados.* The groups exhibiting higher clay subsoils (groups 1, 2 and 5) are mainly found over the southern coastal plains where the heavier rainfall has led to greater leaching and nutrient-depleted topsoils. These soils could be used for forestry and aquaculture but have limited agricultural potential under present economic conditions. It is recommended that areas with extremely restricted drainage and severe nutrient limitations should not be developed, but could instead be managed for biodiversity conservation or recreation and tourism.

Our analysis of these soils and their variability across the country demonstrates the value of applying cluster analysis to finely-scaled data focusing on specific soil properties. This approach helps to ensure that land use recommendations are sustainable and appropriate to soil capabilities, which is preferable to the previous national land use policy where all savanna lands were considered uniformly unsuitable for agriculture. Furthermore, the same methodology could be applied to other savanna areas where the data has a sparse spatial coverage or limited extent. Making more focused recommendations is likely to become more necessary as countries around the world are required to exploit their savanna soils more intensively as a consequence of population growth.

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