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Cocoa suitability mapping using multi-criteria decision making: An agile step towards soil security

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ABSTRACT

Cocoa production is impacted by major resource constraints, such as the soil's capability, and in some areas, by unreliable access to markets. A multifaceted approach that employs both biophysical and socio-economic conditions is developed here for mapping areas that are suitable for cocoa production in Papua New Guinea (PNG). This manuscript presents a case study of using multi-criteria decision making by the Analytic Hierarchy Process for mapping the fundamental criteria for cocoa suitability. The results show that temperature, precipitation and soil reveal sections within Western, Gulf and Central (along the west coast joining to National Capital District) province that have very low suitability for cocoa production. In our analysis, precipitation, soil, slope and road, were ranked as the four most important criteria. Additionally, we included stream networks because they may help irrigation and allow cocoa transport via water (e.g. Manus Island). Comparing an already existing cocoa suitability map for PNG to the one created in this study, we found some similarities. For example, the Central, Gulf, and Western (Fly) areas are either unsuitable for cocoa production or have very low potential, and exceptional areas around Rabaul and Kokopo in East New Britain, Popendetta, and Bouganiville were identified. Some new areas suitable for cocoa production in East Sepik, East New Britain, and a major stretch within West New Britain may show low to moderate suitability. The most important finding is the potential to grow cocoa in the highlands, especially, Chimbu (Simbu), Eastern Highlands, Enga, Hela, Jiwaka regions. We found that currently the majority of farmers are growing cocoa in highly suitable areas (76% in class 4, 20%in class 3 and 4% in class 5). The inclusion of slope and roads impacts the impact of flooding conditions and the amount of work and ease of access to markets as important indicators of the connection farmers make between soil suitability and their decision to grow cocoa. This is an agile step towards linking biomass production to soil capability, and connectivity, allowing cocoa suitable areas selection and the production of 'living maps' that continually evolve as more empirical data becomes available. This can be an essential connectivity tool for practitioners to evaluate the potential geographic range for cocoa production.

1. Introduction

It is imperative to secure our soil to ensure food and livelihoods' security in the face of global environmental and societal change (Lal 2009). This is especially crucial in developing countries as unpredictable climatic regimes have led to substantial changes in livelihoods (Kiup, 2017) and the potential to grow different crops. Cocoa (*Theobroma cocoa* L.) is an exported product that contributes to Papua New Guinea (PNG's) economy and its production is dominated by smallholder farmers. An illustration of the reliance on this crop as an income source for individuals and nationally is the devastation brought by the cocoa pod borer (CPB) in the early 2000′s. Production plummeted affecting thousands of smallholder farmers and larger plantations, and caused the PNG economy to suffer (Walton et al., 2020). After tackling CPB to some extent, an almost 8-fold increase in cocoa production for export over the next few years has been forecasted by the PNG government (DAL, 2017).

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The global demand for high-quality cocoa remains strong, presenting opportunities for the cocoa industry in PNG to intensify and grow whilst minimising expansion. To achieve this, several policies and plans provide the national planning framework guiding PNG's agricultural development with a few strictly focused on soil and cocoa quality (FAO, 2018).

Cocoa is vital for PNG economy and farming communities (Curry et al., 2012). Cocoa bean production in PNG crossed 40 thousand tons by 2017. East Sepik, Bougainville, Madang and East New Britain provinces remained the major contributors to the total amount of cocoa produced (Fig. 1) and exports from PNG (https://www.agriculture.gov.pg/cocoa/).

It is speculated that only a quarter of the country's landmass (lowlands and highlands) is suitable for agriculture (Bourke et al., 2009), cash cropping, one of the prospects to earn a steady income in rural PNG, is generally unavailable to smallholders living in high rainfall or remote and high altitude areas, where land quality is assumed to be poor (Curry et al., 2012). Although it has been identified that 63% of the land used for agriculture in PNG is on mountains and hills, however, growing cocoa in the highlands of PNG is not a standard practice (Bourke et al., 2009).

Cocoa suitability mapping is equipped to address this—where can cocoa grow? It is understood that the soil's capability and its current condition will impact cocoa production (Snoeck et al., 2016). To this end, the concentration of cocoa production in the equatorial tropics is described briefly by Wood (1985) and De Geus (1973) by identifying the climate and land conditions in which cocoa will grow, including:

Non-windy areas, rainfall of 1250 to 3000 mm yr^{-1} and a short dry season, soil depth no less than 1.5 m, and soil pH within a range of 5.5 – 7.5. Of these criteria the soil depth would indicate the capability of an area to grow cocoa and if there is opportunity to manage the pH the potential to improve the soil's condition for cocoa production.

In PNG, Hanson et al. (1998), provide environmental criteria unsuitable for cocoa production:

(1) Annual rainfall less than 1800 mm or greater than 5000 mm,
(2) Slope gradient greater than 30°, and

Six landform classes having specific recurring combinations of soil types, slope gradients, and level of inundation, from which inferences on site drainage, fertility and stability was created. Which led to a classified map (Fig. 2) of the productivity potential of cocoa in PNG by combining rainfall and landform classes to form 29 Agro-ecological zones was created in 1998 with an aim:

'Such information supports the design of a national network of research trials representative of environmental variations in the most suitable socio-economic regions and the spatial prioritisation of extension services' (text taken from Hanson et al., 1998).

A closer inspection of Fig. 2 shows that the PNG highlands are classified as unsuitable for cocoa production. However, recent reports suggest that cocoa is growing in the highlands (Fig. 1- Simbu region) of PNG (elevation greater than 600 m), which was previously considered unsuitable for cocoa (Hanson et al., 1998). Therefore, this provides an opportunity to classify suitable areas for cocoa production in PNG through a new lens. Additionally, this may facilitate the ambitious yield increases set out by the government, which has set an ambitious target of 310,000 tonnes of annual cacao exports by 2030. While previous land suitability attempts only consider rainfall and landform, the soil's capability and socio-economic factors need to be taken into account, such as the proximity to roads and markets, affecting the connection farmers make of the soil's suitability to grow cocoa.

To take into account these various factors, the multicriteria decision analysis (MCDA) can be combined with the geographical information system to produce a more robust analysis (Malczewski and Rinner, 2015). The techniques applied in the MCDA seek to assign weights and combine different GIS criteria based on the aim of the study (Sallwey et al., 2019). Literature highlights the usefulness of MCDA where data is limited, which is the case in PNG (Giove et al., 2009; Paquette and Lowry, 2012; Paul et al., 2016; Rousseau et al., 2017). Even though MCDA may be used in data scarcity scenarios, proper validation is required to evaluate the results, which is absent in many studies (Fuentes et al., 2020). Additionally, the modelling algorithms and their performance depend on the type, quantity and quality of the datasets used. MCDA techniques can integrate different data sources with expert's judgement in the decision-making process (Giove et al., 2009), which has been successful in different areas of research (Gamper et al., 2006; (Russo et al., 2015); Paul et al., 2016). As the MCDA technique requires the selection and assignment of weights of defined criteria, some subjectivity is introduced in the decision-making process (Buchanan et al., 1998).

From the different MCDA alternatives, the Analytical Hierarchy Process (AHP, 2018) has been widely employed as it allows for a consistency check in the MCDA, in return leads to a reduction of bias in the analysis (Mu and Pereyra-Rojas, 2017). Therefore, the use of AHP has increasingly been used in site suitability studies (Sallwey et al., 2019). Additionally, the main advantages of AHP over other techniques that make it the most popular amongst all the other MCDA techniques is that it is simple, flexible, and carries an intuitive appeal to users (Giove et al., 2009, Ozkan et al., B. 2020). Its simplicity and flexibility is put forward through the development of a set of tools to perform AHP, including online applications (Yalew et al., 2016), allowing work in multi-user projects to obtain a consensus between participants (Goepel, 2018). A similar approach is documented in recent publications that explored barley crop options, suitability for development, and the current extent of barley production (Seyedmohammadi et al., 2019).

Leveraging publically available data can improve the accessibility of cocoa suitability information for granting more geographic decision power to farmers, cocoa value chain stakeholders, and policymakers to effectively scale agricultural improvement and ultimately decide what crops can grow where. More importantly, this provides access to stakeholders on soil capability to prepare robust soil connectivity tools (McBratney et al., 2014; (Field and Sanderson, 2017), not only this, but as the information used in this article is publicly available, geographically agile, and quasi-global it is accessible to a broad range of users for soil condition and codification (McBratney et al., 2014) purposes.

McBratney et al. (2014) outlined a series of soil functions and how each one links back to the soil security dimensions, within that, soil capability and condition would play a major role for biomass production. As the primary aim of this paper is to find cocoa suitability within PNG, which directly serves the soil function of biomass production, therefore, soil capability was utilised for mapping. In future, this can be used as a soil connectivity tool where farmers can manipulate soil condition based on site-specific constraints for cocoa intensification. The objective is to outline a cocoa suitability map for farmers and policy makers, so that cocoa production provides for the needs and aspirations of the community and the country. For this reason, we have approached this research from both a scientific and market access point of view as cocoa production is highly dependable on roads and access to water for shipping produce across islands.

2. Materials and method

2.1. Location

The study was carried out in PNG, located in the pacific islands, which covers an area of approximately 452,860 km^2 (See supplementary figure 1 a). This country was selected due to its capability to produce *Theobroma cocoa* L. (Cocoa). A significant area in the country is used for agriculture, with cocoa, coffee, and coconut being the most important cash crops. It is speculated that cocoa cultivation has changed slightly

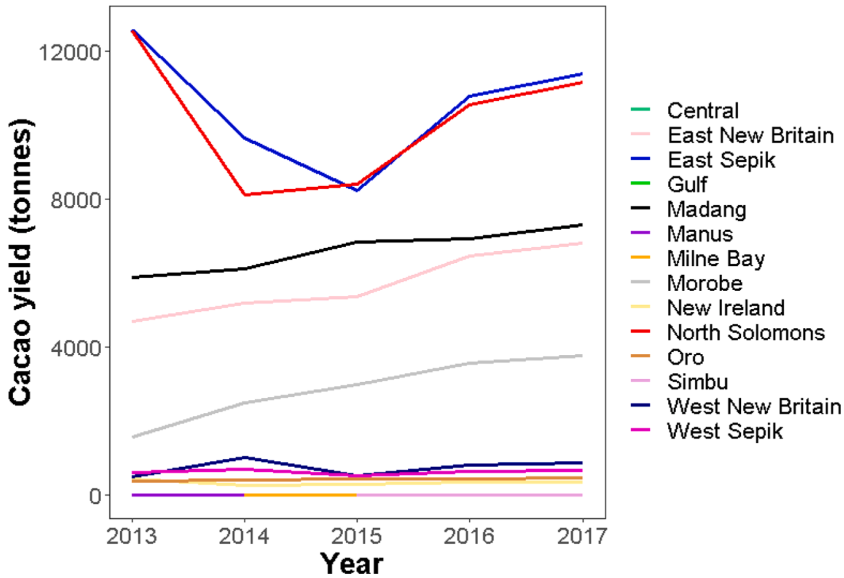


Fig. 1. The total cocoa production by Province and by calendar year (2013 – 2017). Cocoa producing provinces are; Central, East New Brownitain, East Sepik, Gulf, Madang, Manus, Milne Bay, Morobe, New Ireland, North Solomons (Bougainville), Oro (Northern Province), Simbu (Chimbu), West New Brownitain, and West Sepik (In alphabetical order)..[11]

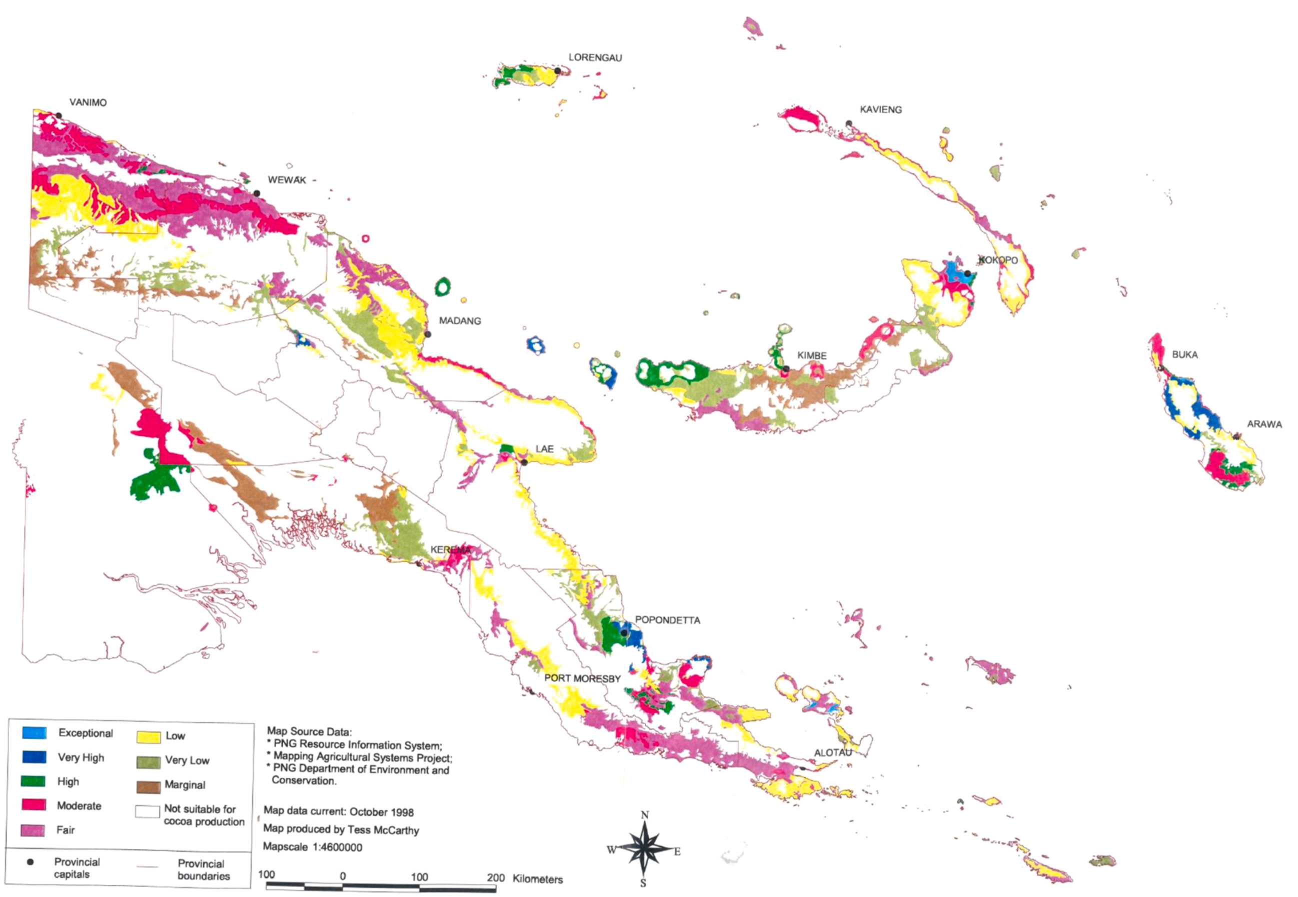


Fig. 2. Scanned map of productive potential for cocoa (taken from Hanson et al., 1998).

from the 1990s with production seen in the highlands of PNG. This offers the opportunity to map the areas that have the potential to grow cocoa.

Papua New Guinea has a hot, humid tropical climate throughout the year with two distinctive seasons i.e. wet (December – March) and dry (June – September). The average monthly rainfall ranges between 250 – 350 mm and average temperature is between 26 - 28 °C with high humidity (70 – 90%). Variability in climate is also strongly influenced by the El Niño conditions in the southeast Pacific, which bring drought conditions to PNG, especially in the drier areas of the country. Soils in PNG are known to be influenced by ancient or recent volcanic deposits, and 13 soil orders occur (refer to Section 2.3 for further details). Water resources occur as a result of rainfall and runoff, leading to the formation of over 12 major rivers of great importance to both PNG and Australasia e.g. Sepik and Fly. Given the abundance of rainfall and surface water resources, groundwater has not been exploited in this study.

2.2. Data and pre-processing techniques

Different datasets were used to evaluate the suitability of lands for cocoa plantations. These were considered as different criteria for the decision-making process. Under present conditions, it can be assumed that both the biophysical and market access criteria are major constraints to cocoa production in Papua New Guinea.

Biophysical:

The Shuttle Radar Topography Mission (SRTM, see Farr et al., 2007) digital elevation data is an international research effort that obtained digital elevation models on a near-global scale. The SRTM V3 product (SRTM Plus) is provided by NASA JPL at a resolution of 1 arc-second (approximately 30 m). This dataset has undergone a void-filling process using open-source data (ASTER GDEM2, GMTED2010, and NED). A slope raster was obtained at a 30 metre resolution from the DEM dataset.

Climate data from the WorldClim version 1 dataset was obtained using Google Earth Engine (Himans et al., 2005). This product has average monthly global climate data for minimum, mean, and maximum temperature and for precipitation. For this study, we used maximum temperature as that captured the range of temperature suitable for cocoa production and annual precipitation.

Papua New Guinea soil map provides the reference soil groups (RSGs) that are allocated to sets based on dominant identifiers, i.e. the soil-forming factors or processes that related to soil formation. (http://worldmap.harvard.edu/data/geonode:DSMW_RdY).

Market access:

A map of proximity to roads and rivers was generated from road and water vectors (https://download.geofabrik.de/australia-oceania/papua-new-guinea.html).

All criteria maps were rasterized (30 metre resolution), converted to the same coordinate system (GCS WGS84), and clipped to the extension of Papua New Guinea. The steps followed for processing and analysis are provided in Fig. 3.

2.3. Map reclassification and rating

Since MCDA requires all data to be standardised and converted to the same schema (Sallwey et al., 2019), all maps were reclassified and ranked as shown in Table 1 based on a review of commonly used classes, the data distribution, and parameter ranges. We divided the maps into two categories:

1. Biophysical:

a Maximum temperature (De Geus,1973),
b Rainfall: Higher rainfall was ranked lower because it can cause fungal diseases in cocoa, such as Phytophthora (by Hanson et al., 1998). Lower rainfall is also ranked low due to desiccation of cocoa roots or drought stress (Freyne et al.,1996).
c Sites with low slopes have less runoff and are more suitable to promote infiltration. Therefore, lower slopes were ranked higher (Hanson et al., 1998).
d Soil map of PNG: The soil map of Papua New Guinea shows the major soil-types found in PNG (Fig. 4 and table 2). We ranked soil types on the following principles of soil capability:

1. Soils with a clay-rich subsoil: a. Acrisols, acidic with low fertility and requires management ranked as very low suitability for cocoa production (1), and b. Luvisols, fertile soils ranked as moderate suitability (3);

2. Relatively young soils or soils with very little or no profile development, or very homogenous sands with moderate fertility, Cambisols, ranked as moderate suitability (3);

3. Soils with severe limitation to rooting: a. Rendzinas, shallow soils with moderate fertility ranked as low suitability due to root restrictions; and b. Lithosols ranked as very low suitability;

4. Soils that occur predominantly in steppe regions and have humus-rich top-soils and a high base saturation, Phaeozems. Due to unrestricted root development, these are ranked high (4);

5. A group of RSGs that are or have been strongly influenced by water, Fluvisols. These are moderately suitable for cocoa as they require drainage related management;

6. Organic soils key out to separate them from mineral soils, Histosols, very low (1) suitability for cocoa due to very poor drainage conditions;

7. The soil groups of volcanic origin, Andosols, ranked as exceptional (5) because these are deep soils presenting adequate physical soil properties for cocoa.

The soil suitability ranking is based on available literature on soil and cocoa ((Shoji et al., 1993) Bleeker 1983: Micheli et al., 2006; (Singh et al., 2019); Sanchez 2019).

The dominant soil types based on percentage of area covered show that Cambisols with moderate suitability cover approximately 40% of the area, followed by soils ranked low for cocoa production i.e., Rendzinas (~10%) and Acrisols (~ 18%), whereas the highly desirable Andosols and Phaeozems cover approximately 3% and less than 1% area respectively. Singh et al. (2019) reported that the main soil types growing cocoa are cambisols (Inceptisols) and Andosols, this may be due to the relatively wider area covered by these two soil types (table 3).

Major soil types based on area covered (%) decreased in the following order: Cambisols > Acrisols > Fluvisols > Randzinas > Andosols > Lithosols and others.

2. Market access:

Since the purpose of the paper is to map potential areas for cocoa farming suitability, smaller distances to roads and water areas were indicative of higher suitability. Long distances from the road and river were ranked lower because they imply higher investments, transport, inputs and labour costs. Roads were a collection of national (Primary), regional (Secondary and tertiary) and local (Tracks and paths) vectors. Two water-related layers were merged into a single layer representing stream networks in the region. The information provides information on the major rivers, streams (a small river or stream) and riverbanks.

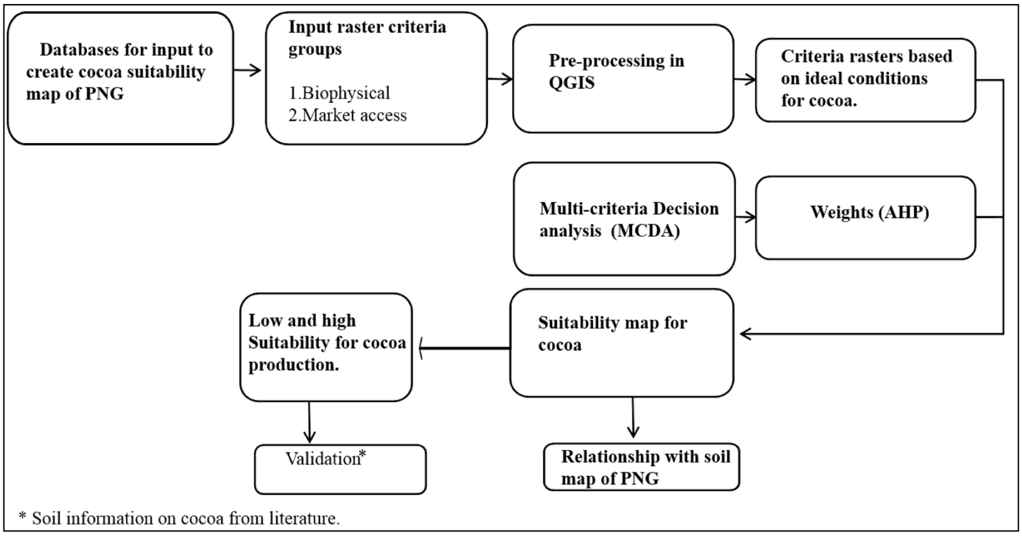
2.4. Decision criteria and site suitability map

The cocoa suitability map to locate areas was based on MCDA using AHP and pairwise comparisons. The AHP technique is one of the most commonly used MCDA tools, which applies an eigenvalue approach to the pairwise comparisons (Vaidya and Kumar, 2006), this process reduces the subjectivity associated with the definition of weights (Kazakis, 2018). The pairwise comparisons were carried out using the Saaty's pairwise comparison scale between criteria pairs (Saaty, 2012), which were treated independently. The scale ranges between 1, where both criteria are equally important, and 9, where one criterium is far more important than the other. Different pairwise comparisons were carried out to obtain a consolidated decision matrix through the geometric mean of individual matrices according to Eq. (1):

$$c_{i,j} = exp\left[\frac{1}{N}\sum_{i=1}^{N} \ln a_{i,j(k)}\right] \quad (1)$$

where c_{ij} is the consolidated decision matrix, being i and j the rows and

[1] In this article we will use the province name provided before the parenthesis; Chimbu (Simbu), Bougainville (North Solomons), West Sepik (Sandaun), and Oro (Northern Province).



1.Biophysical: Maximum temperature (⁰C); Rainfall (mm); and Slope (degrees) Downloaded from Google Earth Engine platform.

2.Market access: Road proximity (meters); and water proximity (meters). Downloaded from http://www.geofabrik.de/data/shapefiles.html.

Fig. 3. Flowchart of the methodology used in this study.

Table 1
Criteria and grade used for the cocoa suitability study.

Criteria groups	Criteria	Range	Rating	Suitability
Biophysical	Max Temperature (°C)	30–25	5	Exceptional
		25–21	4	High
		21–18	3	Moderate
		18–15	2	Low
		>15	1	Very low
	Rainfall (mm)	1800–2600	5	Exceptional
		2600–3300	4	High
		3300–4000	3	Moderate
		4000–5000	2	Low
		>5000	1	Very low
	Slope (degrees)	0–2	5	Exceptional
		2–5	4	High
		5–10	3	Moderate
		10–30	2	Low
		>30	1	Very low
	Soil capability	Andosol	5	Exceptional
		Phaeozems	4	High
		Cambisols, Fluvisols, Luvisols	3	Moderate
		Rendzinas	2	Low
		Acrisol, Lithosols, Histosols	1	Very low
Market access	Road proximity (meters)	<100	5	Exceptional
		100–300	4	High
		300–500	3	Moderate
		500–2000	2	Low
		>3000	1	Exceptional
	Water Proximity (meters)	<100	5	High
		100–300	4	Very
		300–500	3	Moderate
		500–2000	2	Low
		>3000	1	Very low

columns of the matrices, k is each participant, N the total number of participants, and $a_{ij(k)}$ corresponds to the decision matrix of each participant.

The AHP technique was evaluated through a Consistency Ratio (CR), which corresponds to the ratio between the consistency index of the pairwise comparison matrix (CI) and the consistency index of a random-like matrix, known as random index (RI), where values smaller than 0.1 are considered acceptable to continue the decision making analysis (Mu and Pereyra-Rojas, 2017).

The consistency index is estimated by Eq. (2):

$$CI = \frac{\lambda max - n}{n - 1} \tag{2}$$

where n is the number of compared elements (n = number of criteria) and λ_{max} is the largest eigenvalue of the matrix. All AHP analysis was carried out using the online AHP-OS software (https://bpmsg.com/ahp-online-system/) (Goepel, 2018).

The final map of site suitability was obtained using Eq. (3):

$$SI = \sum_{i=1}^{n} W_i R_i \tag{3}$$

where SI stands for suitability index (ranging from 1 to 5, being 5 the most suitable locations), W and R correspond to the weights and rating of each criterion (i), respectively. The site suitability map was subsequently reclassified into 5 classes which accounts for very low, low, moderate, high, and exceptional suitabilities. The pre-processing, reclassification and rating of all criteria layers and the obtaining of the suitability maps were done using the QGIS software (QGIS Development Team, 2009).

2.5. Soil capability and connectivity

In this study, a comparison between the soil map and the cocoa suitability map was made to identify soil capability under each suitability class. Although not used in this study, the soil maps also provide averages of some chemical parameters useful to understand the nutritional needs of cocoa condition management (mainly: pH (H_2O),%Clay, % Org.C, CEC, Base saturation, N, P), hence the soil chemical potential suitability and then determine the prospective fertiliser requirements. Additionally, independent soil data was used for validation to inform the soil connectivity aspect of the paper, simply by posing ‘where are farmers growing cocoa within PNG?’. The dataset used was taken from a study conducted on quantifying soil conditions under cocoa (Nelson et al., 2011).

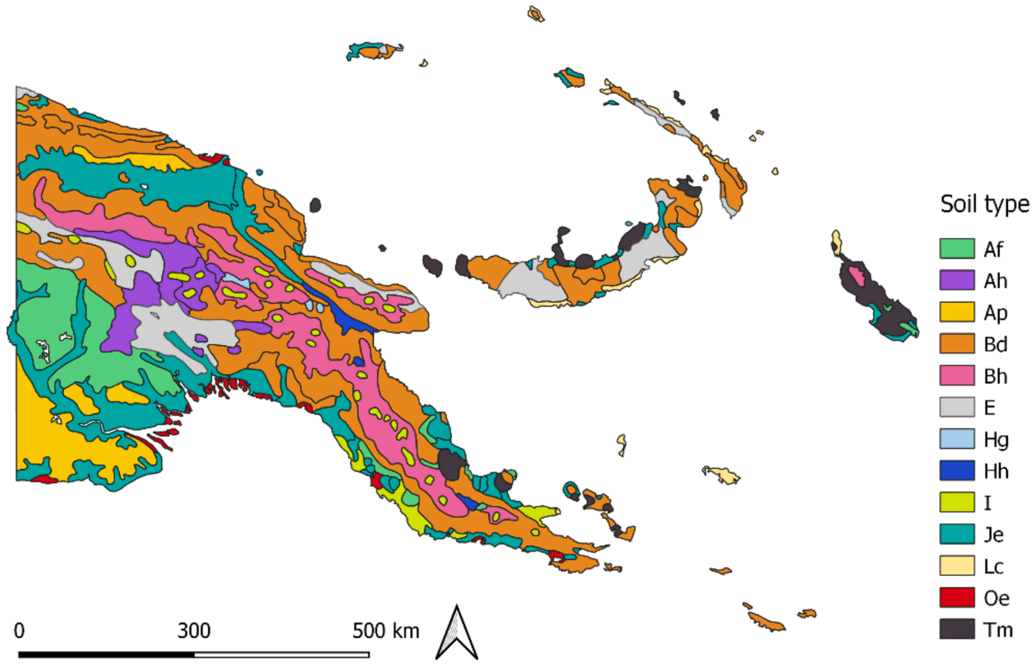


Fig. 4. Description of soil types. Ferric Acrisols (Af), Humic Acrisols (Ah), Plinthis Acrisols (AP), Dystric Cambisols (Bd), Humic Cambisols (Bh), Rendzinas (E), Gleyic Phaeozems (Hg), Haplic Phaeozems (Hh), Lithosols (I), Eutric Fluvisols (Je), Chromic Luvisols (Lc), Eutric Histosols (Oe) and Mollic Andosols (TM).

3. Results and discussion

3.1. Criteria maps

We used information from the literature for identifying classified criteria maps. In our view, the six criteria we selected to map cocoa suitability fulfil the objective of this paper and are commonly mentioned in the literature associated with the cocoa crop. They are straightforward to gather and include, temperature, precipitation, slope, and soil information in the biophysical category, and at supra-community level we included proximity to roads and water. The criteria maps show that temperature, precipitation and soil are predominant to determine sections within Western, Gulf and Central (along the west coast joining to National Capital District) province that have very low suitability for cocoa production (Fig. 5). These criteria maps are aimed at supporting a final product, a cocoa suitability map, and we expect these patterns will reflect in the end product. The slope gradient is one of the main factors creating the landscape and is generally associated with temperature (Paranunzio et al., 2019). In this case, slope and temperature seem to have an inversely proportional relationship. Overall, slope maps can highlight the importance of slope gradients and associated erosional and depositional environments and, therefore, dictate soil formation (Hanson et al., 1998).

In terms of market access, it can be seen the most prohibitive criteria, based on the area covered by very low suitability ranks, are those that relate to the distance to roads and water bodies. In PNG, it has been reported that the deteriorating conditions of basic infrastructures like roads and bridges are problems that affect both cocoa smallholder producers and the plantations (Aipi, 2012). On top of that, PNG physical geography presents major constraints on the provision of basic infrastructure and services such as roads (Curry et al., 2012). Cash crop development is hindered by major environmental constraints, and in some areas, by unreliable access to markets. Overall, the criteria employed in this paper are notable in integrating biophysical and supra-community level information, harnessing the multidisciplinary approach adopted for analysis.

3.2. Analytic hierarchy process

The comparisons between different criteria layers generate a consolidated decision matrix (table 4). Since the pairwise comparison matrix led to a consistency ratio (CR) of 0.008526, it was assumed as consistent and we continued with further stages of the decision-making process. Subsequently, the decision hierarchy for the evaluated criteria was calculated.

As it can be seen, precipitation, slope, road, and soil were ranked as the four most important criteria used. *Theobroma cocoa* L., the tree behind the much-loved chocolate, is especially vulnerable to changes in climate, such as, precipitation and temperature regimes (Hanson et al., 1998). Precipitation, which appears to be the dominant driver in cocoa success, has the greatest impact together with fluctuations in temperature. For example, Läderach et al. (2013) notes that high temperatures in humid tropical areas such as in Malaysia are ideal conditions for cocoa growing. However, production suffers when decreased water availability due to elevated evapotranspiration or drought conditions are coupled with higher temperatures. While it's demonstrated that climate have the strongest impacts on cocoa production, on the other end of the spectrum, pathogens such as black pod disease reaches its highest incidence following high rainfall and cool temperatures (Hanson et al., 1998; Oluyole et al., 2013; Oyekale 2012). Therefore, very high rainfall areas and very cold and hot areas were ranked lowest in this study (table 1).

More recently, studies Kahsay et al., 2018; Seyedmohammadi et al., 2019) have combined GIS technology and AHP with MCDA to use soil, slope, temperature, precipitation and roads as criteria to masque suitability areas. Additionally, we included stream networks as a level importance like temperature because some villages/islands transport cocoa on boats to bigger towns. An example is Manus Island in the north of PNG which supplies cocoa to East Sepik, Port Moresby (Capital city) or New Ireland on boats. Water as a criterion is also highly important since it depicts the medium where the water if needed can be available for irrigation in the evolving climate change scenarios. In our knowledge, the criteria chosen demonstrates their importance for cocoa suitability.

Table 2
Description of soil types and a reason for rank to classify soil based on soil capability.

Soil type	Soil capability	Rank
Ferric Acrisols (Af) Mostly formed on old land surfaces with hilly or undulating topography. Soil taxonomy: Ultisols with low-activity clays.	Ferric: ≥ 5% reddish to blackish concretions and/or nodules or ≥ 15% reddish to blackish coarse mottles, with accumulation of Iron (Fe) and Manganese (Mn) oxides. **Limitations:** have a higher clay content in the subsoil than in the topsoil and a low base saturation in the 50–100 cm depth. These can be strongly weathered acid soils with low base saturation at some depth. Increasing acidity and potassium chloride-extractable aluminium with depth often causes aluminium toxicity, limiting root elongation into the subsoil. A major limitation is due to segregation of Fe in a Ferric horizon that can lead to poor aggregation of the soil particles in Fe-depleted zones and compaction of the horizon. A plinthic horizon can create a hardpan or irregular aggregates fragments on exposure to repeated wetting and drying. It is moderately capable but in present condition requires fertilisation and management before cultivation as both physically and in respect of nutrients, these soils are poor for agriculture. **Impact on root:** Hostile sub-soil environment due to higher clay content in sub-soil, acidity and aluminium toxicity often hamper root elongation into the subsoil, thereby limiting available water supplies. Therefore, ranked 1 for cocoa production. **Suitable crop:** Acidity-tolerant cash crops such as pineapple, groundnut, finger millet, cashew and rubber can be grown with some success. Increasing areas of Acrisols are planted to oil-palm (e.g. in Malaysia and on Sumatra).	1
Humic Acrisols (Ah)	Humic: having ≥ 1% soil organic carbon in the fine earth fraction as a weighted average to a depth of 50 cm from the mineral soil surface.	1
Plinthic Acrisols (AP)	Plinthic: ≥ 15% (single or in combination) of reddish concretions and/or nodules or of concentrations in platy, polygonal or reticulate patterns; high contents of Fe oxides, at least in the concretions, nodules or concentrations.	1
Dystric Cambisols (Bd) Mostly on level to mountainous terrain. Soil taxonomy: Brown soils/Brown forest soils and are now under Inceptisols.	Dystric: Having a base saturation less than 50%. **Limitations:** These young alluvial soils have moderate to high productivity. Cambisols generally make good agricultural land and are used intensively. Commonly, a mottled subsoil with high silt and clay contents can cause root penetration issues. Therefore, soil can range from being well to imperfectly drained. **Impact on root:** depends on clay content of the sub-soil and due to this cocoa production is moderate to low, therefore, ranked as 3. **Suitable crop:** Cocoa, and cambisols with groundwater influence in alluvial plains are highly productive paddy soils.	3
Humic Cambisols (Bh)		3
Rendzinas (E) Mostly found on high or medium altitude. Soil taxonomy: Mollisol: Rendolls.	**Limitations:** On these limestone derived soils 'root room' is reduced due to physical impedance of root development, which combined with nutrient imbalances (high Ca:K and Mg:K) reduce the capacity of these soils to sustain viable yields. Fertlie due to a mollic horizon that contains or directly overlies calcaric material containing ≥ 40% calcium carbonate equivalent or that directly overlies calcareous rock containing ≥ 40% calcium carbonate. **Impact on root:** Although shallow these soils generally have moderate to high fertility levels, however, root penetration is a limitation because the excessive internal drainage and the shallowness can cause drought even in a humid environment. **Suitable crop:** There is some scope for tree crops on the uplifted coral terraces therefore ranked as 2.	2
Gleyic Phaeozems (Hg) Soil taxonomy: Dusky-red prairie soils where most of them now belong to Udolls under Mollisols.	Soil materials develop gleyic properties if they are saturated with groundwater (or were saturated in the past, if now drained) for a period that allows reducing conditions to occur (this may range from a few days in the tropics to a few weeks in other areas). **Limitations:** These soils can leach more intensively with a dark, humus-rich surface horizons. Phaeozems may or may not have secondary carbonates but have a high base saturation in the upper metre of the soil. These are porous, fertile soils and make excellent farmland, both in terms of fertility and physical properties. **Impact on root:** Cocoa root development is unrestricted. This is an important cocoa growing soil and with the well-structured tap root to >80 cm can be expected to produce close to maximum, if the genotype planted is suitable. At some instances these soils can have abrownupt textural change resulting in the tap root splitting and dividing at shallow depth. Therefore, these soil were not given a 5 rank, although these are capable of providing maximum cocoa yields. **Suitable crop:** Cocoa.	4
Haplic Phaeozems (Hh)	High potential for arable crops, tree crops and pasture.	4
Lithosols (I) Usually formed on steep slopes.	**Limitation:** Soils which are limited in depth by continuous coherent and hard rock within 10 cm of the surface. In brownoad terms, these soils are too shallow or stony for agriculture and there capacity and capability to be cultivated is extremely low even if the present condition is managed by terracing and removal of stones by hand (labour intensive). **Impact on root:** Lithosols have no	1

(continued on next page)

Table 2 (*continued*)

Soil type	Soil capability	Rank
	agricultural potential without radical soil management.	
Eutric Fluvisols (Je) These are formed on the Floodplains or tidal marshes. Soil taxonomy: Fluvents/Entisols	Eutric: Having a base saturation greater than 50%. **Limitation:** Fluvisols accommodate genetically young soils in fluvial, or river sediments. Many Fluvisols correlate with Alluvial soils and under natural conditions can be flooded periodically. The cocoa trees are tolerant to short periods of inudation. Soil profiles with evidence of stratification; weak horizon differentiation but a distinct topsoil horizon with high fertility may be present. **Impact on root:** Tap root development at times can be restricted due to high clay content and in an attempt to compensate the plant produces many large primary roots. Soil nitrogen and phosphorous levels can be very low, indicating soil would require fertiliser application following reclamation to improve cocoa yield. These soils are capable to produce higher cocoa yields but require management for better drainage. **Suitable crop:** Suitable for cocoa production alternatively paddy rice cultivation.	3
Chromic Luvisols (Lc) Soil taxonomy: they were formerly named Grey-brown podzolic soils and belong now to the Alfisols with high-activity clays.	Chromic (cr) (from Greek chroma, colour): having between 25 and 150 cm of the soil surface a layer, ≥ 30 cm thick, that has, in ≥ 90% of its exposed area, a Munsell colour hue red der than 7.5YR and a chroma of > 4. **Limitation:** Luvisols have a higher clay content in the subsoil than in the topsoil, as a result of pedogenetic processes (especially clay migration) leading to an argic subsoil horizon. Luvisols have high-activity clays throughout the argic horizon and a high base saturation in the 50–100 cm depth. **Impact on root:** In certain places, the dense subsoil causes temporarily reducing conditions with a stagnic colour pattern and restrict tap root penetration, therefore, ranked 3. In majority, these are fertile soils and suitable for a wide range of agricultural uses. **Suitable crop:** Suitable for cocoa and other tree crops such as coconut.	3
Eutric Histosols (Oe) Found at all altitudes, but the vast majority occurs in lowlands.	**Limitation:** Histosols comprise soils formed in organic material accumulating as groundwater peat (fen), rainwater peat (raised bog) or mangroves. Therefore, productivity potential ranked as very low. Although rich in carbon, Histosols often have high carbon to-nitrogen ratios, are quite acidic, and are deficient in some micronutrients. **Suitable crop:** Better left as potential source of carbon storage. Some areas have large timber (mangrove) resources.	1
Mollic Andosols (Tm) Soil taxonomy: Andisol.	Mollic: thick, dark-coloured, high base saturation, moderate to high content of organic matter, not massive and hard when dry. Soils containing a mollic epipedon are amongst the world's most productive soils (Liu et al., 2012). **Limitation:** Overall, these are one of the most productive soils of the world. These are volcanic ash and humic allophane soils and the transformation from fresh ash to a deep, productive andosol is quite rapid and usually takes as little as ten years. The natural fertility is high and is renewed by continuous weathering of minerals. At certain areas phosphate fixation may be an issue. **Impact on root:** Generally, the tap root can grow to more than 2.5 m, In certain areas a hardpan may occur within 50 cm of the surface it becomes evident when the cocoa trees are 3 −5 years old at which stage a large proportion topple over. Provided the cemented layer is identified and is brownoken up before planting hole is dug to below the depth of the pan, cocoa yields on these soils are expected to be high. **Suitable crop:** planted to a wide variety of crops including sugar cane, tobacco, sweet potato (tolerant of low phosphate levels), tea, vegetables, wheat, and orchard crops like cocoa, coffee and coconuts.	5

Table 3
Dominating soil types of PNG and its rating.

Soil type	Rating					
	1	2	3	4	5	Total
Ferric Acrisols (Af)	8.04					8.04
Humic Acrisols (Ah)	4.59					4.59
Plinthis Acrisols (AP)	6.46					6.46
Dystric Cambisols (Bd)			33.42			33.42
Humic Cambisols (Bh)			10.81			10.81
Rendzinas (E)		8.76				8.76
Gleyic Phaeozems (Hg)				0.24		0.24
Haplic Phaeozems (Hh)				0.64		0.64
Lithosols (I)	2.56					2.56
Eutric Fluvisols (Je)			18.47			18.47
Chromic Luvisols (Lc)			1.23			1.23
Eutric Histosols (Oe)	1.12					1.12
Mollic Andosols (Tm)					3.66	3.66
Total	22.77	8.76	63.93	0.88	3.66	100%

3.3. *Cocoa suitability*

The suitability map obtained from the AHP is presented in Fig. 6. Five major cocoa suitability classes were identified using the three biophysical and two market access criteria. An assessment of the areas covered by the different suitability classes is presented in Table 7.

Biophysical limitations, such as pronounced dry seasons, are compartmentalized in the Central, Gulf, and Western (Fly) provinces that have low suitability for cocoa. Our results (Fig. 6) shared a similarity with the map produced by Hanson et al. (1998) (Fig. 2):

1 The maps have a similar pattern for most areas such as Central, Gulf, and Western (Fly), where the areas are either unsuitable for cocoa production or have very low potential. This is clearly

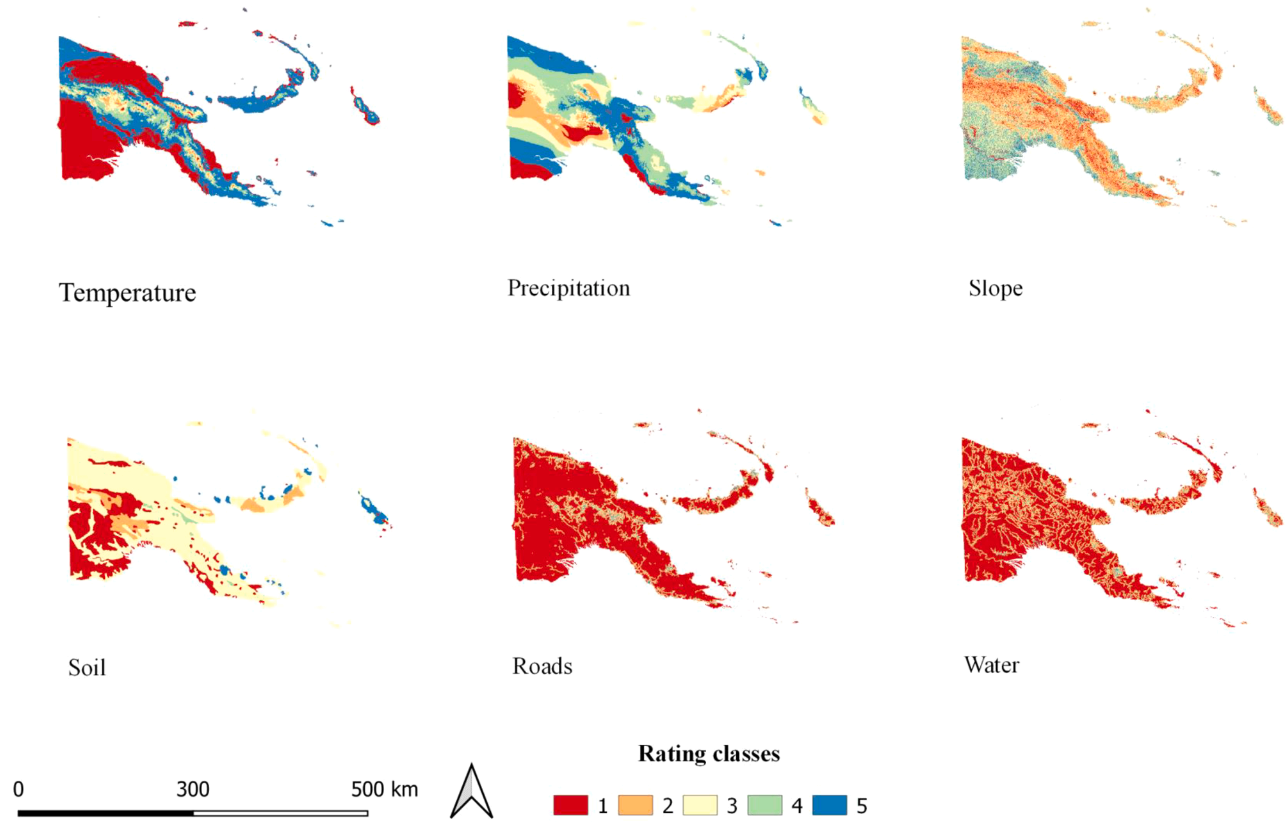


Fig. 5. The criteria maps with rating classes.

Table 4
Different weighting schemas for the groups of variables (Table 1) used in the MCDA analysis.

Weights	Temperature	Rainfall	Slope	Soil	Roads	Water	CR
Group result	0.128	0.252	0.184	0.148	0.163	0.126	0.009

Table 5
Consolidated pairwise comparison matrix obtained through the AHP technique. Values close to 1 mean variables have equal importance, values smaller or greater than 1 indicate smaller or greater importance of the row criteria compared to the column criteria.

	Temperature	Precipitation	Slope	Soil	Roads	Water
Temperature	1	0.420	0.562	1	0.945	1.074
Precipitation	2.378	1	1.681	1.565	1.414	1.565
Slope	1.778	0.594	1	1.189	1	1.681
Soil	1	0.638	0.840	1	0.840	1.316
Roads	1.057	0.707	1	1.189	1	1.189
Water	0.930	0.638	0.594	0.759	0.840	1

Table 6
Decision hierarchy of MCDA.

Criteria	Priority percent	Rank
Temperature	12.8%	2
Precipitation	25.2%	6
Slope	18.4%	5
Soil	14.8%	3
Roads	16.3%	4
Water	12.6%	1

reflected in Fig. 5 with unsuitability due to temperature, precipitation, soil and access,

2 Exceptional areas around Rabaul and Kokopo in East New Britain, areas around Popendetta, and Bougainville are identified in both maps where almost all criterias used are highly suitable.

Some new areas suitable for cocoa production are also identified:

1 The map from this study shows moderate suitability in East Sepik, for example, moving east from the main city of Wewak, Yangoro-Saussia, Maprik, Wosera-Gawi, Ambunti-Dreikikir and Angoram due to favourable bio-physical conditions,
2 The map identifies high potential to grow cocoa in Aitape-Lumi and Vanimo in West Sepik, and

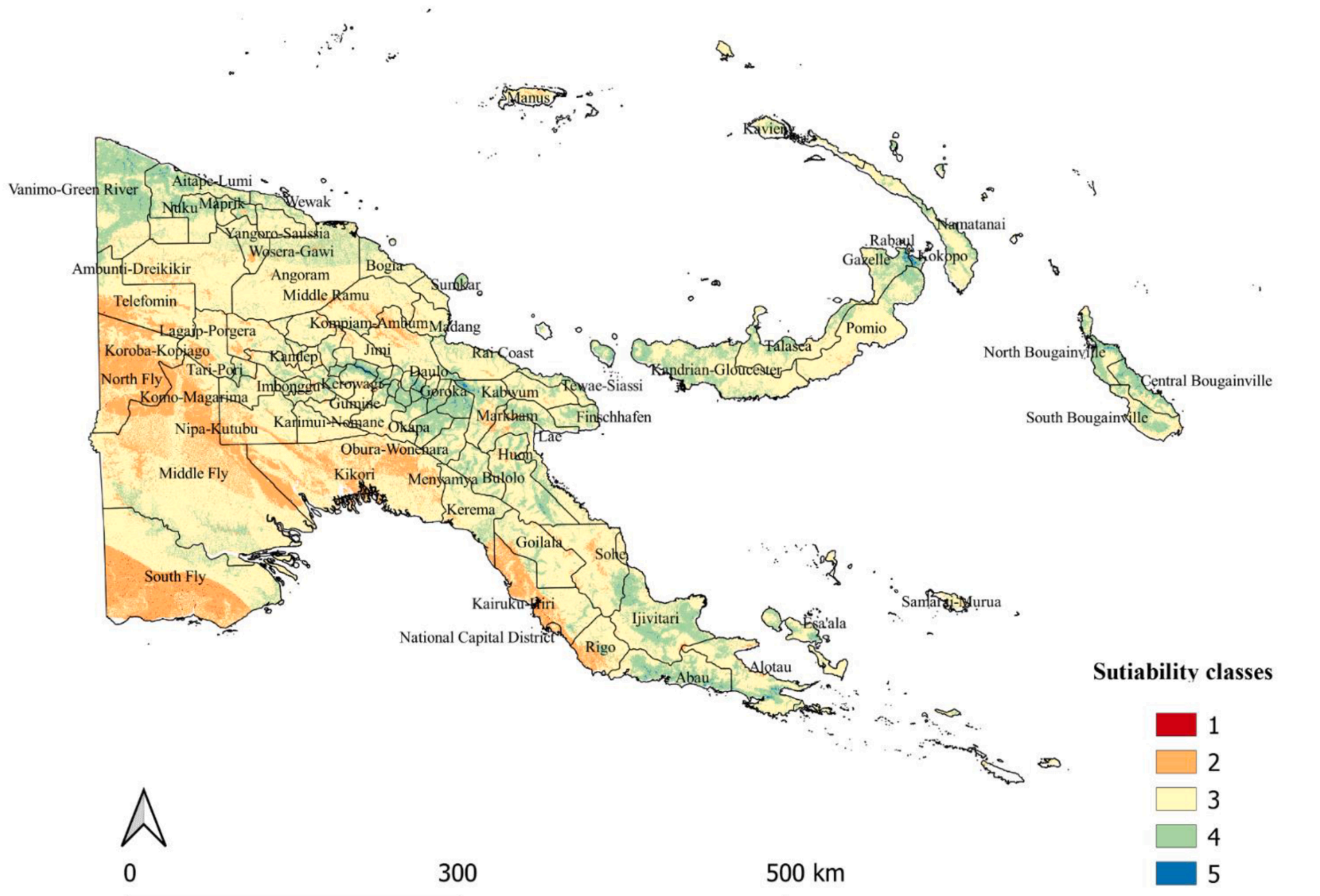


Fig. 6. Suitability classes map on a boundary map of PNG obtained by coupling the reclassified criteria maps and the AHP technique. Fig. 3. An outline map of Papua New Guinea with labelled provinces. The following provinces within the region are labelled; Highlands Region: Chimbu (Simbu), Eastern Highlands, Enga, Hela, Jiwaka, Southern Highlands, and Western Highlands; Islands Region: East New Brownitain, Manus, New Ireland, Bougainville (North Solomons), and West New Brownitain; Momase Region: East Sepik, Madang, Morobe, and West Sepik (Sandaun); and Southern Region: Central, Gulf, Milne Bay, Northern Province (Oro), and Western (Fly).

Table 7
The percent area covered by cocoa suitability class.

Class	% Area	Area in Km^2
1	0.11	476
2	13.76	62,101
3	67.82	306,133
4	17.91	80,858
5	0.40	1787

3 Pomio in East New Britain, and a major stretch within West New Britain may show low to moderate suitability under the current scenario for cocoa suitability.
4 Last but not the least, the map created in this study shows potential to grow cocoa in the highlands, especially, Chimbu (Simbu), Eastern Highlands, Enga, Hela, Jiwaka regions. Observing the cocoa suitability map and consulting the literature, areas of highlands that have high and moderate potential are Goroko, Tari-pori and Kandep, and Jimi, Koroba, and Kompiam respectively (Schmid et al., 2001).

The ongoing cocoa establishment work in the highlands of PNG will have significant implications for local farmers and other regions across the globe where similar biophysical properties exist. This is not a typical case for where cocoa can be grown in PNG and globally. The cocoa suitability map can identify the areas in highlands that have high suitability for cocoa production (Fig. 6). A recently published article on Australian Centre for International Agricultural Research (ACIAR) website called "Cocoa in PNG climbing to new heights" has reported cocoa growing in PNG highlands (ACIAR, B. 2020). The report provides evidence that cocoa can be grown 800 m above sea level. In PNG, this creates a critical need for re-defining ideal conditions for cocoa production. This first vision of cocoa growing in the highlands of PNG can contribute positively to local farmers. Where cocoa blocks are seen to offer significant regional and national economic benefits, instruments such as subsidies and research and development funding may be used to promote this. Through the ongoing research and development work, it was observed that cocoa trees are growing at elevations higher than 1600 m in Karimui (Chimbu) and in Pangia (Southern Highlands). While further work is required, the cocoa suitability map, in concert with recent effort provides a significant opportunity to drive the establishment of new cocoa blocks in the Highlands of PNG. Additionally, it also represents an opportunity for researchers around the world to look at cocoa varieties for higher altitudes.

The potential for what are today speculative options of cocoa growing at higher altitudes to transition into multifunctional landscapes highlights the case for adopting an expansive view that covers not only the maintenance of existing cropping systems but also the establishment of new ones. By this we mean, a diversified system where cocoa can grow as a companion tree or a monocrop. Cocoa production systems typically employ shade trees to provide sun protection to the understory cocoa trees and generally, there may be a positive interaction with soil chemical fertility (Beer, 1987) due to the leaf-litter nutrient contributions to the soil (Santana and Cabala-Rosand, 1982).

Additionally, the average temperatures in the cocoa belt, as elsewhere, are predicted to increase through global climate change, evapotranspiration and thus tree water demand are expected to surge as well. This could lead to increased drought stress of cocoa trees, especially during the dry season (Läderach et al., 2013). Thus, it is reasonable to assume that water availability during the dry season (May -October) will play a key role in determining the future climatic suitability of the PNG cocoa belt for cocoa farming (Carr and Lockwood, 2011). This will have biophysical and socio-economic implications on cocoa production system. As it stands, the access to and cost of labour may be a key driver in observed yield trajectories (Wood, 1975), and it's expected that more hours will be required to cater for unprecedented conditions. Cocoa production and the associated management of soil are generally labour intensive (i.e. 340 man-days per acre in the first year in PNG). For the criterias used in this study, management options presently exist to overcome constraints, for example, temperature can be controlled by shade trees and planning planting zones, irrigation can complement rain, to overcome slope issues cocoa can be planted in contours, however, zero or very long-distance access to the road is the worst constraint. Finally, the management of soil conditions requires adequate investment, which is rarely done and can be labour intensive and increases in the direction of hierarchical management (Konam et al., 2011).

3.4. Soil capability

Partly, soil capability refers to the presence or absence of soil limitations relevant to production of cocoa (Table 2), and as simple as 'will this soil allow us to produce cocoa?'. Root depth and stoniness are a good examples of soil capability (Field and Sanderson, 2017) and are used to classify soil suitability in this present case. As expected, on comparing cocoa suitability with the 13 soil types used in this study, the suitable soils i.e. Humic Cambisols, Gleyic Phaeozems, Chromic luvisols, and Mollic Andosols do not contribute to forming class 1 of the cocoa suitability map, on the other hand the low suitability soil type i.e. Plinthic Acrisols have zero participation in forming class 5 (Table 8). The Acrisols collectively contribute mainly to class 2 and class 3 of cocoa suitability, similarly, Rendzinas, Lithosols, and Eutric Histosols contribute to class 2 and 3, and Eutric Fluvisol and chromic Luvisol to class 3. Mollic Andosols and Phaeozems contribute majorly to class 4 and 5.

When considering the cocoa suitability class, most soils that were ranked low based on soil capability form class 1, 2 and 3. However, some soil types that were ranked very low for example, Acrisols, Lithosols and Histosols turned out to be moderately suitable for cocoa, the reason for this could be the other criterias are highly suitable within the given area (i.e. rainfall, slope and access to roads and water).

One limitation is that the soil map is very broad, 13 soil groups within PNG, therefore, spatially continuous soil data that are accurate at local scales is required and its collection should be prioritised. At present, soil information is scant due to limited soil sampling surveys; however, a future iteration of this concept will benefit from empirical soil information to further contextualize soil, climate and cocoa suitability changes across spatial and temporal scales.

Table 8
Percent area for soil types in each suitability class.

Soil type	Suitability class 1	2	3	4	5
Ferric Acrisols (Af)	0.121	51.844	46.697	1.331	0.007
Humic Acrisols (Ah)	0.015	15.649	73.746	10.572	0.019
Plinthis Acrisols (AP)	1.047	35.454	62.446	1.053	0.000
Dystric Cambisols (Bd)	0.011	7.614	69.923	22.246	0.206
Humic Cambisols (Bh)	0	1.071	79.464	19.202	0.264
Rendzinas (E)	0.008	9.565	80.624	9.796	0.007
Gleyic Phaeozems (Hg)	0	0	7.078	79.250	13.672
Haplic Phaeozems (Hh)	2.914	6.104	42.201	48.301	3.394
Lithosols (I)	0.310	35.409	58.905	5.370	0.007
Eutric Fluvisols (Je)	0.067	11.860	70.712	17.167	0.194
Chromic Luvisols (Lc)	0	2.638	73.657	23.690	0.015
Eutric Histosols (Oe)	1.012	38.591	51.472	8.808	0.117
Mollic Andosols (Tm)	0	0.045	32.445	64.862	2.648

3.5. Soil connectivity

Upon validating the classes against the dataset from Nelson et al. (2011), it can be seen that 72% of cocoa from the previous survey (see supplementary figure 2a) is grown on class 4, 24% on class 3 and 4% on class 5 (Table 9). This shows that majority of cocoa is growing in areas identified as highly suitable for cocoa and may have a level of soil understanding. Soil connectivity is a central desire for smallholders to use local knowledge for land-use decisions. PNG plans to dramatically increase its current road extent (Alamgir et al., 2019) in the coming years to promote economic development. If road development occurs as currently planned, it will have substantial impacts on production systems (Schmid et al., 2001). As the cocoa suitability map is based on available spatial information, it requires extensive consultation and agreement by the community through cultural mapping. This also ensures the continued use, support and reinvigoration of traditional soil knowledge, and here we validate that with scientific knowledge.

Globally, cocoa farmers develop intuitive knowledge of the condition and capability of their soils over time through observations. Farmers often identify the suitability of a soil for cocoa production by the presence of dark soils, good soil depth, limited soil compaction, good texture ((Ollier et al., 1971) Isaac et al., 2009; Dawoe et al., 2012; Kome et al., 2018; Wartenberg et al., 2018), and the presence of numerous earthworms (Dawoe et al., 2012; Wartenberg et al., 2018). Cocoa farmers in southwestern Nigeria are known to name soils on the basis of their suitability (Osunade, 1988). One of the earliest soil local knowledge in PNG has been reported amongst the highlanders (Bleeker 1983). PNG farmers classified their soils on four major criterias; particularly, what they have classified as reddish, and alluvial would perhaps be Rendzinas and Fluvisols, respectively. A recent study from hilly region of Central Vietnam combined scientific and local knowledge in land assessment based on GIS technology, MCDA-AHP, and PRA methods successfully for land evaluation (Herzberg et al., 2019).

3.6. Future work

In this paper, we have shown the links between cocoa suitability mapping and soil capability. Although we have only explored single function of soil i.e. 'biomass production', this approach can be used for other functions. As an example, the areas compartmentalized in the Central, Gulf, and Western (Fly) provinces that have low suitability for cocoa, such as, the peatland of Gulf Province provides opportunities for carbon pool development plan (Alamgir et al., 2019). Offsets could be obtained by not altering current land-use in these provinces- to reduce carbon emissions to sequester carbon in peatlands. This links to the 'Soil Capital' dimension within the soil security framework, where, soil condition i.e. the organic carbon content is the currency of this natural capital.

Within the framework of soil security, condition refers to the necessary state of soil that would enable cocoa production and requires us to assess 'will this soil continue to support cocoa production into the future?'. Simply put, this is an assessment of soil conditions (Table 9-colour red indicate where the values are below threshold and green above threshold for cocoa production) that can be easily manipulated for cocoa production (Field and Sanderson, 2017). This opens opportunities (Kidd et al., 2015) to dive into application of digital soil assessments (DSA) and digital soil mapping (DSM) for soil connectivity and codification purposes. In future, the maps created can also serve as a basis for developing fertiliser formulas adapted to the regions and even

Table 9
Description of condition of the soil data points used for validation. The colour red indicate where the values are below threshold and green above threshold for cocoa production.

Provinces	Clay	Texture description	C	N	P	K	Class	Soil
Bougainville	30	dark brown, sandy loam	2.16	0.26	6	0.19	4	Lc
Bougainville	20	dark brown, silty clay loam	1.68	0.20	24	0.33	4	Tm
Bougainville	20	black, clay loam	2.52	0.18	5	0.05	4	Tm
Bougainville	23	very dark grey brown, sandy loam	1.33	0.12	9	0.43	4	Tm
East Sepik	23	very dark grey brown, loam	1.65	0.16	15	0.21	4	Bd
East Sepik	15	dark brown, light clay	1.86	0.17	2	0.13	4	Je
East Sepik	35	dark brown, medium clay	1.40	0.16	6	0.04	4	Bd
East Sepik	38	dark brown, medium clay	2.82	0.27	12	0.41	3	Bd
East Sepik	35	dark brown, medium clay	3.42	0.41	12	0.03	3	Bd
East Sepik	35	dark red brown, loam	2.37	0.24	9	0.07	3	Bd
East Sepik	30	very dark brown, sandy loam	2.29	0.21	11	0.12	4	Bd
East Sepik	23	very dark brown, sandy loam	1.08	0.11	16	0.22	4	Je
ENB	30	black, sandy loam	2.96	0.33	71	2.15	4	Tm
ENB	30	dark brown, clay loam	3.77	0.39	61	2.16	4	Tm
ENB	28	dark yellow brown, sandy clay loam	2.97	0.31	26	2.55	4	Bd
ENB	28	red brown, sandy clay loam	2.27	0.24	160	1.44	4	Tm
ENB	30	dark brown, light clay	2.52	0.30	35	2.37	4	Tm
ENB	28	dark red brown, light clay	2.69	0.29	67	3.12	4	Tm
ENB	23	dark red brown, light clay	1.72	0.15	17	1.59	4	Tm
ENB	38	dark brown, sandy clay loam	2.86	0.29	72	2.90	4	Tm
ENB	35	dark red brown, light clay	2.43	0.26	13	0.91	5	Bd
Madang	40	dark brown (with white mottle), light medium clay	2.46	0.24	23	0.42	3	Bd
Madang	36	very dark grey brown, light clay	4.34	0.42	16	0.48	4	Tm
Madang	43	very dark grey brown, loam	3.87	0.44	16	1.09	4	Tm
Madang	38	brown, silty loam	2.63	0.25	48	0.28	4	Bd
Madang	35	very dark grey brown, light clay	4.87	0.41	9	0.19	3	Bd
Madang	43	black, silty clay loam	1.74	0.21	64	1.38	4	Je
Madang	35	black, silty clay loam	3.36	0.36	27	0.82	4	Bd
Madang	40	very dark grey, loam	2.73	0.25	15	0.83	3	Je
Morobe	28	very dark grey, loam	2.08	0.21	42	0.10	4	Bd
Morobe	20	very dark grey, sandy loam	2.27	0.19	21	2.31	5	Hh
Morobe	20	very dark grey brown, loam	4.59	0.36	9	0.34	4	Hh
Morobe	30	dark red brown, light clay	6.30	0.44	14	0.23	4	Bd
NIP	18	dark brown, sandy loam	2.40	0.22	7	0.04	4	Bd
NIP	30	very dark grey brown, medium clay	2.83	0.31	50	0.03	3	Lc
NIP	35	black, medium heavy clay	2.92	0.35	107	0.07	3	E 3
NIP	35	dark brown, light medium clay	3.73	0.36	89	0.31	4	Bd
NIP	20	dark grey brown, medium clay	2.97	0.26	4	0.07	4	Bd
Northern	25	dark grey brown, coarse sandy medium heavy clay	5.04	0.33	18	0.16	4	Je
Northern	25	dark grey brown, light clay	3.72	0.34	35	0.11	4	Tm
Northern	33	dark grey brown, light clay	7.73	0.63	26	0.42	3	Bh
Northern	33	dark grey brown, light medium clay	5.06	0.45	15	0.10	4	Tm
Northern	30	very dark grey brown, light clay	1.98	0.18	23	0.20	4	Tm
Northern	28	dark grey brown, loam	2.57	0.23	6	0.16	4	Bd
West Sepik	35	dark grey brown, light clay	1.80	0.18	25	0.14	3	Bd
West Sepik	33	very dark grey brown, light clay	2.04	0.23	28	0.29	4	Bd
West Sepik	35	very dark brown, loam	2.50	0.23	14	0.08	4	Je
West Sepik	30	very dark grey brown, light clay	2.93	0.18	21	0.12	4	Bd
WHP	23	dark brown, sandy clay loam	2.52	0.25	96	0.66	3	Bd
WHP	30	dark brown, light clay	2.72	0.31	33	0.41	3	Bd

farmers' fields for intensification and minimising deforestation through expansion. For example, indicators of soil under cocoa's condition may be readily inferred by observing yields, both across soils and time, which vary readily with underlying chemical fertility and pH (Smythe, 1966; Quansah et al., 2001). Indeed, the soil units' chemical parameters could be complemented by a few, but simple parameters collected directly in the cocoa fields (e.g., real soil pH, leaf deficiencies, soil colour, depth and aspect, associated trees). Combining the soil map and field parameters makes it possible to determine the most appropriate commercial fertiliser formula (Snoeck et al., 2018) against which changes in suitability over space and time can be quantified (Kahsay et al., 2018).

4. Conclusion

The combined use of MCDA and GIS is an innovative tool for the selection of suitable sites for cocoa. Rainfall, slope, and soils presented the higher ranks amongst experts when evaluating different land suitability criteria for cocoa orchards. By using publicly available data in a low local data environment, these techniques can be used in combinations with AHP for a consistency assessment. This information was used to generate a cocoa suitability map. Compared with data from a previous cocoa productive potential map, our results resemble potential areas but also show a potential for cocoa expansion towards highlands. A large proportion (80%) of current cocoa orchards occurs in highly and exceptionally suitable classes for cocoa plantations. Additionally, a former soil condition study confirms that the generated map provides an agile step towards connecting the links between soil capability, soil connectivity, and cocoa suitability. The present results, combined with local soil chemical data, could be used to assess fertiliser requirements for farmers, but this is a matter for future research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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