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Resources Conservation
Service; United States
Agency for International
Development; and the
International Center for
Tropical Agriculture in
cooperation with
Penn State University

Soil and Cacao Genomics Survey of Sierra Nevada de Santa Marta Region, Colombia

Cover Caption

The cover photo was taken from foothills in the north-central part of the survey area. The view is to the northwest over the northern part of the survey area and shows an area of mixed agriculture and residential development.

The landscape of Sierra Nevada of Santa Marta Region resulted mainly from erosion deposits, which originated from the slopes of the uplifting mountain ranges. The Sierra Nevada of Santa Marta Region is in northern part of Colombia. The area is experiencing an expansion of urban dwellings as a result of population pressure and prolonged and frequent droughts.

Disclaimer

The soil survey and cacao genomics report will be published online. Rasterized maps that delineate soils, properties, and interpretations and include the characteristics of the cacao genomics will be freely available to the public. The soil information and maps are not suitable for site-specific managment.

About This Survey

How To Use This Survey

This publication consists of text, tables, and maps. The text includes descriptions of detailed soil map units and plant genetics layers. It provides an explanation of the information presented in the tables. It also includes a glossary of terms used in the text and tables and a list of references.

The links below can be useful in planning the use and management of small areas. The plant genetics layers in the map can be useful for understanding the distribution and types of cacao genetics found on farmers' fields. A geographic information system (GIS) in the Arc-GIS platform was developed in conjunction with this document. This GIS is useful for exploring the data and understanding the soils and genetic diversity of cacao in the region. Data acquired during the survey and after laboratory analysis were combined to create the database underlying the Arc-GIS platform for the Cacao for Peace project (CfP) in the Sierra Nevada de Santa Marta (SNSM).

To find information about your area of interest, locate that area on the online map. Note the map unit symbols that are in that area. Go to the Contents, which lists the map units by symbol and name and shows where each map unit is described. You can view the specific location of each plant and follow the links to photos, genetic data, and a summary of the genetic id for each sampled tree. Also see the Contents for sections of this publication that may address your specific needs.

This soil survey report will be published on line. Rasterized maps that delineate soils, properties, and either interpretations or suitability ratings will also be freely available to the public. The soil information and maps are not scaled for specific, onsite management decisions.

Arc-GIS Soil and Cacao Genetics Resource Links

Following is a link to a GIS-based website that provides information from the survey.

https://arcg.is/1HmGrL

Following are links to data layers for tree samples, soil samples, and soil profile descriptions for the Cacao for Peace project.

Tree Samples

https://services.arcgis.com/SXbDpmb7xQkk44JV/arcgis/rest/services/CfP_Tree_Samples/FeatureServer

Soil Samples

https://services.arcgis.com/SXbDpmb7xQkk44JV/arcgis/rest/services/CfP_Soil_Samples/FeatureServer

Soil Profile Descriptions

https://services.arcgis.com/SXbDpmb7xQkk44JV/arcgis/rest/services/CfP_Soil_Profile_Descriptions/FeatureServer

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Acknowledgments

The completion of this project would have not been possible without the support of the United States Agency for International Development (USAID), the United States Department of Agriculture (USDA), the International Center for Tropical Agriculture (CIAT), Pennsylvania State University, the Foreign Agriculture Service (FAS), the Colombian Cacao Producers Federation (FEDECACAO), and the United Nations Office against Drugs and Crime (UNODC). The support of the Colombian Government and participation of many individuals and farmers have also been crucial for the success of this project.

We thank our colleagues at FAS for their technical, administrative, and logistical support, without which this project would not have been possible. We are grateful for the funding provided by USAID and for the vision and leadership provided by the FAS Program Manager and staff in Colombia. They helped us navigate through various challenges and obstacles from project design through implementation. Finally, we would like to thank the NRCS leadership for their flexibility, unwavering commitment, and willingness to share soils information technology and applications with the rest of the world and particularly with the people of Colombia.

We would like to thank the NRCS colleagues, scientists, leaders, and administrative staff, including Lillian Woods, Dave Lindbo, Michael Robotham, and Paul Reich, and the International Center for Tropical Agriculture (CIAT) for support with staff, laboratory analysis, soil-map development, field work, accommodations, and other logistics.

This project was not without setbacks, but working together we surmounted these challenges to get to the finish line. We are very proud of what we have accomplished together, and we are hopeful that the deliverables are within or beyond expectations and will set the stage for future collaborations.

In addition to the Cacao for Peace team members, we would like to thank the following people whose contributions made this project possible:

- Marita McCree, NRCS International Programs Division (IPD), for international travel facilitation, notably passport and visa acquisitions, host country regulations, and country clearances.
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- Lillian Woods, IPD, for overall project support and assistance with interagency agreements, particularly for attending many long interagency and interinstitutional planning and implementation teleconferences with national and international partners.
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- Amber Kenjar for arrangements to ship soil samples from Colombia to Lincoln, Nebraska.
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- Cesar Botero for coordinating the field work and the soil sample processing and analysis.
- Jaime VanClief and Andres Romero, FAS, for facilitating funding and for entrusting the SPSD with demonstrating the value and utility of soils information and related delivery tools. This information improves agricultural productivity, sustainable land use, and environmental stewardship, thereby benefiting farmers and society as a whole.

Finally, we express our sincere gratitude to the leadership of USDA–NRCS for authorizing NRCS to participate in this unique project, for their continued support to advance the SPSD international soils program, and for the confidence they bestowed on the Cacao for Peace team to plan, design, and execute this project.

Soil Services and Information Branch

This survey is a publication of the Soil Services and Information Branch of the United States Department of Agriculture, Natural Resources Conservation Service, Soil and Plant Science Division. It was written in collaboration with the International Center for Tropical Agriculture (CIAT) in Cali, Colombia, and Pennsylvania State University. Funding was provided by United States Agency for International Development (USAID); and administrative assistance was provided by the United States Department of Agriculture (USDA), Foreign Agriculture Service (FAS). The online maps from this survey may be copied without permission. Enlargement of a map, however, could cause misunderstanding of the detail of mapping. If enlarged, the maps do not show the small areas of contrasting soils that could have been shown at a larger scale.

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Preface

This soil and cacao genomics survey was developed cooperatively by United States Agency for International Development (USAID) and United States Department of Agriculture (USDA) in conjunction with the International Center for Tropical Agriculture (CIAT), Pennsylvania State University, Foreign Agriculture Service (FAS), Colombian Cacao Producers Federation (FEDECACAO), and United Nations Office against Drugs and Crime (UNODC) as part of the Cacao for Peace (CfP) Initiative. The CfP seeks to improve rural well-being in Colombia through agricultural development that is inclusive and sustainable and has a positive impact on cacao farmer's incomes, economic opportunity, stability, and peace. The CfP is analyzing soil, water, and genetic characteristics in the Sierra Nevada de Santa Marta Region. The successful implementation of the CfP initiative requires a detailed soil survey to support natural resource management and field conservation practices. The data are intended to serve as the source document for soils within the designated borders of the Sierra Nevada de Santa Marta Region.

This survey contains information that affects current and future land-use planning in Sierra Nevada de Santa Marta. It contains predictions of soil behavior for selected land uses and information on major genetic groups of cacao trees. The survey highlights soil limitations, actions needed to overcome the limitations, and the impact of selected land uses on the environment. It is designed to meet the needs of Colombian farmers to better understand the properties of the soils, the genomics of the cacao plants, and the effects of these properties on various natural ecological characteristics. This knowledge can help the local cacao growers to understand, protect, and enhance the soil resources and to grow suitable cacao varieties in the region.

The report is intended to identify soil properties that are used in making various land use or land treatment decisions and to identify the major cacao plant genomes in the area. Statements made in this report are intended to help the land users identify and reduce the limitations on various land uses.

Soil properties that affect land use are described in this survey. The location of each map unit is shown on the detailed soil map. Each soil in the survey area is described, and information on specific uses is given. Help in using this publication and additional information are available at the International Center for Tropical Agriculture (CIAT) and online. The soil maps and field data collected and processed for the CfP initiative are available on web-based platforms and apps for portable devices, such as cellular phones.

This project lays the foundation for the continuation of the CfP Initiative. The initiative supports the priorities of the Government of Colombia and works to ensure sustainable growth in the agricultural sector. The initiative has the goal of increasing farmer incomes by increasing cacao yields and improving cacao quality. Drawing upon innovations and lessons learned from the historical development of conservation in the United States, NRCS has been able to provide technical assistance and to collaborate in many ways in the planning, design, and implementation of the project.

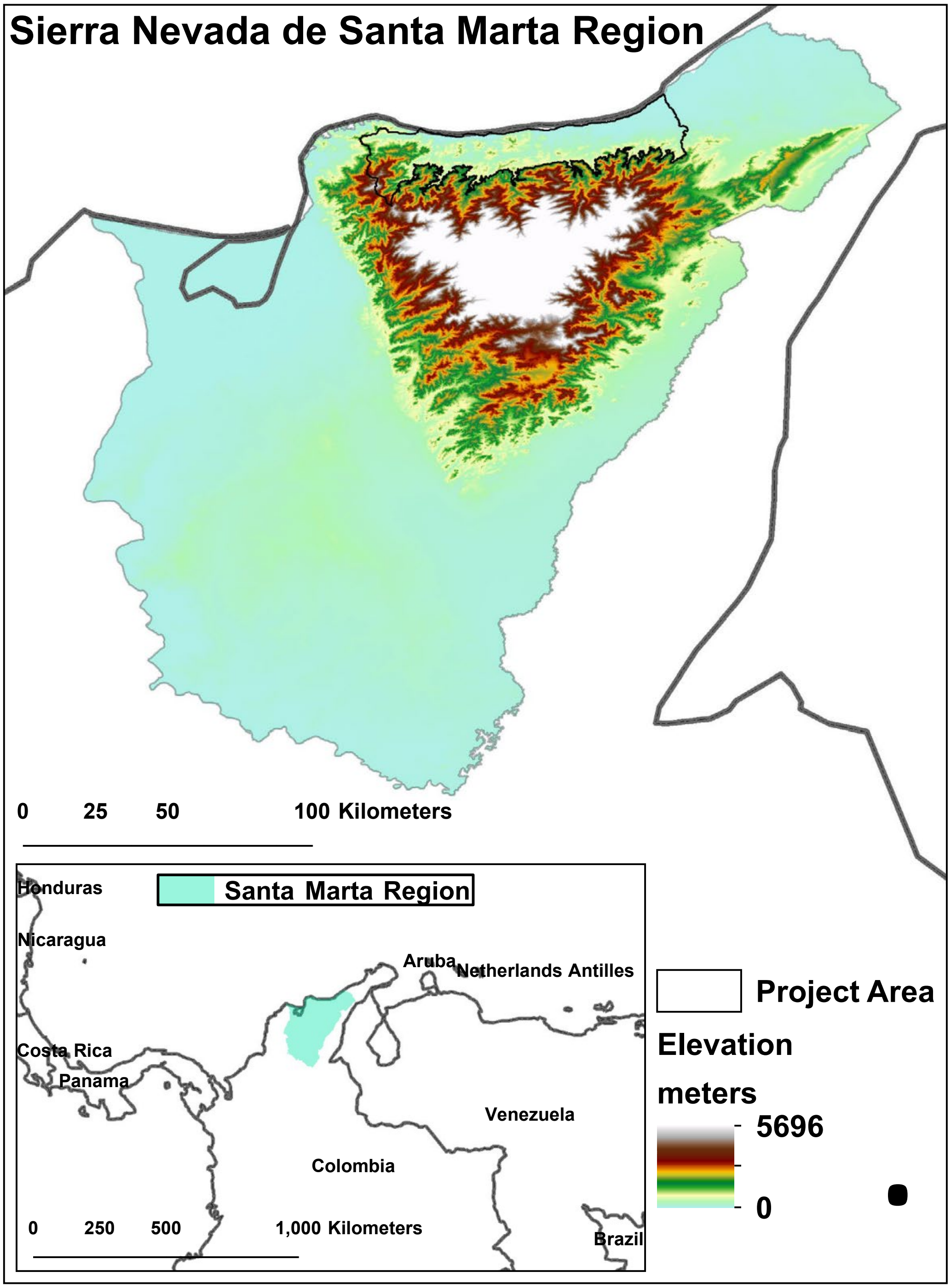

Figure 1.—Elevation and location of Sierra Nevada de Santa Marta Region showing the boundaries of the soil survey project area

Soil and Cacao Genomics Survey of Sierra Nevada de Santa Marta Region, Colombia

By Libohova, Z.,[1] J.M. Martín-López,[2] M. da Silva[2], C. Lagoueyte,[1] J. Cruz,[1] P. Drohan,[3] S. Maximova,[3] M. Guiltinan,[3] M.G. Ferruzzi,[1] D. Guarín,[3] P. Reich,[1] C. Kome,[1] Y.P. Zapata,[2] G. Gallego-Sánchez,[2] C. Quintero,[2] C. Botero,[2] N.P. Winter,[3] and M. Robotham[1]

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[2] International Center for Tropical Agriculture (CIAT)
[3] Pennsylvania State University

This survey was made collaboratively by the United States Department of State; the United States Agency for International Development (USAID); and the United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) and Foreign Agriculture Service (FAS); the International Center for Tropical Agriculture (CIAT); Pennsylvania State University; and other partners. The survey provides information about the soils, cacao genomics, and miscellaneous areas in the Sierra Nevada de Santa Marta region (fig. 1).

How This Survey Was Made

The survey was initiated as part of the Cacao for Peace Initiative. The successful implementation of this initiative requires a detailed soil survey to support natural resource management and field conservation practices.

The USDA Foreign Agriculture Service (FAS) in cooperation with International Center for Tropical Agriculture (CIAT), Pennsylvania State University, Colombian Cacao Producers Federation (FEDECACAO), and United Nations Office against Drugs and Crime (UNODC) identified Sierra Nevada de Santa Marta as a site for conducting a soil survey at a scale of 1:24,000.

The soil survey was conducted with a combination of traditional and digital soil mapping approaches. It included field observations, data collection, soil and plant sampling, and laboratory analysis of physical, chemical, and biological properties. A preliminary digital soil map was developed using clustering algorithms (Rubin, 1967). The variables included longitudinal curvature (Wilson and Gallant, 2000), Topographic Wetness Index (TWI)(Beven and Kirkby, 1979), Multiresolution Valley Bottom Flatness (MRVBF)(Gallant and Dowling, 2003), relative slope position (Boehner and Selige, 2006), and vertical distance to channel network (Conrad et al., 2015). Five major soil classes were identified based on slope positions as defined by Schoeneberger et al. (Soil Survey Staff, 2012). The positions were summit; shoulder; backslope; footslope or toeslope; and plains. The sites for sampling were predetermined based on the farms assisting in the CfP Initiative. The field observation sites were selected based on soil classes, geology, and accessibility (roads) to ensure sampling represented the soil classes and the three major rock types (metamorphic, igneous, and sedimentary). Sites in protected areas, such as National Parks, were excluded from the survey.

Figure 2.—Location of survey area in Colombia. (http://goto.arcgisonline.com/maps/World_Imagery)

Soil scientists observed the landscape and slope characteristics, such as gradient, length, and shape; the general drainage pattern; bedrock and parent material depositions; and native and cultivated plants. Soils were sampled on about 30 farms in spring 2019. At each farm, three holes were hand dug and augured to study the soil "profile," which is the sequence of natural layers, or horizons. Soil scientists recorded such characteristics as color, texture, and kind and amount of rock fragments.

Plant litter and leaves were collected for genotyping and cadmium analysis. An example of the sampling design at a farm site is shown in the appendix (fig. A–7).

Based on the major soil map units and accessibility, 13 sites were selected for full pedon characterization. Soil scientists recorded characteristics of the soil profiles, such as soil color; texture; kind and amount of rock fragments; reaction with diluted (10 percent) HCl; size and shape of soil aggregates; distribution of plant roots; and other features that enabled them to identify soils and assign taxonomic classes (units). The profile extends from the surface down into the unconsolidated material in which the soil formed. The unconsolidated material is devoid of roots and other living organisms and has not been changed by other biological activity. A total of 660 soil samples were collected and analyzed for physical (sand, silt, clay, bulk density), chemical (macro and micronutrients, pH), and biological (organic matter) soil properties at the International Center for Tropical Agriculture (CIAT).

The soil analysis results were used to produce soil property maps. Measured soil properties based on genetic horizons were generated for specified soil depths using equal area spline functions (Bishop et al., 1999; Malone et al., 2009). The depths were 0–30 cm (H1), 30–60 cm (H2), 60–100 cm (H3), and 100–200 cm (H4). Soil property maps for each depth were generated using the Random Forest statistical approach based on the relationship between each soil property and factors representing soil forming factors (Jenny, 1941). The topography soil forming factor was represented by slope; slope curvature; relative slope position; topographic position index; topographic wetness index; distance to channel network; valley depth; valley bottom and ridgetop; and landforms. The organisms soil forming factor was represented by Normalized Difference Vegetation Index (NDVI). The parent material soil forming factor was represented by the geological map (Servicio Geológico Colombiano, 2019). Soils were also included using the soil classes from the cluster analysis and the existing coarser soil map (Instituto Geográfico Agustin Codazzi, 2019). Soil property maps were generated using 70 percent of the measured data and validated using the remaining 30 percent of the data. The accuracy of soil property maps was evaluated based on statistical parameters of root mean square error (RMSE), mean absolute error (MAE), root mean square error of prediction (RMSPEr), and R2.

The soil survey data includes five major map units based on slope positions (summit; shoulder; backslope; footslope or toeslope; and plains) combined with three major geologies (metamorphic, igneous, and sedimentary). The total number of soil map units is 12. The soils on plains formed only on sedimentary rocks. The soils on footslopes formed only on metamorphic rocks. The soils on toeslopes formed only on igneous rocks. This survey includes a description of the soils and their location. It also includes a discussion of their suitability, limitations, and management with focus on cacao. The soils in the survey area formed in regular patterns that are related to the geology, landforms, relief, climate, and vegetation. Each soil map unit is associated with a particular kind of landscape or with a segment of the landform. Soil scientists developed conceptual models for describing how the soils were formed and related the models to landforms in the survey area. These models enabled the soil scientists to predict with a considerable degree of accuracy the kind of soil at a specific location on the landscape.

Commonly, individual soils on the landscape merge into one another as their characteristics gradually change. However, for practical purposes related to management, soil scientists determined the boundaries between soils. Soil map unit boundaries were based on established soil-landform relationships and landscape models. Soil profile descriptions were used to assign conceptual taxonomic classes (units). Each taxonomic class has a set of soil characteristics with defined limits. The classes are used as a basis for comparison to classify soils systematically. Soil Taxonomy, the system of taxonomic classification used in the United States, is based mostly on the kind and character of soil properties and the arrangement of horizons within the soil profile. After the soil scientists classified and named the soils in the survey area using local names, they compared the individual soils with similar soils in the same taxonomic class in other areas so that they could confirm data and assemble additional data based on experience and research.

Soil scientists interpret the data from the analyses and tests as well as the field-observed characteristics and the soil properties to determine the expected behavior of the soils under different uses. Interpretations for all soils are field tested through observation of the soils in different uses and under different levels of management. Some interpretations are modified to fit local conditions, and some new interpretations are developed to meet specific needs. Data are assembled from other sources, such as research information, production records, and field experience of specialists. Predictions about soil behavior are based not only on soil properties but also on such variables as climate and biological activity. Soil conditions are predictable over long periods of time, but they are not predictable from year to year. For example, soil scientists can predict with a fairly high degree of accuracy that a given soil will have a high water table within certain depths in most years, but they cannot predict that a high water table will always be at a specific level in the soil on a specific date.

General Characteristics of Sierra Nevada de Santa Marta, Colombia

This section briefly describes the climate, land use, land cover, and physiographic characteristics of Sierra Nevada de Santa Marta.

Climate

The climate of Sierra Nevada de Santa Marta Region is very diverse. It ranges from tropical near the coast to cold alpine at the higher elevations. The climate in the survey area is generally tropical. Precipitation data for the survey were at 5 km grid resolution (Funk et al., 2014) downloaded from http://chc.ucsb.edu/data/chirps/. Temperature data for the survey were at 1 km grid resolution (Karger et al., 2017) downloaded from https://chelsa-climate.org/about/.

The annual temperature in the survey area is 23.7 °C, and mean annual precipitation is 1,722 mm. The temperature, and especially the precipitation, vary seasonally. For the 1979–2013 period, the mean monthly temperature varied from

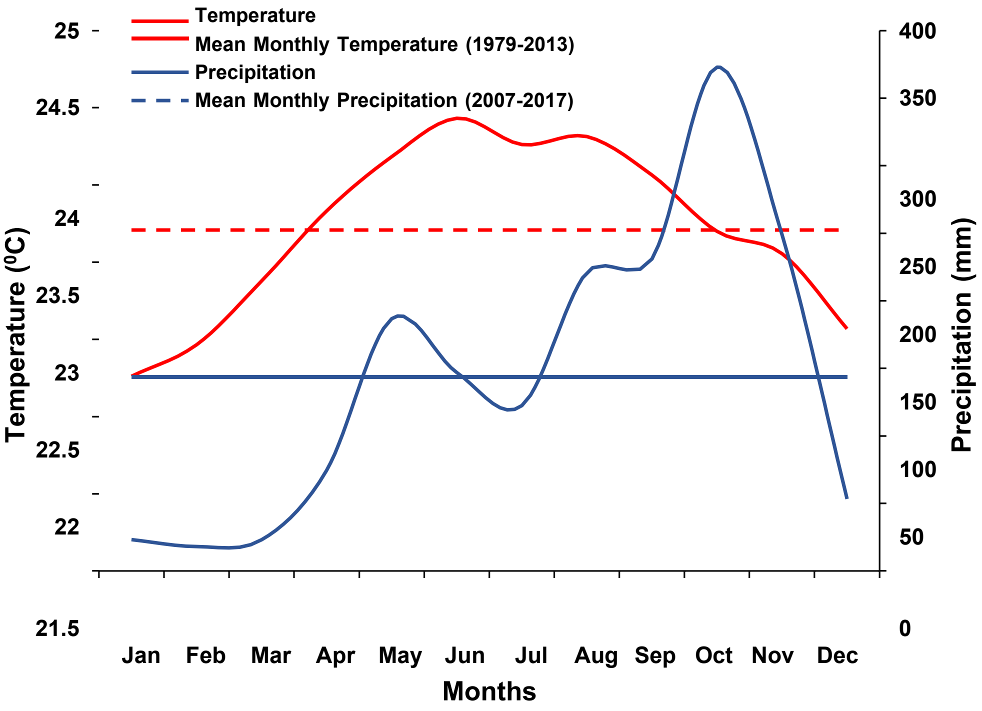

Figure 3.—Mean annual distribution of temperature (1979–2013; Funk et al., 2014) and precipitation (2007–2019; Karger et al., 2017) by month.

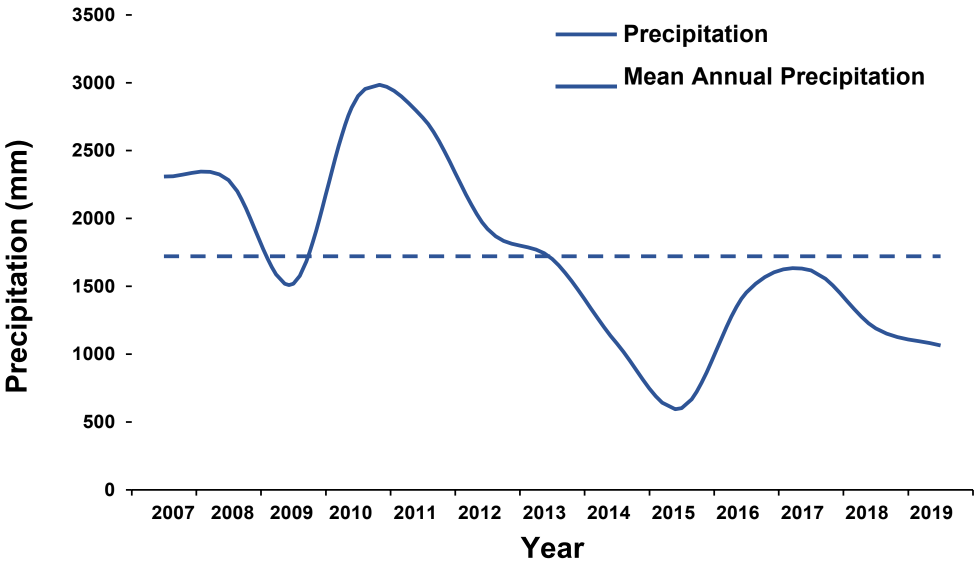

Figure 4.—Distribution of mean annual precipitation 2007–2019.

11.7 °C to 28 °C (Funk et al., 2014). The mean monthly precipitation varied from 1 mm to 1,000 mm during 2007–2019 period. Much of the precipitation falls between mid-September and mid-November, corresponding to two distinct rainy seasons: April–June and October–November (fig. 3). The monthly distribution of precipitation shows two distinct peaks. The first peak occurs in May during Spring. The second, and highest, peak occurs in October, which is during the hurricane season.

During 2007–2019, the mean annual precipitation showed a decreasing trend, especially after 2013 (fig. 4). The amount of precipitation continues to be below the 1,722 mm average for the rest of the 2013–2019 period.

The spatial distribution of temperature and rainfall shows the mountainous areas as cooler and wetter (fig. 5) than other areas (Funk et al., 2014; Karger et al., 2017).

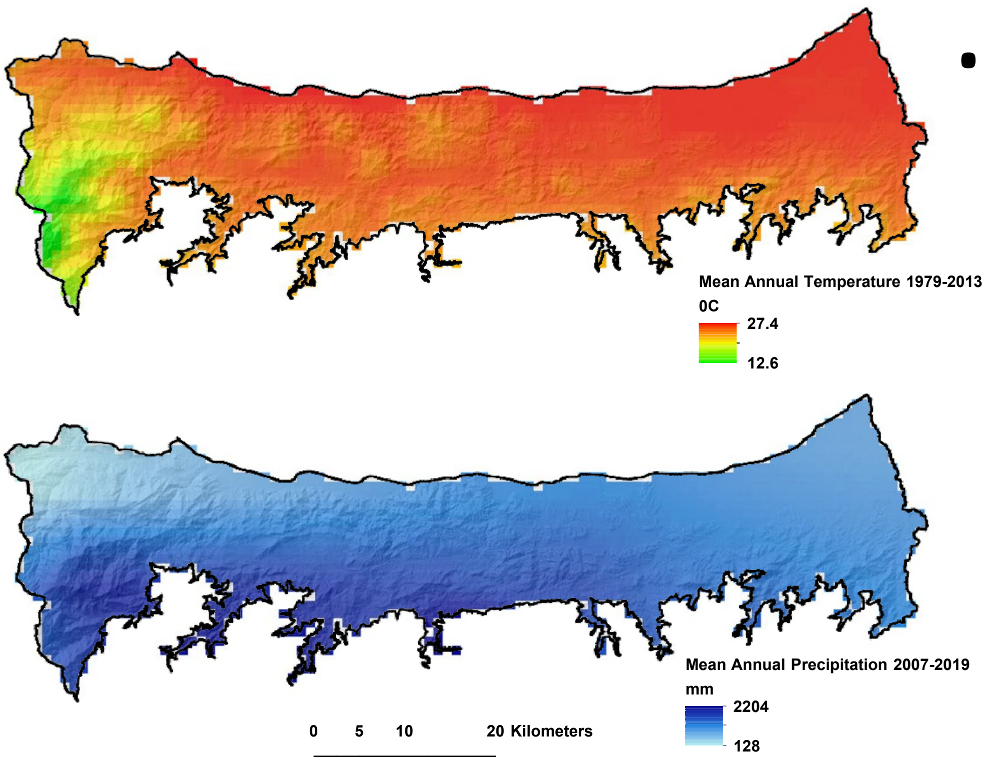

Figure 5.—Spatial distribution of mean annual temperature (1979–2013) and precipitation (2007–2019). The rainfall data is from "Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS)," which is a 35+ year quasi-global rainfall data set (Climate Hazards Center at UC Santa Barbara). The temperature data is from "Climatologies at High Resolution for the Earth's Land Surface Areas" (CHELSA), which is a high resolution (30 arc sec) climate data set hosted by the Swiss Federal Institute for Forest, Snow, and Landscape Research WSL.

Land Use, Land Cover, and Physiographic Characteristics

Sierra Nevada de Santa Marta Region is situated in the most northern mountain range of South America. The northern part of the region is comprised of sediments deposited on alluvial plains and makes up about 32 percent of the survey area. The major sediment source for the alluvial plains originates from the Sierra Nevada Mountain Range, which is south of the alluvial plains. The predominate rock types in the project area are equally divided between Cretaceous metamorphic (35%), Tertiary intrusive igneous (33%), and sedimentary (32%) (fig. 6; Servicio Geológico Colombiano, 2019). The survey area is dissected by rivers and streams that descend from the mountains and head generally north toward the sea.

Approximately a third of the survey area is relatively flat and dominated by moderate-density agriculture. The remaining two-thirds is hilly and mountainous, extending up towards the foothills of the Sierra Nevada Mountain Range. The survey area is characterized by high relief, mostly in the southern and central parts, and by elevations ranging from 0 to 2,849 meters above sea level. The mean elevation for the sedimentary rock formation on alluvial plains is 723 meters. Next is igneous rock at 273 meters. Metamorphic rock is at the highest mean elevation, about 535 meters. The stream network is very dense due to high relief and precipitation. About 36 major streams run north from the Sierra Nevada Mountain Range toward the sea. (fig. 7).

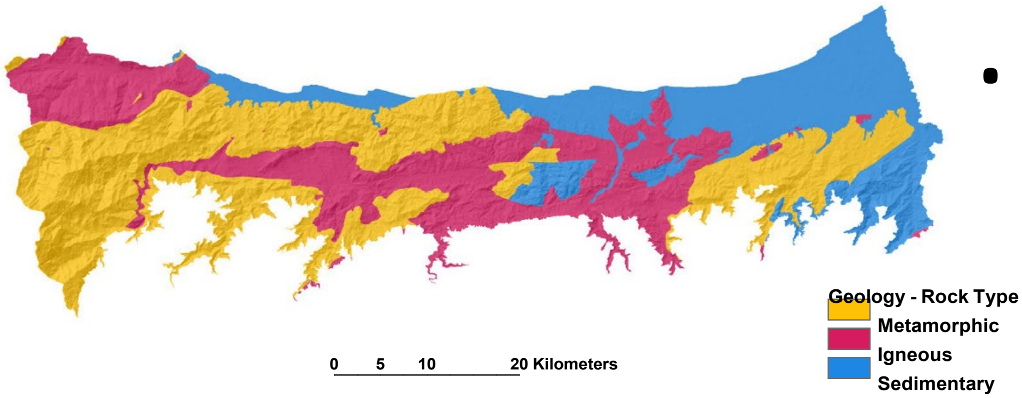

Figure 6.—Geology of the Sierra Nevada de Santa Marta survey area (Servicio Geológico Colombiano, 2019).

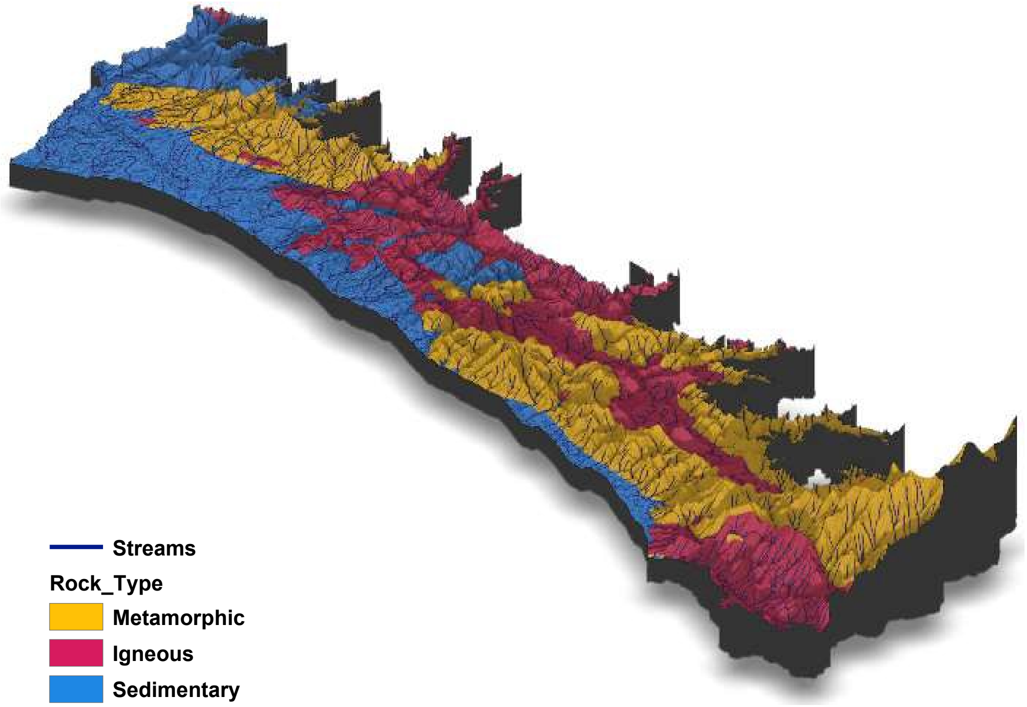

Figure 7.—General view of the survey area showing the elevation of the major geologic formations.

Topography and Major Slope Positions

A preliminary digital soil map was developed using terrain and topographic attributes from the Shuttle Radar Topography Mission (SRTM) data (USGS, 2019) digital elevation model (DEM). The terrain attributes were Longitudinal Curvature, Topographic Wetness Index (TWI), Multiresolution Valley Bottom Flatness (MRVBF), Cross Sectional Curvature, Relative Slope Position, and Vertical Distance to Channel Network (VDCHN). Clustering algorithms were used (Rubin, 1967) (fig. 8).

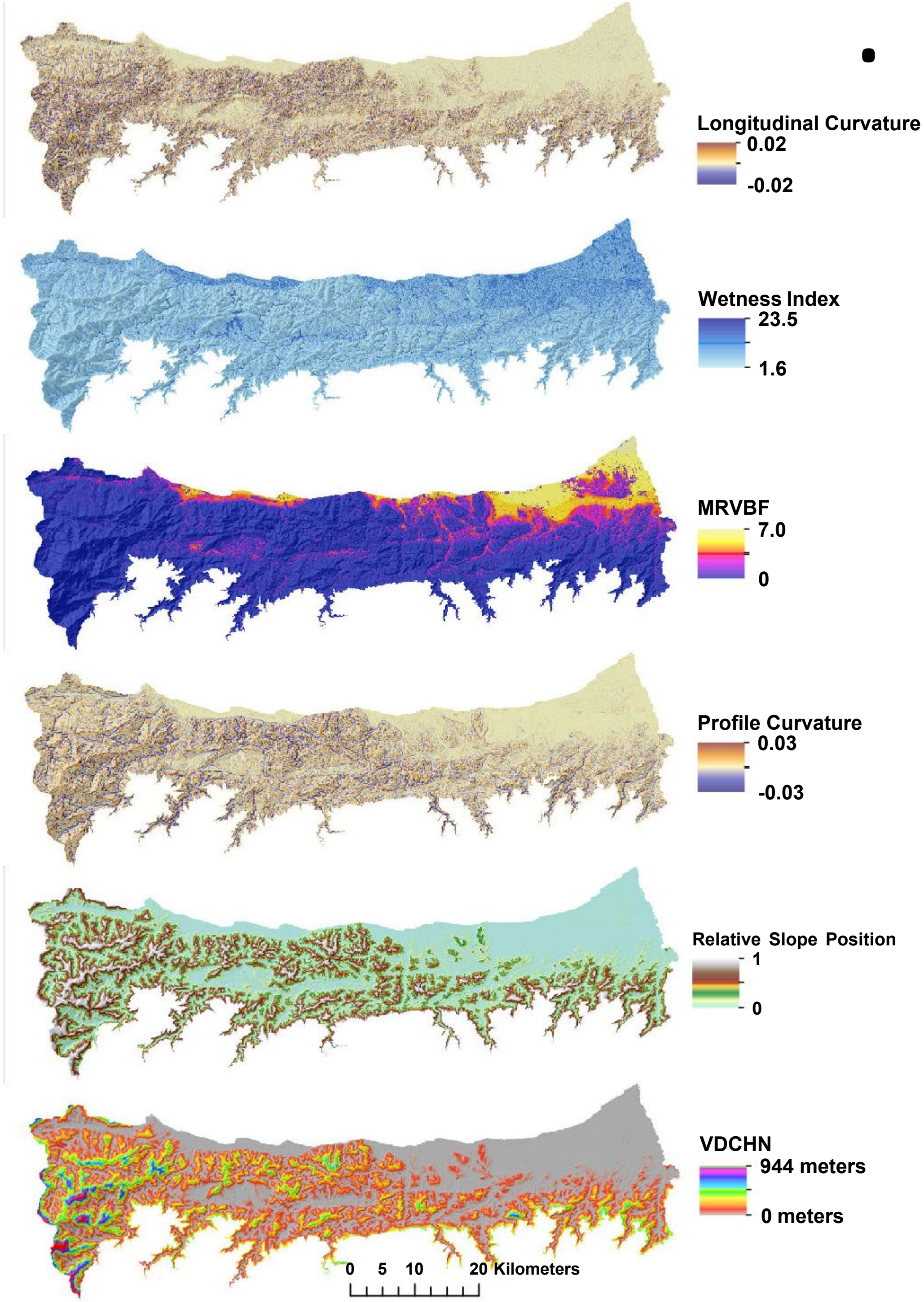

Figure 8.—Terrain attributes derived from elevation and used for predicting soils.

Agriculture

Background

The Sierra Nevada de Santa Marta is a complex ecosystem along the northernmost coast of Colombia. It has diverse climatic zones across a strip of only 42 km (26 miles) and covers altitudes from near sea level up to 5,700 m (18,700 ft). It is adorned with breathtaking landscapes stretching from pristine beaches to towering blueish green flora in distant horizons. It has an intricate hydrologic network of about 36 streams and rivers. The Sierra Nevada is one of the world's highest coastal ranges and offers diverse landforms, soil types, and climates. It supports an unparalleled variety of flora and fauna, culminating in a rich biodiversity with a very high degree of endemism that is unique to the area.

Agro-Ecological Zones

The agro-ecological zones range from a tropical climate at the coast to a perpetual snow line above 4,880 m (16,000 ft) and include a cold Alpine climate zone.

- The Guajira-Barranquilla xeric scrub region is near the Caribbean seacoast to the north of the range.
- The Sinú Valley dry forests cover the range's lower slopes, up to an elevation of 500 m (1,600 ft).
- The Santa Marta montane forests are above 500 to 800 m (1,600 to 2,600 ft).
- The lower-elevation supports dry forests and xeric shrublands.
- The moist lowland forests cover the windward northern and western flanks of the range between 500 and 900 m (1,600 and 3,000 ft) and the drier eastern and southern flanks from 1,000 to 5,800 m (3,300 to 19,000 ft).
- A transitional forest zone of smaller trees and palms is above 900 m (3,000 ft).
- The cloud forests are above 1,000 m (3,300 ft).
- The sub-Andean forests, which are at 1,000 to 2,500 m (3,300 to 8,200 ft), have canopies that are 25 to 35 m (82 to 115 ft) tall.
- The higher-elevation Andean forests, which are between 2,500 and 3,300 m (8,200 and 10,800 ft), grow to 15 to 20 m (49 to 66 ft).
- The Santa Marta Páramo is a high altitude belt of montane grasslands and shrublands interspersed with marshes and acid bogs. It is in the zone between 3,300 and 5,000 m (10,800 and 16,000 ft).
- The Santa Marta Páramo is the northernmost enclave of Páramo in South America and is along the Andes belt.
- Above 5,000 m (16,000 ft), the snow cap is permanent.

Cropping Systems

Historically, indigenous peoples in the Sierra Nevada de Santa Marta area grew plants and animals to produce food, homes, and ornaments (Steiner and Vallejo, 2010). They also cultivated grasses for clothing and home roofing material. Archaeological sites show evidence of mid- to large-size population centers, consisting of stone pathways, terraces, protected waterways, and spaces dedicated to agricultural production. Products included cultivated corn, pineapple, yucca, and other local foods for self-sustenance. Over time, subsistence farming gradually evolved to include cash crops that contributed to the economy.

More recently, large-scale commercial farming has developed on the alluvial plains. This style of agriculture developed to meet the demands of a growing population and for export. Modern agricultural techniques are employed mainly in those areas where they are adaptable to the topography. Agrichemicals, such as pesticides and chemical fertilizers, are widely used. Large tracts of flatter lands in dry areas are irrigated and tilled to varying degrees. A wide variety of cropping systems are practiced today. They include vestiges of sustenance farming, variable intercropping mixes, agroforestry, and corporate monoculture plantations. Many small farmers, especially on the mountain fringes, still practice traditional farming methods. Reports indicate varying degrees of tillage and agrochemical use to enhance productivity and efficiency.

Primary Agricultural Products

The wide range of landscapes, including lowlands and mountains, include obvious climatic variations. These variations support the production of a remarkably wide range of both tropical and temperate-zone crops, including bananas, sugarcane, wheat, barley, and potatoes.

Ranked as the fourth-largest producer of coffee in the world, Colombia is famous for its high-flavor coffee. Based on contribution to gross domestic product (GDP), however, coffee is not the most important crop. By GDP, the rankings of agricultural output are cattle at 45 percent; fruits at 15.2 percent (including plantains at 5.2 percent and bananas at 2.8 percent); coffee at 9.5 percent; rice at 4.9 percent; flowers at 4.2 percent; vegetables at 4.1 percent; and other agricultural products at 17.1 percent.

The Magdalena and Guajira Departments are large producers of corn, cut flowers, bananas, rice, tobacco, sugarcane, cocoa beans, oilseed, vegetables, fique, and forest products. Other agricultural products grown in the region include a wide variety of beans, sorghum, peppers, tomato, pumpkin, eggplant, onion, melon, pepper, chili, yuca, cucumber, watermelon, millet, sesame seed (ajonjolí), yam, and oil palm. Sea products include fish and shrimp.

Challenges and Opportunities

The abundance of natural resources in the Sierra Nevada de Santa Marta region has triggered the expansion of extractive industries and rapid population growth. The agricultural contribution to Colombia’s gross domestic product has fallen consistently since 1945 as a result of increased diversification of the economy. Agriculture, nonetheless, remains an important source of employment, providing about a fifth of the jobs in Colombia. Protecting the Sierra Nevada de Santa Marta’s natural resources is a major preoccupation for protesters who are opposed to massive ocean port development projects.

An estimated 70 to 80 percent of the original forest has been cleared in the last 50 years. The wet forest of the lower levels has been reduced to thinned-out fragments by settlements, farming operations, logging, firewood harvesting, and conversion to pasture. The resulting deforestation causes severe erosion and mud slides in the rainy seasons and severe siltation of the rivers. Another threat is intense cultivation techniques that seemingly lower plant diversity.

Large belts of forest have been converted to coffee cultivation and pasture, at times displacing small farms. Examples include an increase in ranching and palm oil cultivation over natural ecosystems. Other areas have been cleared to create pasture and are kept clear by annual burns. Higher up, the Ancho and Frío River Basins and other parts of the cloud forest have been modified for rearing sheep and cattle, farming potatoes and fruit, and extracting wood. Forest clearance threatens populations of large animals, especially endangered species. Examples include panther and ocelot, which are hunted for food, for high value skins, and as a perceived threat to cattle. Reports indicate that 33.4 percent of the pre-colonial Santa Marta montane forests have been transformed by human activity.

Parts of the ecoregion are protected by the Sierra Nevada de Santa Marta National Park, Tayrona National Natural Park, and Sierra Nevada de Santa Marta Biosphere Reserve. These areas, however, were still being cleared in 1998, including parts of the indigenous reserves of the Cogui, Arsario, and Arhuaco people.

Government institutions and non-government organizations are making concerted efforts to promote sustainable agriculture and land use efficiency. Activities include strengthening organic farming programs; using proximal sensors to improve banana yields; using genomics to promote disease resistance, increase sustainable yields, and promote agroforestry; and promoting sustainable agricultural practices. The government has also created an enabling environment to revive and expand the production of cocoa as a dominant alternative crop.

General Soil Map Units

The general soil map units are broad areas that have a distinctive pattern of soils, relief, and drainage (fig. 9). Each map unit on the general soil map represents a unique natural landscape (fig. 10). A map unit consists of one or more major soils and some minor soils. The soils making up one unit can occur in other units but in a different pattern.

The general soil map can be used to compare the suitability of large areas for general land uses. Areas of suitable and not suitable soils can be identified on the map.

Because of its small scale, the map is not suitable for planning the management of a farm or field or for selecting a site for a road or building or other structure. The soils in any one map unit differ from place to place in slope, depth, drainage, and other characteristics that affect management.

The soils in the survey area vary widely in their potential for major land uses. Soil potential ratings are based on the practices commonly used in the survey area to overcome soil limitations. These ratings reflect the ease of overcoming the limitations. They also reflect the problems that persist even if such practices are used.

Each map unit is rated for cacao suitability. Other ratings, which are not included in this report but will be available online, are cultivated crops, pasture and hayland, woodland, urban uses, and recreation areas.

Cultivated crops are those grown extensively in the survey area. Pasture and hayland refers to land used as pasture for livestock or used for the production of hay. Woodland refers to areas of native or introduced trees. Intensive recreation areas are campsites, picnic areas, ballfields, and other areas that are subject to heavy foot traffic.

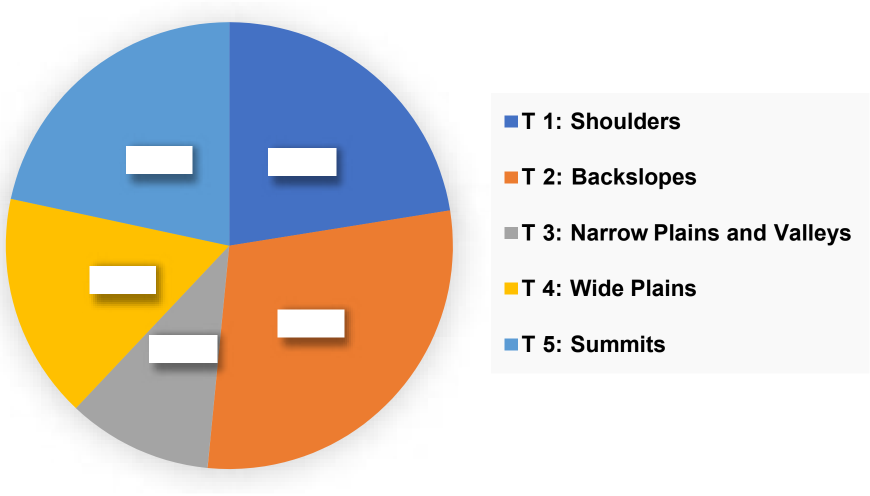

Figure 9.—Distribution of major soil map units by slope or topographic (T) position in Sierra Nevada de Santa Marta.

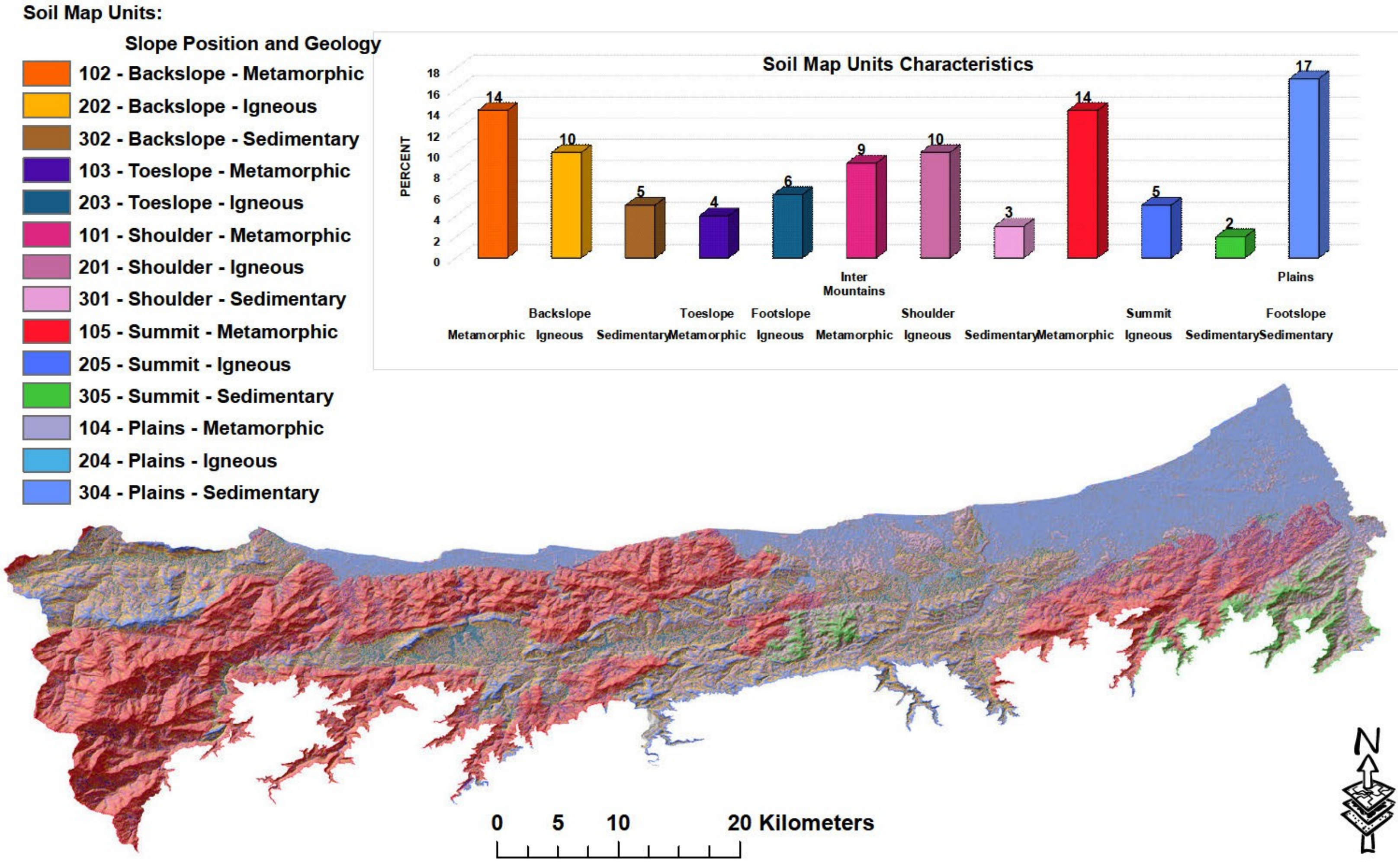

Figure 10.—Slope position and geology of the soil map units (SMU) of the survey area.

Soil Map Units: Slope Position and Geology

About 30 percent of the soil map units are on backslopes; 22 percent are on shoulders; and 21 percent are on summits. About 15 percent are on wide plains, mostly on toeslopes. The distribution of soil map units based on geology is shown in figure 10 and table 1.

Table 1.—General soil map units based on rock type and on slope or topographic (T) position.

SMU symbol	General soil map units	Geology class	Slope/ Topo (T) position	Rock type
101	Shoulder Slopes	10	1	Metamorphic
102	Backslopes	10	2	Metamorphic
103	Narrow Plains and Valleys	10	3	Metamorphic
104	Wide Plains	10	4	Metamorphic
105	Summits	10	5	Metamorphic
201	Shoulder Slopes	20	1	Igneous
202	Backslopes	20	2	Igneous
203	Narrow Plains and Valleys	20	3	Igneous
204	Wide Plains	20	4	Igneous
205	Summits	20	5	Igneous
301	Shoulder Slopes	30	1	Sedimentary
302	Backslopes	30	2	Sedimentary
303	Narrow Plains and Valleys	30	3	Sedimentary
304	Wide Plains	30	4	Sedimentary
305	Summits	30	5	Sedimentary

The characterization of soil map units by slope or topographic position is based on the description of major soil profiles (fig. 11) and auger holes in the survey area.

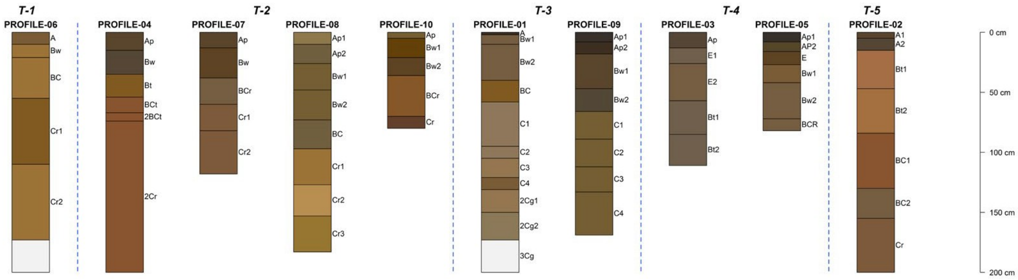

Figure 11.—Genetic horizon thickness and designation of major soil profiles described in the survey area.

1.—Soils on Shoulder Slopes

The soils on shoulder slopes are very deep, well drained, and slowly permeable. They formed in a dissected mountain system on hillslopes, side slopes, and shoulders, generally on northern to northwestern aspects. The general area is composed

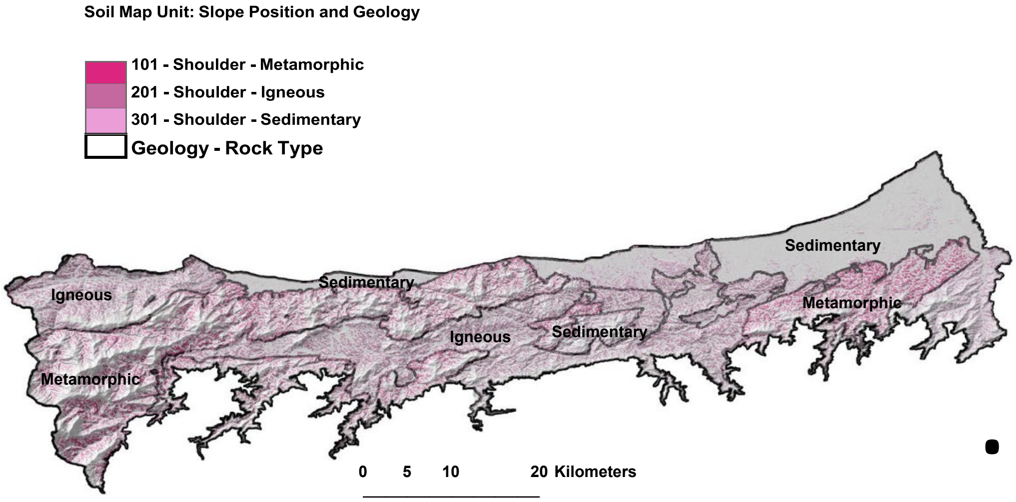

Figure 12.—Distribution of soils on shoulder slopes in Sierra Nevada de Santa Marta.

Figure 13.—Typical landform of soils on shoulders.

of quartzofeldspathic gneiss, migmatites, granulites, amphibolites (metamorphic hornblende and plagioclase within metamorphic rocks), orthogneiss (derived from igneous rock, such as granite), quartzites, and marbles.

Association: Typic Dystrudepts; Typic Udorthents; Fluventic Hapludolls
Intergrade: Gneiss de los Muchachitos

Slopes are 50 percent, moderately complex, linear-linear, and generally northwestern in aspect. Although paralithic materials are continuous, they do not appear to comprise a root restricting horizon. Soil materials are intertwined through the horizons. Particle-size control sections, therefore, appear to extend to 100 cm. Elevations range from about 300 to 385 meters.

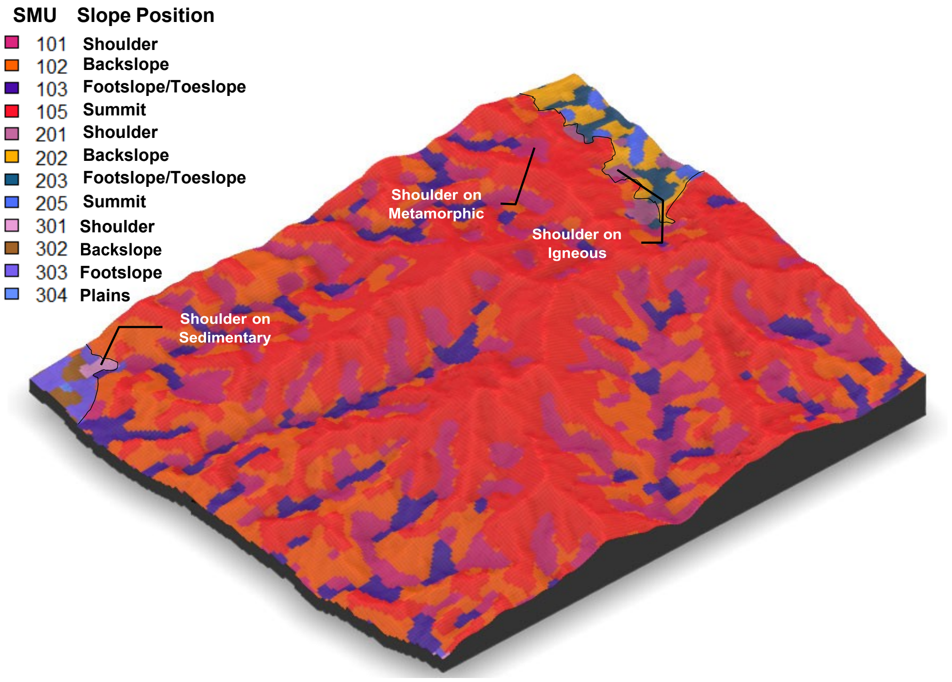

Figure 14.—Landscape setting of shoulder slope soil map units.

The surface layer is dark yellowish brown clay loam. The subsurface is very dark grayish brown and dark yellowish brown silty loam and clay loam. The subsoil is dark yellowish brown and yellowish brown loam and sandy loam. The soil is slightly acid to strongly acid. The content of organic carbon in the upper 30 cm ranges from about 2.2 to 0.4 percent and generally decreases with depth.

Soils on shoulder slopes are on intermountain landscapes (figs. 12, 13, and 14). They formed in materials derived from metamorphic rocks of Quaternary age and igneous and sedimentary rocks (fig. 12). The soils that formed in igneous rocks comprise about 10 percent of the survey area; soils that formed in metamorphic rock comprise 9 percent; and soils that formed in sedimentary rocks comprise 3 percent.

The soils in this unit are well suited to crops. The major crops are sorghum, maize, sweet potatoes, plantain, beans, and sugarcane. Because most of the organic matter is in the surface layer of these soils, the surface layer needs to be maintained and should be protected by conservation practices.

2.—Soils on Backslopes

The soils on backslopes make up about 30 percent of the survey area and are very diverse. They are either moderately deep to deep or deep to very deep. They are well drained. Permeability is slow or very slow. These soils formed in dissected mountain systems on hillslopes, backslopes, and side slopes on multiple aspects, including west, northwest, south, and east. The parent materials are diverse due to the diversity of geologic formations (fig. 15). The dominant parent materials are quartzofeldspathic gneiss; migmatites, which are at the junction between igneous and metamorphic rocks and result from partial fusion; granulites; amphibolites, such as metamorphic hornblende and plagioclase within metamorphic rocks; orthogneiss derived from igneous rock, such as granite; quartzites; and marbles. Slope ranges from 40 to 60 percent and is typically moderately complex and linear-linear (fig. 16). The majority of the soil associations are Typic Udorthents; Entic Hapludolls; Typic Dystrudepts;

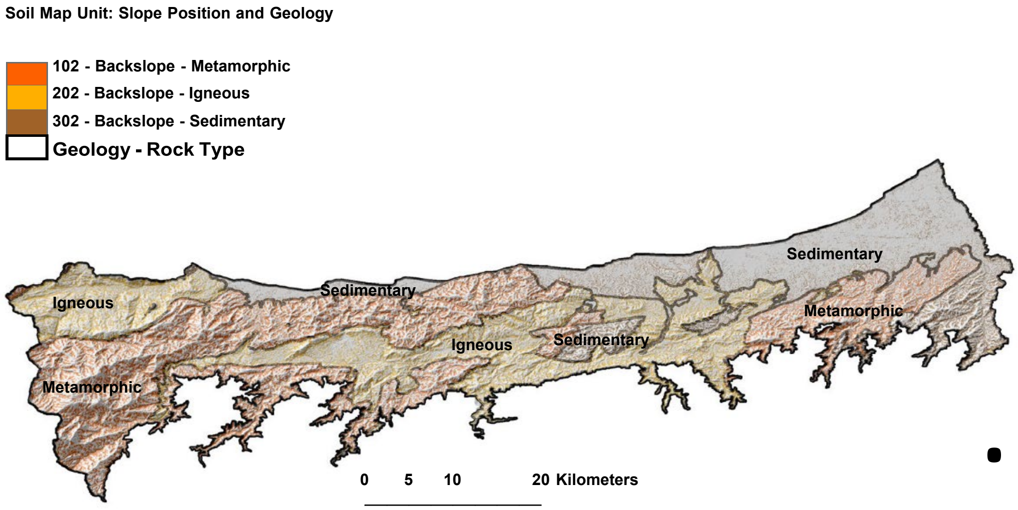

Figure 15.—Distribution of soils on backslopes in Sierra Nevada de Santa Marta.

Figure 16.—Typical landscapes for the soils on backslopes.

Rock outcrops and Typic Dystrudepts; Typic Udorthents; and Fluventic Hapludolls. Elevations range from 200 to 560 meters.

Soils on backslopes are on intermountain landscapes (fig. 17). They formed in materials derived from metamorphic rocks of Quaternary age, igneous rocks, and sedimentary rocks. The soils that formed in metamorphic rocks comprise about 14

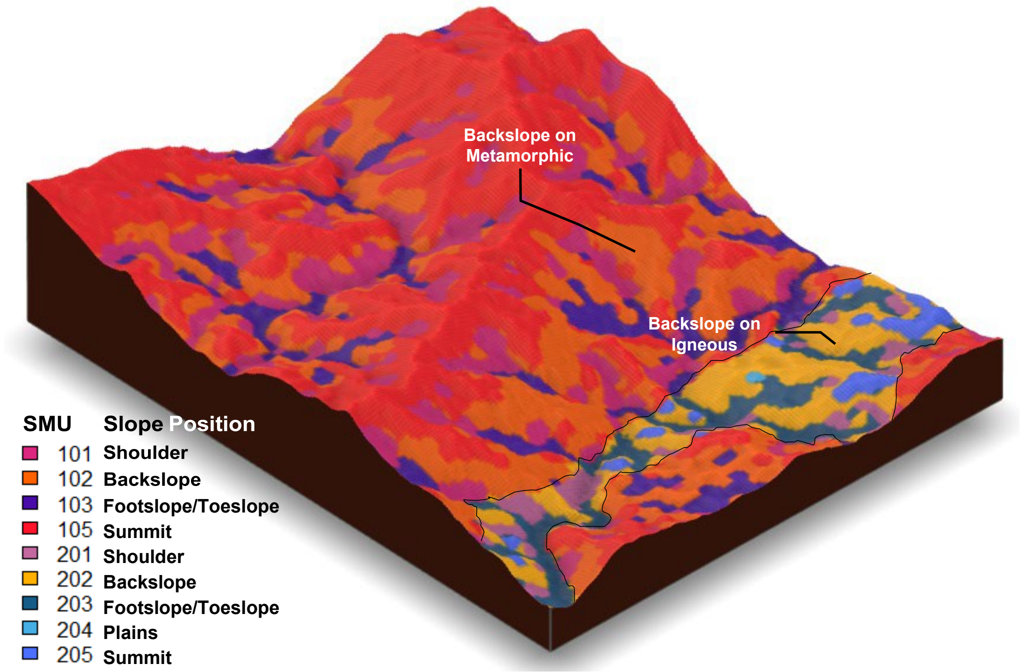

Figure 17.—Landscape setting of soil map units on backslopes.

percent of the survey area; soils that formed in igneous rock comprise 10 percent; and soils that formed in sedimentary rocks comprise 5 percent.

The surface layer is dark brown sandy clay loam; dark yellowish brown clay loam; light olive brown and olive brown loam; and brown gravelly loam. The subsurface is very dark grayish brown and dark yellowish brown sandy clay loam; brown and dark yellowish brown clay loam; olive brown channery loam and clay loam; and dark yellowish brown paragravelly loam. The subsoil is yellowish red and variegated red, gray, yellow, and brown clay loam and sandy clay loam; dark brown cobbly and flaggy silt loam and loam; yellowish brown and brownish yellow channery silt loam and loam; and strong brown, yellowish red, and dark reddish paragravelly loam. The soils are slightly acid to very strong acid. The content of organic carbon in the upper 30 cm ranges from 0.9 to 2.9 percent and generally decreases rapidly with depth.

The soils in this map unit are well suited to crops. The major crops are sorghum, maize, sweet potatoes, plantain, beans, and sugarcane. Because most of the organic matter is in the surface layer of these soils, the surface layer needs to be maintained and should be protected by conservation practices.

3.—Soils on Narrow Plains and in Valleys

The soils on narrow plains and in valleys are on footslopes and toeslopes underlaid by metamorphic and igneous rock types (fig. 18). These soils are very deep, well drained, and moderately to slowly permeable. They formed in alluvial deposits derived from metamorphic materials in alluvial plains of Quaternary age and in dissected mountain systems on toeslopes and base slopes of alluvial plains. The soils on alluvial plains increase in elevation in a generally southeastern direction and decrease in elevation in a generally northwestern direction. The soils are subject to rare flooding. In places, the soils on toeslopes and base slopes display stream sediment stratification and consistent pedogenesis to a depth of 58 cm. Soils closer to the stream banks are actively eroding to some degree (figs. 19 and 20). Areas away from streams display a

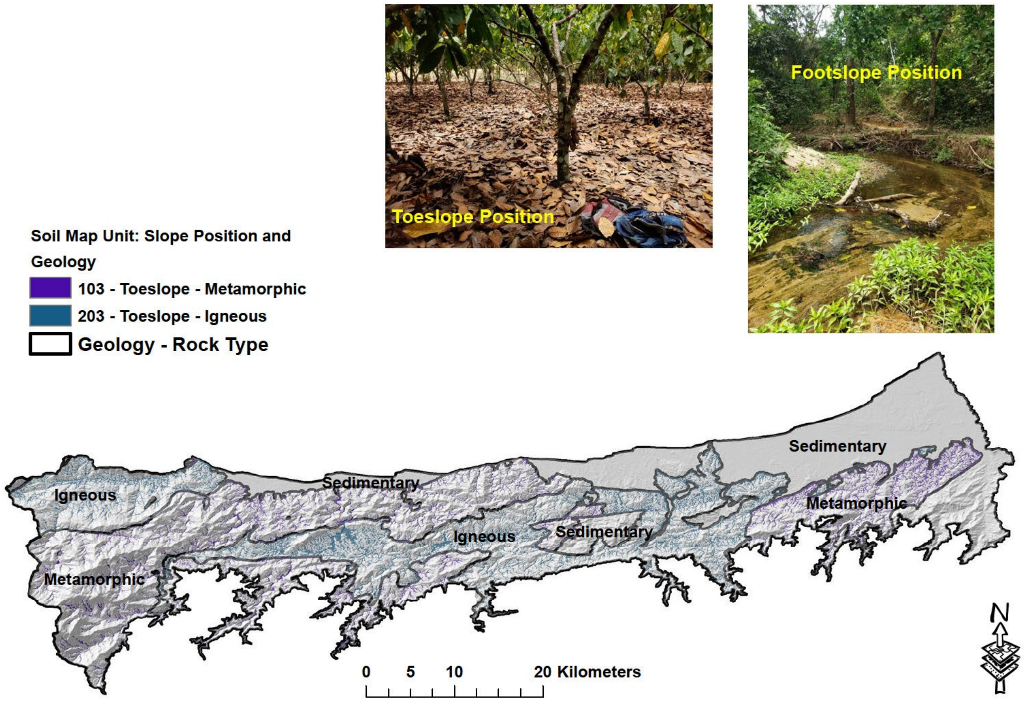

Figure 18.—Distribution of soils on narrow plains and in valleys in Sierra Nevada de Santa Marta.

Figure 19.—Typical landform for the soils on footslopes formed on metamorphic parent material and toeslopes formed on igneous parent material.

stable surface as shown by lack of visible sediments (fig. 19). Examples of sediments include detritus or clean sand deposits from recent flood events on terraces and trails.

The most common soils associations are Typic Ustorthents; Lithic Haplustepts; Typic Haplustalfs; Typic Dystrudepts; Typic Udorthents; and Fluventic Hapludolls and rock outcrops. Elevations range from about 32 to 91 meters for soils on alluvial deposits and from about 85 to 100 meters for soils in dissected mountain systems on toeslopes and base slopes of alluvial plains. The general area is composed of granodiorite, quartz diorites, quartz monzonite, and Gneiss de los Muchachitos Intergrade. Slopes are 4 percent, gently sloping, simple, linear-linear, and generally have a west-southwest aspect toward a drainageway.

Soils in dissected mountain systems on toeslopes and base slopes of alluvial plains formed in alluvial deposits. The deposits were derived from metamorphic rocks

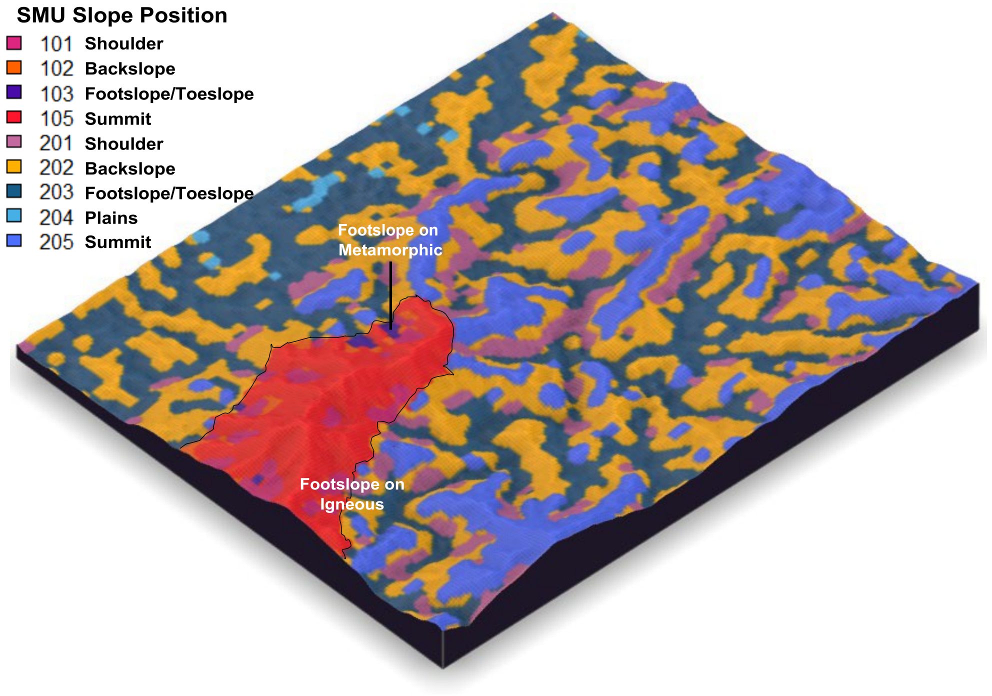

Figure 20.—Landscape setting of soil map units on narrow plains and in valleys.

of Quaternary age and igneous rocks. The soils that formed in metamorphic rocks comprise about 6 percent of the survey area, and the soils that formed in igneous rock comprise 4 percent.

The surface layer is dark grayish brown sandy loam and light black and very dark brown sandy clay loam and loam. The subsurface is brown, yellowish brown, and brownish yellow sandy loam and dark brown and very dark grayish brown gravelly sandy clay loam and sandy loam. The subsoil is stratified light olive brown, yellowish brown, and gray loamy sand and gravelly sandy loam and somewhat stratified olive brown gravelly sandy loam and sandy loam. The soils are moderately acid to strongly acid or are slightly acid to very strongly acid. The content of organic carbon in the upper 30 cm ranges from about 1.3 to 2.7 percent and generally decreases with depth. These soils are somewhat dissected. Some soil components experience increased flooding frequency in lower positions near drainageways.

The soils in this unit are well suited to crops. The major crops are sorghum, maize, sweet potatoes, plantain, beans, and sugarcane. Because most of the organic matter is in the surface layer of these soils, the surface layer needs to be maintained and should be protected by conservation practices.

4.—Soils on Wide Plains

The soils on wide plains make up about 16 percent of the survey area. They are on the Monguí formation, which consists of an alluvial plain system that is generally outside the mountain system. The area is composed of gentle flats near the river to the south and gently sloping to nearly level undulations near the ocean on the north (figs. 21 and 23). The soils are moderately deep to very deep, well drained, and slowly or very slowly permeable. They formed on alluvial plains just outside of flood plains, on toeslopes, and in areas of talf. Typically, the soils are on terrace landforms. In some areas, however, no obvious riser is observed. The soils are generally composed of

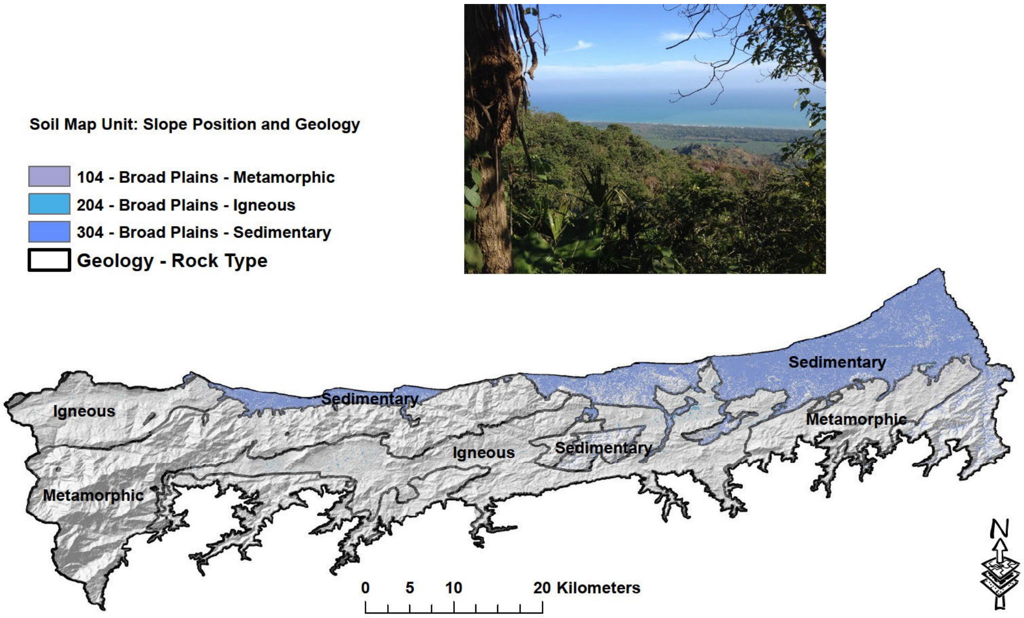

Figure 21.—Distribution of soils on wide plains in Sierra Nevada de Santa Marta.

Figure 22.—Typical landforms for the soils on wide plains formed in areas of alluvial deposits.

loamy and silty alluvial deposits and claystones, siltstones, arenites (sedimentary clastic rock with sand grains in between), and conglomerates. Slopes are 1 or 2 percent, nearly level, simple, linear-linear, and generally trend very gently toward the streams and rivers (fig. 22). Anecdotally, floodwaters reach slightly lower elevations. Elevations range from about 5 to 25 meters. Major soil associations are Aquic Haplustepts, Typic Fluvaquents, and Typic Quartzipsamments.

The soils on wide plains are in areas of alluvial plains (fig. 22). They mostly formed in material derived from thick, fluvial marine and sedimentary rock deposits, such as claystones, siltstones, and arenites (sedimentary clastics). Less than 0.5 percent of these soils formed in material derived from igneous and metamorphic rock.

The surface layer is very dark grayish brown and dark brown silty clay or dark olive brown and gray loam. The subsurface is dark grayish brown and brown silt loam and silty clay loam or dark yellowish brown and brown loam. The subsoil is dominantly dark grayish brown, dark brown, and brown silty clay loam and silty clay. In places, it is brown gravelly silt loam. The soils are slightly acid to strongly acid. The content of

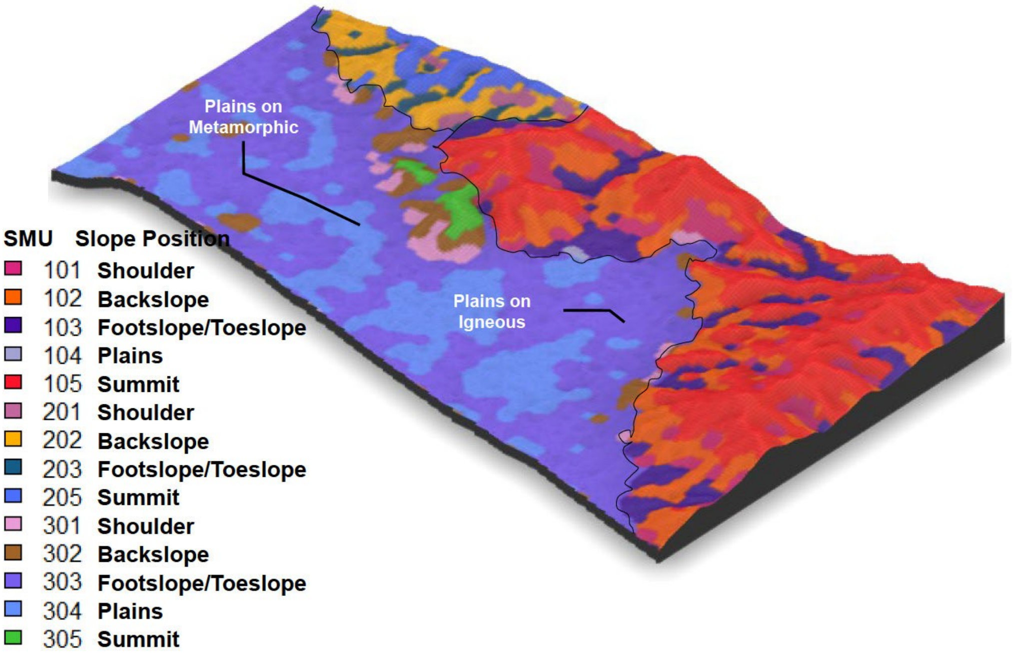

Figure 23.—Landscape setting of soil map units on wide plains.

organic carbon in the upper 30 cm ranges from about 0.4 to 2.8 percent and generally decreases with depth, especially below 50 cm.

The soils in this unit are well suited to crops. The major crops are sorghum, maize, sweet potatoes, plantain, beans, and sugarcane. Because most of the organic matter is in the surface layer of these soils, the surface layer needs to be maintained and should be protected by conservation practices.

5.—Soils on Summits

The soils on summits make up about 22 percent of the survey area. They are very deep, well drained, and slowly to very slowly permeable. The soils formed in dissected mountain systems on ridge summits (figs. 24 and 26). The summits are composed of arenites (sedimentary clastic rocks of sand grain size), siltstones, and limestone interspersed with tuffs, gaps, agglomerates, and lava rhyolites (felsic volcanic rock) and andesites. Slope is 1 percent and linear-linear. The soils are along ridgetops in narrow areas about 5 to 30 meters wide.

Physiography: Guatapurí Formation
Association: Lithic Ustorthents, Typic Haplustepts, Rock outcrops

The soils on summits are on intermountain landscapes (figs. 25 and 26). They formed in materials derived from metamorphic rocks of Quaternary age, igneous rocks, and sedimentary rocks. The soils that formed in metamorphic rocks comprise about 14 percent of the survey area; soils that formed in igneous rock comprise 5 percent; and soils that formed in sedimentary rocks comprise 2 percent.

The surface layer is dark grayish brown and brown clay. The subsurface is reddish yellow and strong brown clay, silty clay, and silty clay loam. The subsoil is variegated brown, yellow, and gray silt loam combined with weathered bedrock. The soil is strongly acid or very strongly acid. The content of organic carbon in the upper 30 cm ranges from about 0.3 to 4.5 percent and generally decreases with depth.

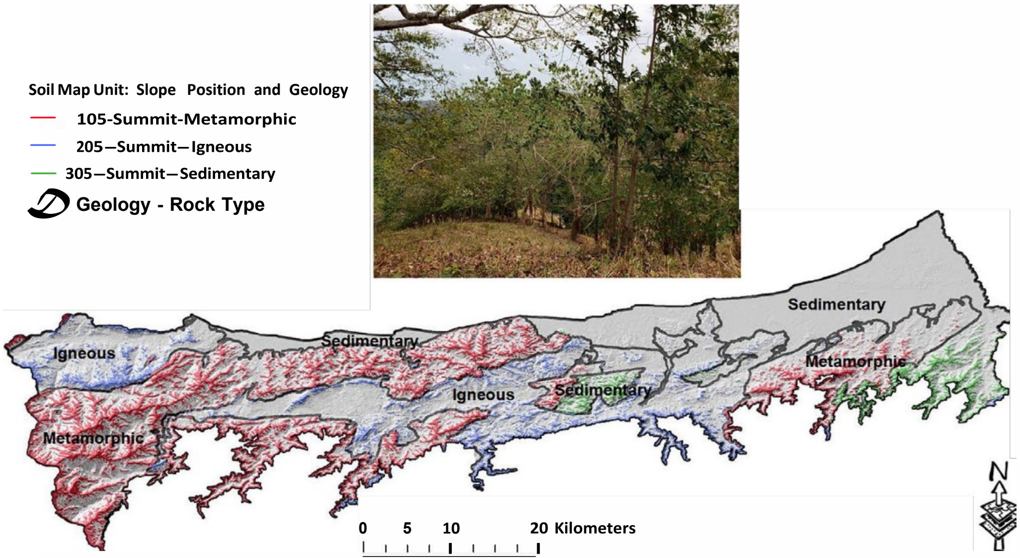

Figure 24.—Distribution of soils in the summit slope position in Sierra Nevada of Santa Marta.

Figure 25.—Typical landform of soils on summits.

The soils in this unit are well suited to crops. The major crops are sorghum, maize, sweet potatoes, plantain, beans, and sugarcane. Because most of the organic matter is in the surface layer of these soils, the surface layer needs to be maintained and conservation practices should be used to protect against erosion.

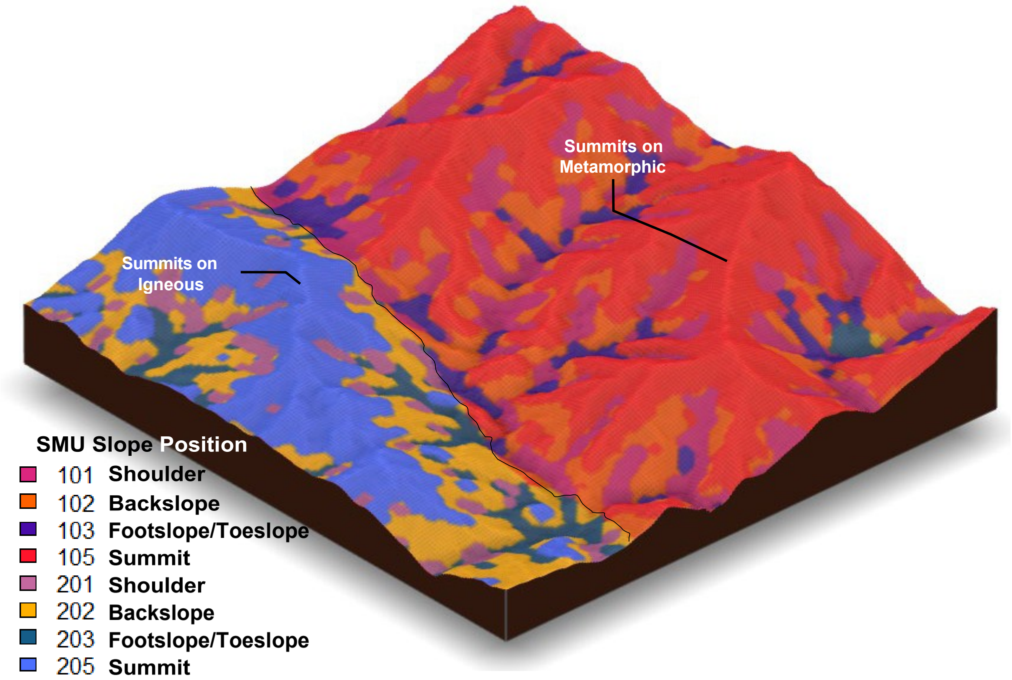

Figure 26.—Landscape setting of soil map units on summits.

Detailed Soil Map Units

The map units delineated on the detailed soil map in this survey area represent the soils or miscellaneous areas in the Sierra Nevada de Santa Marta (fig. 10). The soil profile descriptions in this section, along with the soil map and the soil property maps can be used to determine the suitability and potential for specific uses. They also can be used to plan the management needed for those uses.

A map unit delineation on the soil map represents an area dominated by one or more major kinds of soil or miscellaneous areas. A map unit is identified and named according to the taxonomic classification of the dominant soils. Areas of soils of a single taxonomic class rarely, if ever, can be mapped without including areas of other taxonomic classes. Consequently, every map unit is made up of the soils or miscellaneous areas for which it is named and some minor components that belong to taxonomic classes other than those of the major soils. Because of the limited access to the survey area, the taxonomic classification is provided for each of the soils described and sampled within each map unit. Within a taxonomic class, the limits for the properties of the soils are precisely defined. On the landscape, however, the soils are natural phenomena, and they have the characteristic variability of all natural phenomena. Thus, the range of some observed properties may extend beyond the limits defined for a taxonomic class. Confidence intervals for major soil properties are provided to illustrate soil properties and ranges of soil variability with depth.

Most minor soils have properties similar to those of the dominant soil or soils in the map unit and are thus affected only slightly differently by use and management. These are called noncontrasting, or similar, components. They may or may not be mentioned in a particular map unit description. Other minor components, however, have properties and behavioral characteristics divergent enough to affect use or to require different management. These are called contrasting, or dissimilar, components. They generally are in small areas and could not be mapped separately because of the scale used. Some small areas of strongly contrasting soils or miscellaneous areas are identified by a special symbol on the map.

The presence of minor components in a map unit in no way diminishes the usefulness or accuracy of the data. The objective of mapping is not to delineate pure taxonomic classes but rather to separate the landscape into landforms or landform segments that have similar use and management requirements. The delineation of such segments on the map provides sufficient information for the development of resource plans. If intensive use of small areas is planned, however, detailed onsite investigation is needed to define and locate the soils and miscellaneous areas.

An identifying symbol precedes the map unit name in the map unit descriptions. Each description includes general facts about the unit.

Soils that have profiles that are almost alike make up a soil series. All the soils of a series have major horizons that are similar in composition, thickness, and arrangement. The soils of a given series can differ in texture of the surface layer, slope, stoniness, salinity, degree of erosion, and other characteristics that affect their use. On the basis of such differences, a soil series is divided into soil phases. Most of the areas shown on the detailed soil map are phases of soil series. The name of a soil phase commonly indicates a feature that affects use or management.

For example, Santa Marta 1 (coarse-loamy, subactive, isothermic Oxyaquic Haplustepts on toeslopes) and Santa Marta 12 (fine-loamy, mixed, subactive, isothermic Oxic Haplustepts on footslopes) are both in the Soil Map Unit 203 (Igneous), are similar soils, and are on the same landscape. They differ, however, in such features as surface texture and water saturation within a depth of 100 cm (Oxyaquic). Both soils are in the same soil map unit as a complex.

A complex consists of two or more soils or miscellaneous areas in such an intricate pattern or in such small areas that they cannot be shown separately on the maps. The pattern and proportion of the soils or miscellaneous areas are somewhat similar in all areas.

This survey includes miscellaneous areas. Such areas have little or no soil material and support little or no vegetation. Bedrock exposure is an example.

The detailed descriptions of soil map units are based on 12 soil descriptions (table 2; fig. 27). However, two soil descriptions are based on auger holes. A summary of the information about soil profiles, their location, slope position, and parent material is provided in tables 2 and 3.

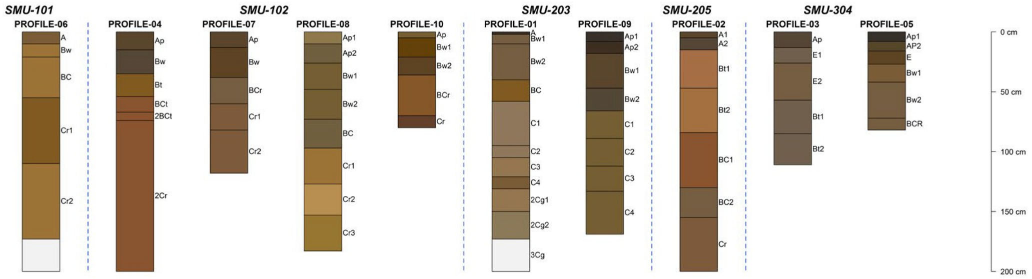

Figure 27.—Genetic horizon thickness and designation of major soil profiles described in the survey area for soil map units.

Table 2.—Soil Map Units, Parent Material, and Coordinates of Soil Profiles.

SMU symbol	Soil profile	Parent material	Lat.**	Long.**
101	06	Metamorphic	11.236872	-73.787415
102	04	Metamorphic	11.184852	-73.306128
102	07	Metamorphic	11.238688	-73.787341
102	09	Metamorphic	11.224134	-73.786738
102	08*	Metamorphic	11.238845	-73.787367
102	10*	Metamorphic	11.222372	-73.787197
202	13	Igneous/Metamorphic	11.229208	-73.721968
203	09	Igneous	11.185335	-73.751448
304	03	Sedimentary	11.260574	-73.28298
304	05	Sedimentary	11.249846	-73.778898
203	01	Igneous/Metamorphic	11.175979	-73.411446
205	02	Igneous	11.183659	-73.483492

* Based on auger hole descriptions.
** Geographic Coordinate System: GCS_WGS_1984.

Table 3.—Soil Map Unit Landscapes, Slope Positions, and Profile Slope Positions.

SMU symbol	Soil name	Landscape	Profile slope position	SMU slope position
101	Santa Marta 06	Mountain System	Shoulder	Summit
102	Santa Marta 04	Mountain System	Backslope	Summit
102	Santa Marta 07	Mountain System	Backslope	Summit
102	Santa Marta 09	Mountain System	Backslope	Footslope/ Toeslope
102	Santa Marta 08*	Mountain System	Backslope	Backslope
102	Santa Marta 10*	Mountain System	Backslope	Footslope/ Toeslope
202	Santa Marta 13	Mountain System	Backslope	Footslope/ Toeslope
203	Santa Marta 12	Mountain System	Toeslope	Backslope
304	Santa Marta 03	Alluvial Plain	Rising Flat	Rising Flat
304	Santa Marta 05	Alluvial Plain	Toeslope	Shoulder
203	Santa Marta 01	Mountain System	Footslope	Footslope/ Toeslope
205	Santa Marta 02	Mountain System	Summit	Backslope

* Based on auger hole descriptions.

The differences between soil profiles and soil map units for some of the slope positions are expected due to the differences in the methods used to assign the positions. The slope positions for the soil profiles were assigned by the soil scientists in the field. The slope positions based on soil map units, however, are based on the soil map units using terrain analysis from elevation. The soil map units based on terrain attributes do not necessarily capture the local or within-soil-map-unit variability of topographic features. The ability of the map units derived from terrain analysis to accurately represent local topography is limited by the quality and resolution of the elevation data as well as the number and type of terrain attributes used in the terrain analysis. Thus, the map units derived from elevation are broader.

101.—Santa Marta fine-loamy, mixed, subactive, isothermic Oxic Haplustepts

Site 6: On shoulder slopes, formed in igneous and metamorphic parent materials

Soil Profile Description

A—0 to 10 centimeters (pit); dark yellowish brown (10YR 4/4) clay loam; weak medium granular structure; very friable; 5% coarse, 3% medium, and 3% fine gravel; slightly sticky, slightly plastic; many fine and medium and common coarse and very fine roots and common medium and coarse pores throughout; moderately acid; clear smooth boundary.

Bw—10 to 21 centimeters (pit); yellowish brown (10YR 5/6) silt loam; weak fine subangular blocky structure; friable; slightly sticky, moderately plastic; common coarse, medium, fine, and very fine roots and common very fine, fine, and coarse pores throughout; thinly layered (0.5 to 3 mm) paralithic materials that are

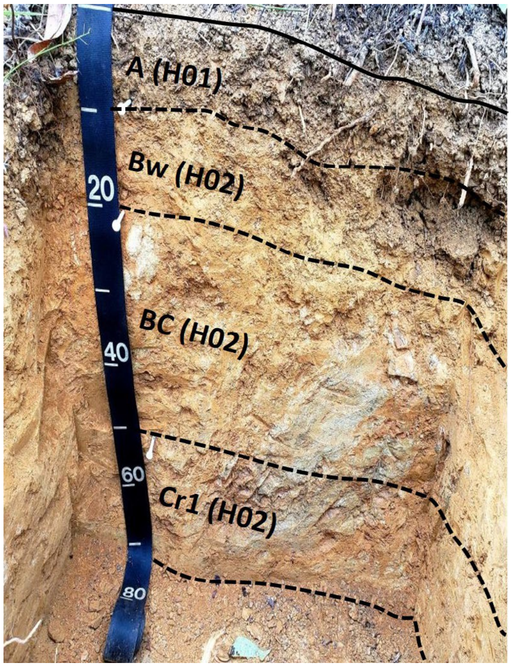

Figure 28 (left).—Soil profile of Santa Marta Map Unit 101, Site 6.
Figure 29 (right).—Closer look at weak fine subangular blocky structure parting to massive; friable to weakly cemented yellowish brown and yellowish red, thinly layered (0.5 to 3 mm) paralithic materials generally moderately tilted to horizontal.

generally moderately tilted to horizontal, easily broken by hand or "peeled" with a knife, and interwoven with soil materials; 3% weakly cemented; common fine brown (10YR 5/3) clay skins; strongly acid; clear wavy to irregular boundary.

BC—21 to 55 centimeters (pit); yellowish brown (10YR 5/6) clay loam; weak fine subangular blocky structure parting to weak medium platy; friable; 10% coarse yellowish red (5YR 5/6) paragravel; clay skins on seams of ped faces; slightly sticky, moderately plastic; common fine and medium roots and common coarse, medium, fine, and very fine pores throughout; strongly acid; clear wavy or irregular boundary.

Cr1—55 to 110 centimeters (pit); dark yellowish brown (10YR 4/6) loam; weak fine subangular blocky structure parting to massive; friable to weakly cemented yellowish brown (10YR 5/4) and yellowish red (5YR 5/6) thinly layered (0.5 to 3 mm) paralithic materials generally moderately tilted to horizontal (fig. 28), easily broken by hand and or "peeled" with knife interwoven with soil materials; discontinuous clay skins on seams of ped faces; slightly sticky, slightly plastic; common fine and very fine roots and few very fine pores throughout; moderately acid; gradual wavy boundary.

Cr2—110 to 173 centimeters (auger); 60% yellowish brown (10YR 5/6) sandy loam; dark red (2.5YR 4/6) rhodic colored paralithic, saprolitic materials interwoven with soil materials; massive; firm to cemented; slightly sticky, slightly plastic; slightly acid.

Cr3—173 to 200 centimeters (auger); 60% yellowish brown (10YR 5/6) sandy loam; dark red (2.5YR 4/6) rhodic colored paralithic, saprolitic materials interwoven with soil materials; massive; firm to cemented; slightly sticky, slightly plastic; slightly acid.

Soil Properties: Distribution by Depth in the Profile

The distribution of soil properties by depth for the representative profile varies by soil property. The distribution of sand, silt, and clay by depth changes between different horizons (fig. 30).

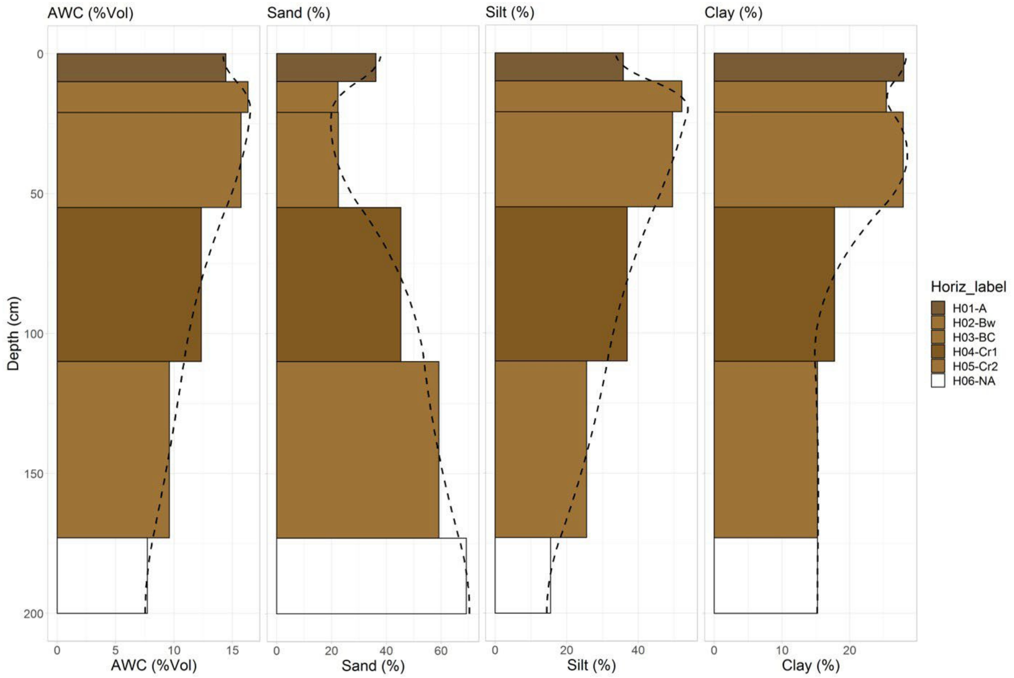

Figure 30.—Distribution of physical soil properties by depth: available water holding capacity and content of sand, silt, and clay.

The sand content is about 38 percent in the A (H01) horizon and decreases to 22 percent in the Bw (H02) and BC (H03) horizons. A rapid increase in sand content, up to 60 percent, in the subsequent deeper layers is associated with weathered bedrock (Cr). In contrast, the content of clay and silt increases slightly from surface horizon (A–H01) to the Bw and BC horizons and is then followed by a decrease in the Cr horizons. The silt content is close to 50 percent in the Bw and BC horizons and decreases on average to 30 percent in the Cr horizons. The content of clay follows similar patterns, decreasing with depth from 28 percent in the A (H01) horizon to 15 percent in the Cr2 layer. Because of the high silt content in the Bw and BC horizons, the available water capacity (AWC) in these horizons is about 0.15 on per volume fraction basis. The content deceases to about 0.10 in the Cr horizons.

The soil organic carbon (SOC) content is about 2.2 percent in the surface horizon (A–H01) and decreases rapidly to 0.5 percent in the Bw (H02) horizon (fig. 31). The SOC content is about 0.1 percent in the subsequent horizons below 50 cm. The effective cation exchange capacity (ECEC) decreases slightly from the surface horizon (A–H01) to the subsurface horizon (Bw–H02). It increases up to 15 meq/100 g soil in the Cr horizons. Other soil fertility indicators, such as content of potassium and phosphorous, are low and generally decrease with depth. The increase in phosphorous content in the Cr1 layer (to about 5 mg/kg soil) is most likely due to the parent material. Cadmium content is very low throughout the soil. Soil reaction is slightly acid to moderately acid. The mean soil pH is around 5.8 and does not vary with depth compared to the other soil properties.

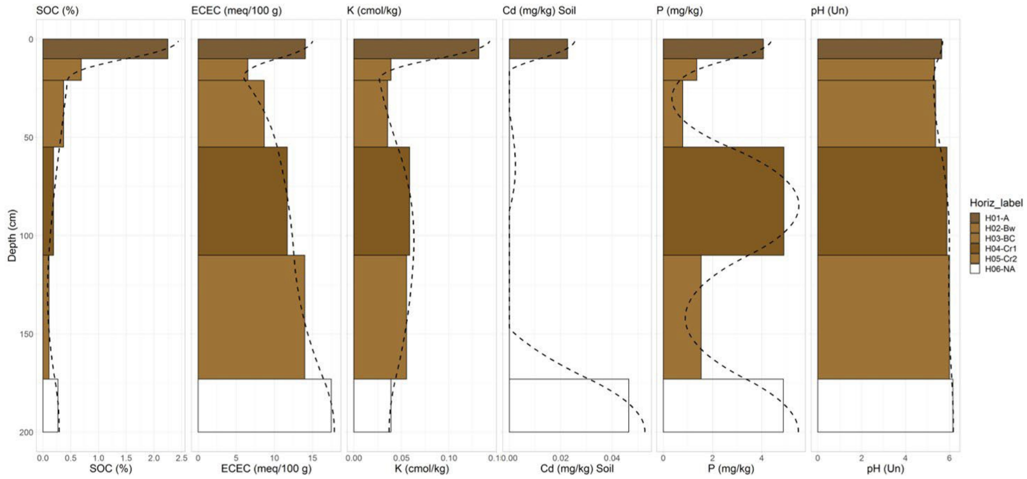

Figure 31.—Distribution by depth of soil fertility properties: soil organic carbon (%), effective cation exchange capacity (meq/100 g soils), potassium (cmol/kg soil), cadmium (mg/kg soil), phosphorus (mg/kg soil), and soil reaction (pH).

Soil Properties in the Soil Map Unit: Distribution by Depth

The distribution of soil properties by depth varies widely within the soil map unit. This variability is shown by the width of the 90 percent confidence intervals (fig. 32). The uncertainty increases with depth for most of the soil properties, generally due to

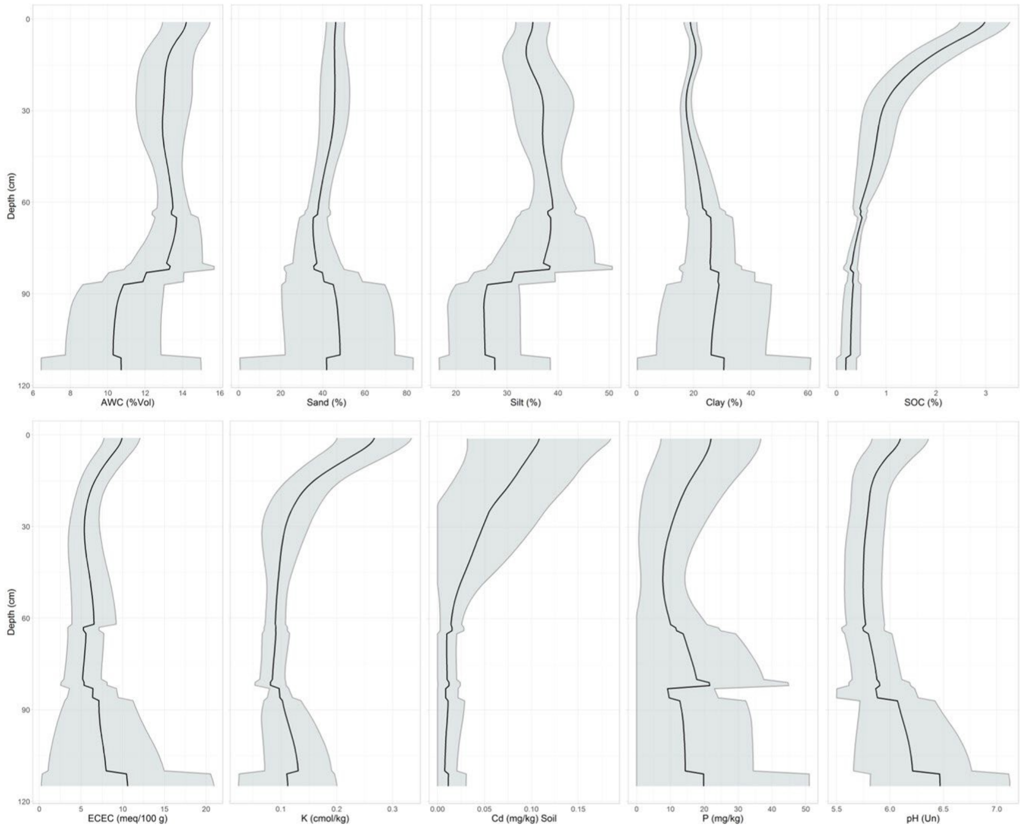

Figure 32.—The gray area is the 90 percent confidence interval for distribution by depth of physical soil properties and soil fertility properties.

the limited number of observations in the subsurface horizons. The width of the interval increases, especially below 90 cm, for AWC, soil texture, ECEC, and pH. Interestingly, the uncertainty for SOC and cadmium is higher in the surface horizons. The wide variability within this soil map unit is related not only to the soil variability but potentially to the management of cacao biomass. The leaves and cacao shells are typically returned to the soil; in most cases, only on the surface. This practice may lead to an increase of bioavailable soil cadmium in surface horizons.

102.—Santa Marta fine-loamy, mixed, subactive, isothermic Oxic Haplustepts

Site 4: On backslopes, formed in metamorphic parent material

Soil Profile Description

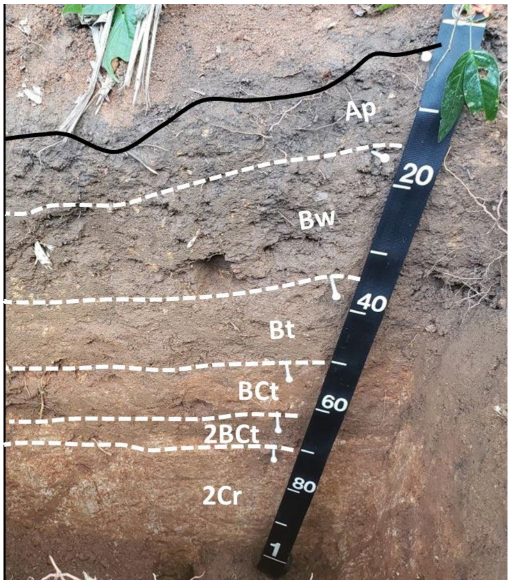

Figure 33.—Soil profile of Santa Marta Map Unit 102, Site 4.

Ap (H01)—0 to 15 centimeters (pit); dark brown (10YR 3/3) sandy clay loam; weak medium granular structure; very friable; 10% medium angular gravel; nonsticky, slightly plastic; many fine and medium and common coarse roots and common fine pores throughout; moderately acid; clear smooth boundary.

Bw (H02)—15 to 35 centimeters (pit); very dark grayish brown (10YR 3/2) sandy clay loam; moderate medium subangular blocky structure; very friable; 10% medium and 3% coarse gravel; slightly sticky, slightly plastic; common coarse, medium, and fine roots and common fine, medium, and coarse pores throughout; moderately acid; clear smooth boundary.

Bt (H03)—35 to 54 centimeters (pit); dark yellowish brown (10YR 4/6) sandy clay loam; weak medium subangular blocky structure; friable; 10% medium and 3% coarse saprolite paragravel; many prominent clay skins along cracks (natural breaks); slightly sticky, moderately plastic; common fine, medium, and coarse roots and many fine and common medium and coarse pores throughout; moderately acid; 3% common fine mica flakes and 3% charcoal; gradual smooth boundary.

BCt (H04)—54 to 67 centimeters (pit); yellowish red (5YR 4/6) sandy clay loam; weak fine subangular blocky structure; friable to 30% weakly cemented coarse saprolitic materials; many clay skins along cracks (natural breaks); slightly sticky, moderately plastic; common very fine, fine, medium, and coarse roots and common medium and fine and few coarse pores throughout; moderately acid; clear wavy boundary.

2BCt (H05)—67 to 74 centimeters (auger); yellowish red (5YR 4/6) clay loam; weak fine subangular blocky structure; firm; many clay skins along cracks (natural breaks); slightly sticky, moderately plastic; common coarse, medium, and fine and few very fine roots and common medium and fine and few coarse pores throughout; moderately acid; gradual wavy boundary.

2Cr (H06)—74 to 200 centimeters (auger); 60% yellowish red (5YR 4/6) sandy clay loam; variegated saprolitic materials, 30% red (2.5YR 4/6), 10% light gray (10YR 7/1), and 5% dark gray (10YR 4/1); weak medium subangular blocky structure parting to weak fine granular; friable; 1% discontinuous clay skins along natural breaks on ped faces; nonsticky, nonplastic; very strongly acid.

Note 1: The paralithic materials found at a depth of 54 cm are noncemented, can be cut with a spade with moderate force, and can be bored with a bucket auger.

Note 2: A discontinuity was perceived in the field, but the physical and chemical data for the horizon at 67–74 cm are consistent with a natural horizon progression from horizons above.

Soil Properties in the Profile: Distribution by Depth

The sand content is about 65 percent in the Ap (H01) horizon and decreases to slightly below 60 percent in the Bw (H02) horizon through the BCt (H04) horizon (fig. 34). The lowest sand content (~40 percent) is measured in the 2BCt horizon (H05). On average, silt and sand content are about 20 percent. The silt content is about 10 percent in the Ap surface horizon (H01), increases to 30 percent in the 2BCt, and is 20 percent below 75 cm. Because of low silt content and high sand content, the available water capacity (AWC) is low. It is about 0.10 on a per volume fraction basis for this soil profile.

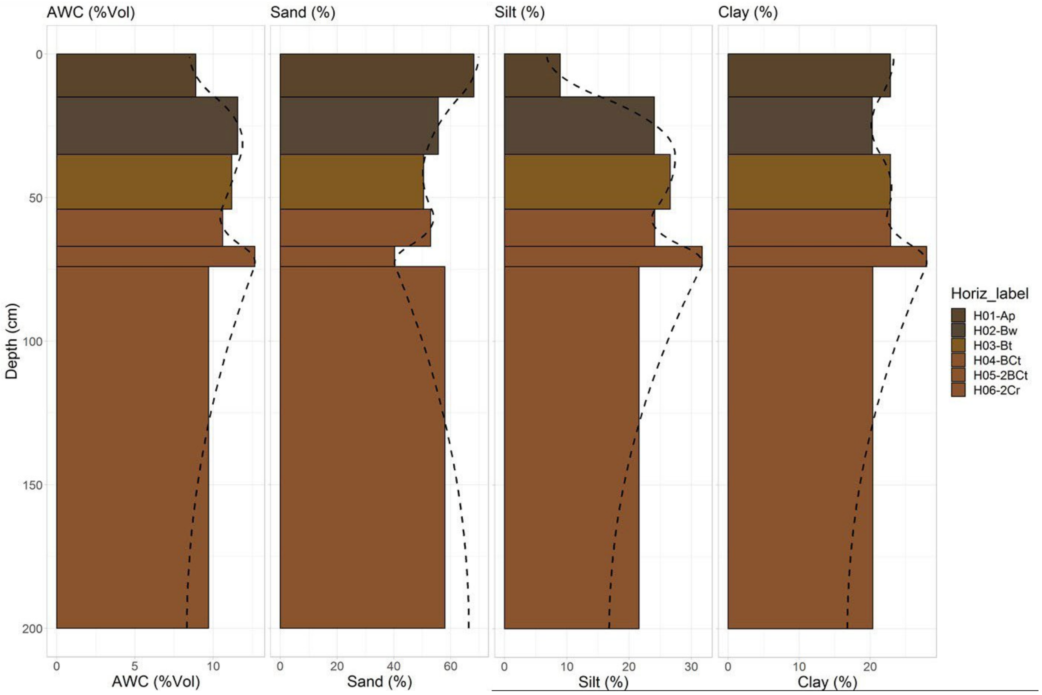

Figure 34.—Distribution of physical soil properties by depth: available water holding capacity (AWC) and content of sand, silt, and clay in Santa Marta 4.

The soil organic carbon (SOC) content is about 1.8 percent in the surface horizon (Ap–H01) and increases slightly in the Bw (H02) horizon. The SOC content decreases rapidly (to less than 0.5 percent) below 35 cm in the subsequent horizons (fig. 35). The effective cation exchange capacity (ECEC) decreases slightly from the surface horizon (Ap–H01) to subsurface horizon (Bw–H02) and then increases up to 7.5 meq/100 g soil in the 2Cr horizon. The other soil fertility indicators, such as content of potassium and phosphorus, are low and generally decrease with depth. Cadmium content is the highest (0.007 mg/kg soil) in the surface layer and decreases below the detection limits in the subsequent deeper horizons. Soil reaction is slightly acid or moderately acid. The mean soil pH is around 5.8 and does not vary with depth compared to the other soil properties.

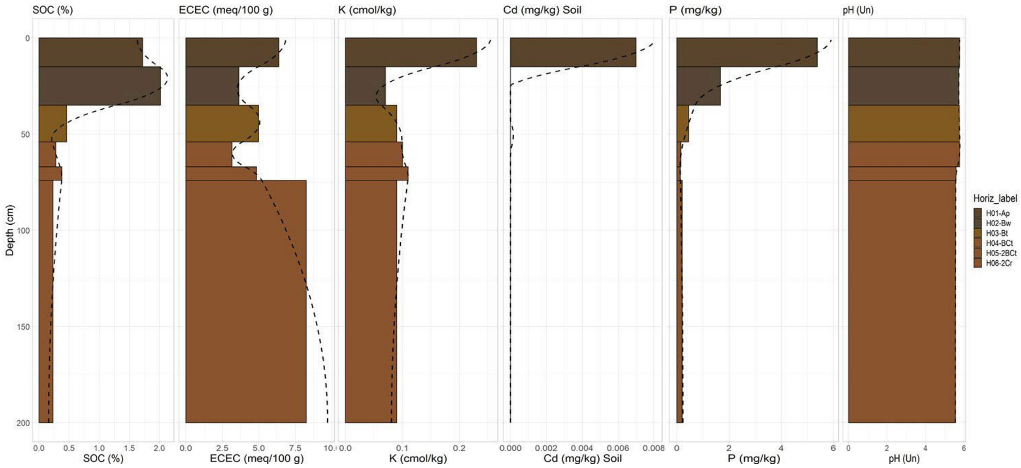

Figure 35.—Distribution by depth of soil fertility properties for Santa Marta 4.

Site 7: On backslopes, formed in metamorphic parent material

Soil Profile Description

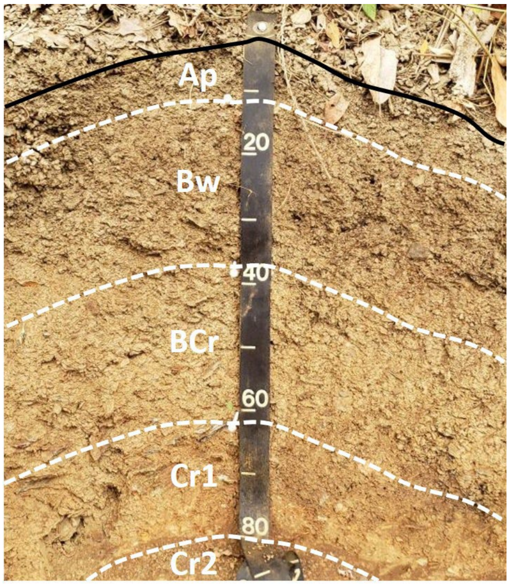

Figure 36.—Soil profile of Santa Marta Map Unit 102, Site 7.

Ap (H01)—0 to 13 centimeters (pit); dark brown (10YR 3/3) clay loam; moderate coarse granular structure; very friable; 5% cobbles (<150 mm); slightly sticky, moderately plastic; many medium, common fine, and few coarse roots and common medium and fine pores throughout; common wormcasts on the surface; slightly acid; clear smooth boundary.

Bw (H02)—13 to 38 centimeters (pit); dark yellowish brown (10YR 3/4) very gravelly clay loam; moderate medium subangular blocky structure; friable; 20% coarse, 15% medium, and 10% fine gravel and 5% cobbles; slightly sticky, moderately plastic; common medium and few fine and very fine roots and common fine and medium pores throughout; slightly acid; clear wavy boundary.

BCr (H03)—38 to 60 centimeters (pit); brown (10YR 4/3) very gravelly loam; weak fine subangular blocky structure parting to weak medium platy; friable; 20% coarse, 10% medium, and 8% fine gravel and 3% cobbles; slightly sticky, moderately plastic; few fine and medium roots and common medium and many coarse pores throughout; discontinuous paralithic, dense, soft layers of biotite (black mica) with 2% other mica flakes; slightly acid; clear wavy and irregular boundary.

Cr1 (H04)—60 to 82 centimeters (pit); dark brown (7.5YR 4/4) very paraflaggy silt loam; moderate medium subangular blocky structure parting to massive; firm; 40% cobble sized, tilted, weathered pararock flagstones that are mainly layered, metamorphic, weakly cemented, and intertwined with soil material; slightly sticky, slightly plastic; few coarse and medium roots and few fine, medium, and coarse pores throughout; slightly acid; gradual wavy boundary.

Cr2 (H05)—82 to 118 centimeters (auger); dark brown (7.5YR 4/4) very paracobbly loam; moderate medium subangular blocky structure parting to massive; firm; 40% pararock cobbles intertwined with soil materials; light gray rock fragments intertwined with reddish soil materials; slightly sticky, slightly plastic; few medium and fine roots and few medium and fine pores throughout; slightly acid.

R—118+ centimeters (auger); strongly cemented and very strongly cemented, gray, metamorphic rock; cannot be easily broken with spade and heavy force.

Note: Although paralithic materials were continuous at 60 cm, the horizon at this depth does not appear to be root restricting. Soil materials are intertwined through the horizons Cr1; thus, the designation of a particle-size control section to 100 cm is appropriate.

Soil Properties in the Profile: Distribution by Depth

The average sand content in this soil profile is about 30 percent, which is two times smaller than that of the Santa Marta 4 soil profile (fig. 37). The sand content varies slightly with depth. The Ap (H01) horizon has the highest amount of sand (38 percent) and the Cr1 (H04) horizon has the lowest amount (about 10 percent). On average, the content of silt is about 35 percent, which is higher than in the Santa Marta 4 soil profile. The silt content is about 33 percent in the surface horizon (Ap–H01) and increases steadily to about 55 percent below 60 cm in the weathered bedrock horizons (Cr1–

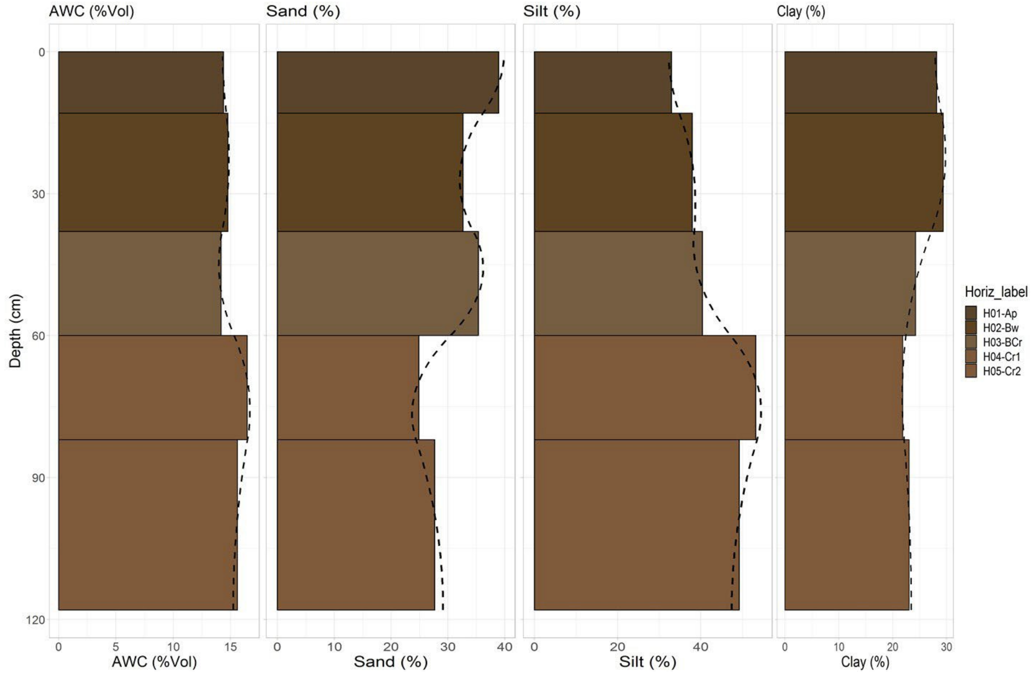

Figure 37.—Distribution of physical soil properties by depth: available water holding capacity (AWC) and content of sand, silt, and clay in Santa Marta 7.

H04 and Cr2–H05). The average clay content is about 25 percent and varies slightly between horizons. It is 22 percent in the Cr1 (H04) horizon and 28 percent in the Bw (H02) horizon. The average AWC is about 15 percent on a per-volume basis and varies slightly throughout the soil profile.

The soil organic carbon (SOC) content is about 2.8 percent in the Ap (H01) horizon and decreases to 2.2 percent in the Bw (H02) horizon (fig. 38). Below a depth of 40 cm, the SOC content decreases rapidly to an average of 0.6 percent. SOC has little variability between horizons (fig. 38). The effective cation exchange capacity (ECEC) is 11.0 and 8.0 meq/100 g soil in the two surface horizons (Ap–H01) and (Bw–H02), respectively. It decreases to 5 meq/100 g soil below 40 cm. Potassium content and phosphorus content follow similar trends of decreasing with soil depth. The mean soil potassium content is about 0.18 cmol/kg soil and decreases from 0.32 cmol/kg soil to about 0.10 cmol/kg soil below 40 cm. Phosphorous content decreases from about 8 mg/kg soil in the (Ap–H01) horizon to 2.0 mg/kg soil below 40 cm. Cadmium content for the surface horizons Ap (H01) and Bw (H02) is about 0.05 mg/kg soil, which is an order of magnitude higher than in the Santa Marta 4 soil profile. The highest value for cadmium in the Santa Marta 4 profile is about 0.007 mg/kg soil. Similarly to in the Santa Marta 4 soil profile, the cadmium content decreases below the detection limits in the subsequent, deeper horizons. Soil reaction is slightly acid. The mean soil pH is around 6.0 and does not vary with depth compared to the other soil properties.

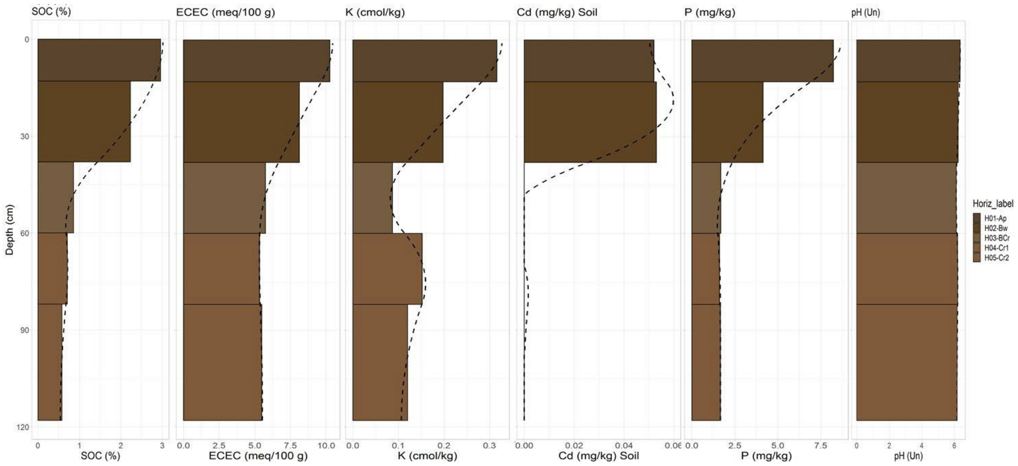

Figure 38.—Distribution of soil fertility properties by depth: soil organic carbon (%), effective cation exchange capacity (meq/100 g soil), potassium (cmol/kg soil), cadmium (mg/kg soil), phosphorus (mg/kg soil), and soil reaction (pH) in Santa Marta 7.

Site 9: On backslopes, formed in metamorphic parent material

Soil Profile Description

Ap1—0 to 10 centimeters (cut); light olive brown (2.5Y 5/4) loam; moderate medium granular structure parting to moderate medium subangular blocky; friable; 4% cobbles and 5% medium and 5% fine gravel; slightly sticky, slightly plastic; common medium and coarse and few fine roots and many medium, common coarse, and few fine pores throughout; very strongly acid; clear smooth boundary.

Ap2—10 to 26 centimeters (cut); olive brown (2.5Y 4/3) loam; moderate medium subangular blocky structure; friable; 5% medium gravel and 3% cobbles; slightly sticky, slightly plastic; common coarse and medium and few fine roots and common fine and few coarse and medium pores throughout; strongly acid; gradual smooth boundary.

Bw1—26 to 48 centimeters (cut); olive brown (2.5Y 4/4) loam; moderate medium subangular blocky structure; friable; 5% medium and 5% fine gravel and 2% cobbles; slightly sticky, slightly plastic; many medium and few coarse and fine roots and common medium and few coarse pores throughout; strongly acid; clear smooth boundary.

Bw2—48 to 73 centimeters (cut); olive brown (2.5Y 4/4) gravelly loam; moderate medium subangular blocky structure parting to weak medium subangular blocky; friable; white, pale yellow, and gray 8% medium and 5% fine gravel and 6% pararock cobbles; nonsticky, slightly plastic; many medium and few fine roots and few fine and medium pores throughout; strongly acid; gradual wavy boundary.

BC—73 to 97 centimeters (cut); olive brown (2.5Y 4/3) very parachannery silt loam; weak fine subangular blocky structure; friable; 15% paracobbles, 10% paraflagstones, and 5% fine and 5% medium paragravel; nonsticky, slightly plastic; few fine and medium roots and few fine and medium pores throughout; strongly acid; gradual wavy boundary.

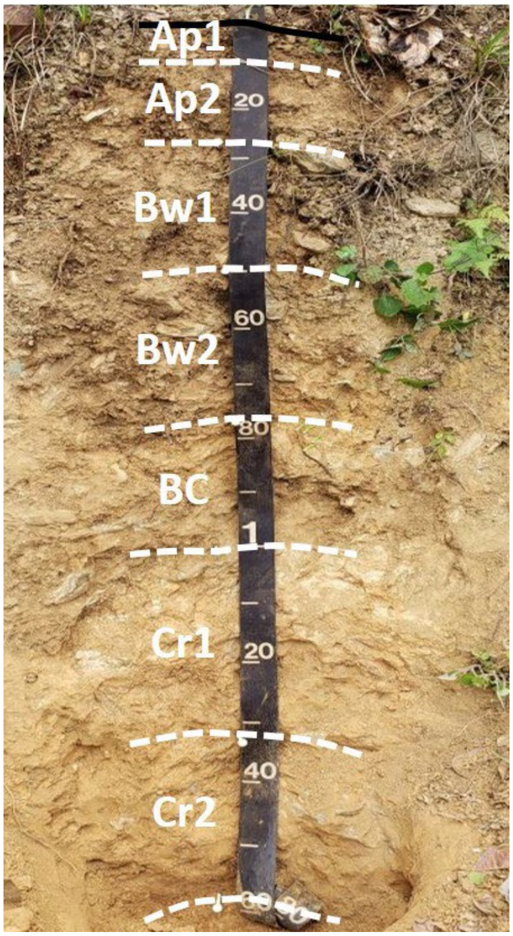

Figure 39.—Soil profile of Santa Marta Map Unit 102, Site 9.

Cr1—97 to 127 centimeters (cut); yellowish brown (10YR 5/6) very parachannery silt loam; weak medium subangular blocky structure; friable; discontinuous, inclined to horizontal 15% paracobbles, 10% paraflagstones, and 5% fine and 5% medium paragravel; nonsticky, nonplastic; few fine roots and common fine and few medium pores throughout; moderately acid; gradual smooth boundary.

Cr2—127 to 153 centimeters (cut); brownish yellow (10YR 6/6) vey parachannery loam; weak medium subangular blocky structure; very friable; discontinuous, inclined to horizontal 15% paracobbles, 10% paraflagstones, and 5% fine and 8% medium paragravel; nonsticky, nonplastic; few medium and fine pores throughout; strongly acid; gradual smooth boundary.

Cr3—153 to 183 centimeters (auger); dark brown (2.5Y 5/6) parachannery silt loam; weak medium subangular blocky structure parting to weak fine subangular blocky; very friable; consolidated pararock 15% parachanners and 10% paraflagstones; nonsticky, nonplastic; moderately acid.

R—183+ centimeters (auger); bedrock.

Note: Although paralithic pararock materials are discontinuous at 73 cm, the horizon is not root restricting until a depth of about 127 cm. Materials are expressed as a horizontal layer on the face of cut but are inclined toward the mountain on natural tilt/uplift.

Soil Properties in the Profile: Distribution by Depth

The distribution of soil properties by depth for the representative profile varies by soil property. The distribution of sand, silt, and clay by depth changes between different horizons (fig. 40).

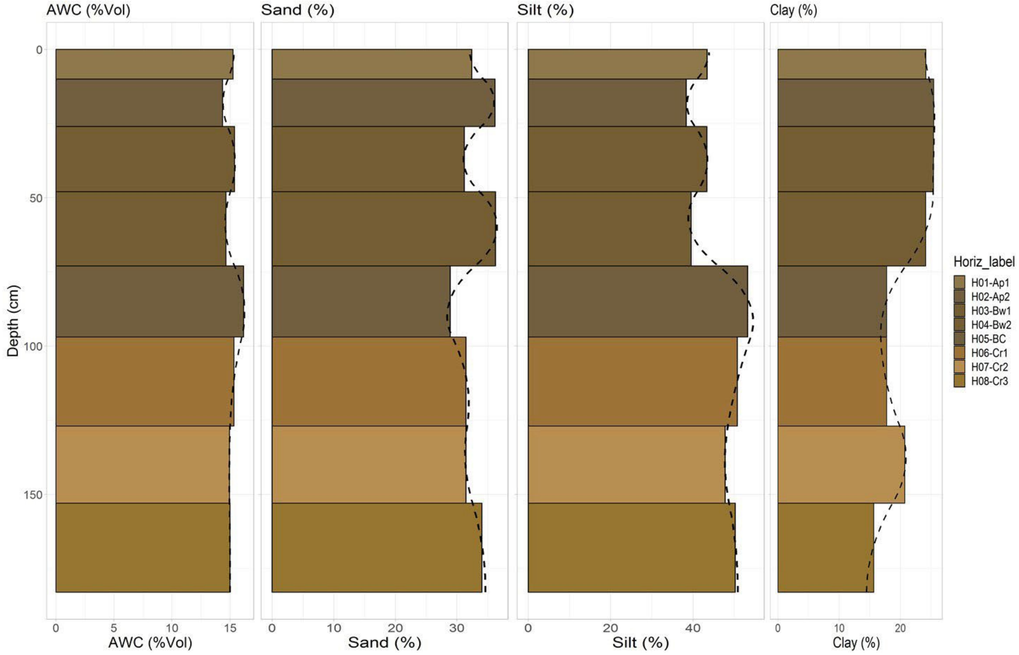

Figure 40.—Distribution of physical soil properties by depth: available water holding capacity and content of sand, silt, and clay in Santa Marta 9.

The average sand content for the Santa Marta 9 profile is about 30 percent and comparable with Santa Marta 7, which is two times smaller than that of the Santa Marta 4 soil profile. The sand content varies slightly with depth, ranging from 28 percent in the BC (H05) horizon to 36 percent in the Bw2 (H04) horizon. On average, the content of silt is about 35 percent and comparable with that of the Santa Marta 7 soil, which is higher than that of the Santa Marta 4 soil profile. The silt content ranges from 40 percent in the Ap2 (H02) horizon to 54 percent in the BC (H05) horizon. It increases slightly with soil depth. The average clay content is about 20 percent. It varies slightly, ranging between 17 percent in the Cr3 (H08) horizon to 24 percent in the Ap2 (H02) horizon and the Bw1 (H03) horizon. The average AWC is about 15 percent on a per-volume basis and varies slightly throughout the soil profile.

Soil organic carbon (SOC) content averages about 1.6 percent in the upper four horizons (Ap1–H01; Ap2–H02; Bw1–H03; and Bw2–H04). It varies slightly between the horizons (fig. 41). SOC content decreases rapidly below 70 cm to about 0.3 percent. The effective cation exchange capacity (ECEC) follows a similar trend and varies slightly in the first upper horizons, ranging from 7.5 to 9.0 meq/10 g soil. ECEC decreases to below 4.0 meq/100 g soil below a depth of 70 cm. Potassium content and phosphorus content follow opposite trends with soil depth. The mean potassium content decreases from 0.09 cmol/kg soil in the upper four horizons to 0.03 cmol/kg soil below a depth of 70 cm. The phosphorus content, by contrast, averages about 80 mg/kg soil in the upper five horizons and increases rapidly to above 200 mg/kg soil below a depth of 100 cm. The average cadmium content in the upper four horizons (Ap1–H01; Ap2–H02; Bw1–H03; and Bw2–H04) is about 0.028 mg/kg soil and decreases rapidly to less than 0.005 mg/kg soil in the BC (H05) though Cr2 (H07) horizons. The cadmium

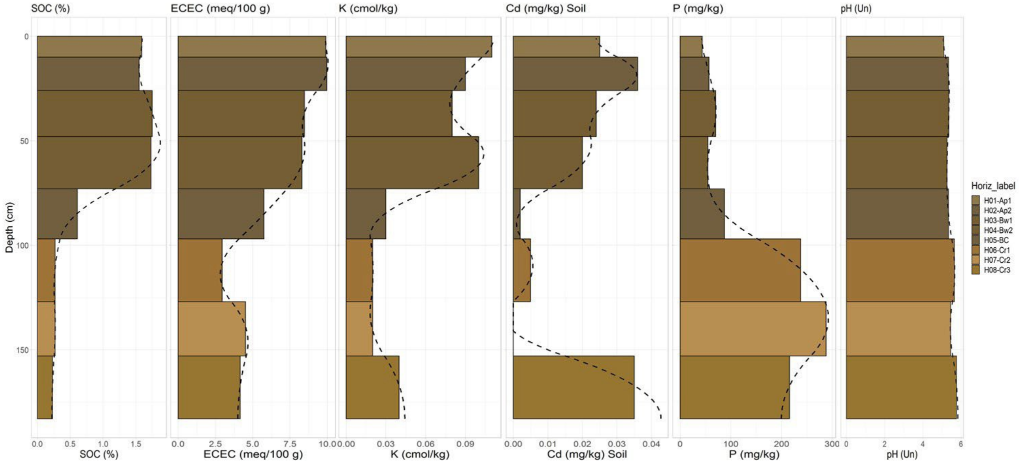

Figure 41.—Distribution of soil fertility properties by depth: soil organic carbon (%), effective cation exchange capacity (meq/100 g soil), potassium (cmol/kg soil), cadmium (mg/kg soil), phosphorus (mg/kg soil), and soil reaction (pH) in Santa Marta 9.

content increases to 0.035 mg/kg soil in the Cr3 horizon below 150 cm. The abrupt changes for ECEC, potassium, cadmium, and P are at the boundaries between A and B horizons and at the boundaries between C horizons and the weathered-bedrock Cr horizons. Soil reaction is moderately acid to strongly acid. The mean soil pH is around 5.5 and varies slightly with depth compared to the other soil properties.

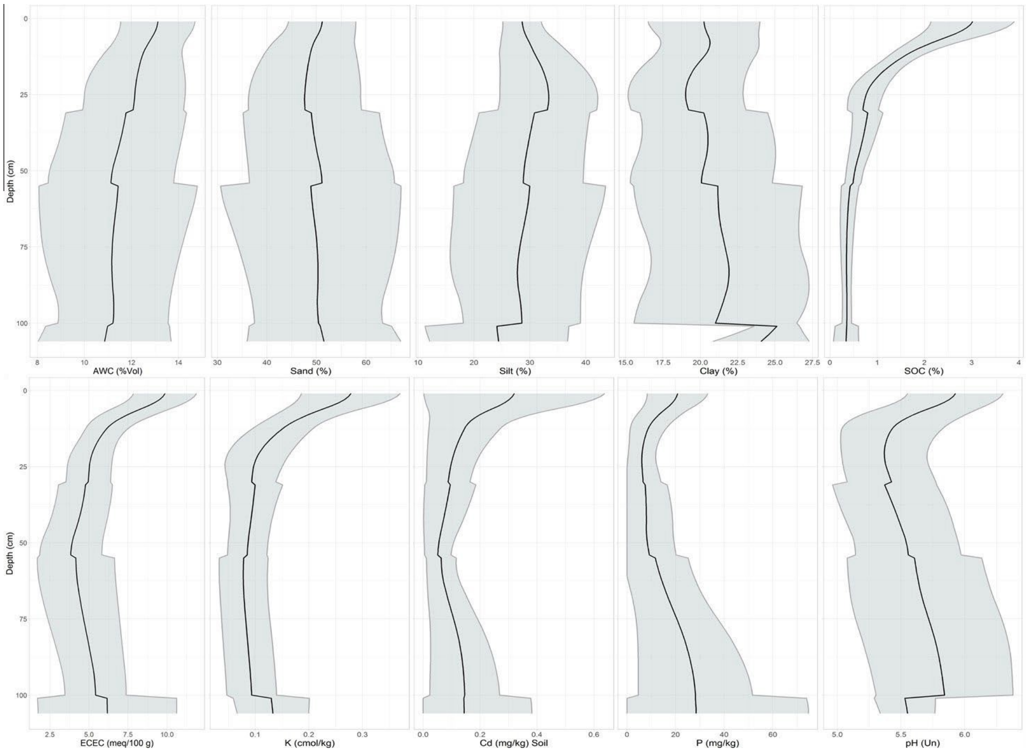

Figure 42.—The gray area is the 90 percent confidence interval for distribution by depth of physical soil properties and soil fertility properties.

Soil Properties in the Soil Map Unit: Distribution by Depth

The distribution of soil properties by depth varies widely within the soil map unit. This variability is shown by the width of the 90 percent confidence intervals (fig. 42). The 90 percent confidence interval is wide and varies slightly with depth, indicating a great uncertainty throughout the soil profile. Generally, the uncertainty increases with depth. SOC is an exception. Uncertainty regarding SOC content is greater in the surface horizons. The confidence intervals increase with depth for most of the soil properties, generally due to the limited number of observations in the subsurface horizons. The width of the interval increases, especially below 30 cm, for AWC, soil texture, cadmium, and phosphorus. The uncertainty for soil pH is high. It varies by 1.0 pH unit in the surface horizon and by as much as 1.5 pH unit in the subsurface horizons. The great uncertainty within this soil map unit is related to the soil variability and potentially to the management of cacao biomass. The leaves and cacao shells are typically returned to the soil, and in most cases only on the surface. This practice may lead to an increase of bioavailable soil cadmium.

202.—Santa Marta coarse loamy, mixed, superactive, isothermic Oxic Haplustepts

Site 13: On backslopes, formed in igneous and metamorphic parent materials

Soil Profile Description

Ap1 (H01)—0 to 5 centimeters (pit); olive brown (2.5Y 4/4) cobbly loam; weak medium granular structure parting to weak fine granular; friable; 15% cobbles and 15% medium gravel; nonsticky, moderately plastic; common fine, medium, and coarse roots and common fine and medium pores throughout; slightly acid; clear wavy boundary.

Bw1 (H02)—5 to 21 centimeters (pit); dark yellowish brown (10YR 3/6) gravelly loam; weak fine subangular blocky structure parting to moderate fine granular; friable; 3% medium gravel; slightly sticky, moderately plastic; common coarse, medium, fine, and very fine roots and common fine and coarse pores throughout; moderately acid; clear wavy boundary.

Figure 43.—Soil profile of Santa Marta Map Unit 202, Site 13.

Bw2 (H03)—21 to 36 centimeters (pit); dark yellowish brown (10YR 3/4) loam; weak fine subangular blocky structure parting to moderate fine granular; friable; 3% cobbles; pararock fragments of limestone and weathered granite; slightly sticky, slightly plastic; common coarse, medium, fine, and very fine roots and common fine and medium pores throughout; moderately acid; gradual smooth boundary.

BCr (H04)—36 to 70 centimeters (pit); 60% strong brown (7.5YR 4/6) and 40% yellowish red (5YR 4/6) loam; weak fine subangular blocky structure parting to massive; friable; 10% stones; single grained weathered granite; medium discontinuous clay skins along faces of weathered granite; slightly sticky, moderately plastic; common coarse, medium, fine, and very fine roots and common coarse, fine, and very fine pores throughout; moderately acid; gradual smooth boundary.

Cr (H05)—70+ centimeters (pit); 70% dark reddish brown (5YR 3/4) and 30% yellow (10YR 7/6) loam; weak fine angular blocky structure; inclined obliquely, stratified weathered granite with soil seams intertwined between paralithic materials; discontinuous clay skins along faces of seams; common coarse and fine roots in cracks and along soil seams; moderately acid.

Soil Properties in the Profile: Distribution by Depth

The average sand content for the Santa Marta 13 profile is about 40 percent (fig. 44). The sand content increases with depth from 35 percent in the Bw1 (H02) horizon to 52 percent in the Cr (H05) horizon. On average, the content of silt is about 40 percent and comparable with that of the Santa Marta 7 soil, which is higher than that of the Santa Marta 4 soil profile. The silt content decreases with depth from 47 percent (Ap–H01; Bw1–H02) to 34 percent (Cr–H05). The average clay content is about 16 percent and varies slightly between horizons. It is 14 percent in the Ap (H01) horizon and 18 percent in the Bw1 (H02), Bw2 (H03), and BCr (H04) horizons. The average AWC is about 13 percent on a per volume basis and decreases slightly throughout the soil profile, decreasing from 15 percent to 12 percent following the silt distribution by depth.

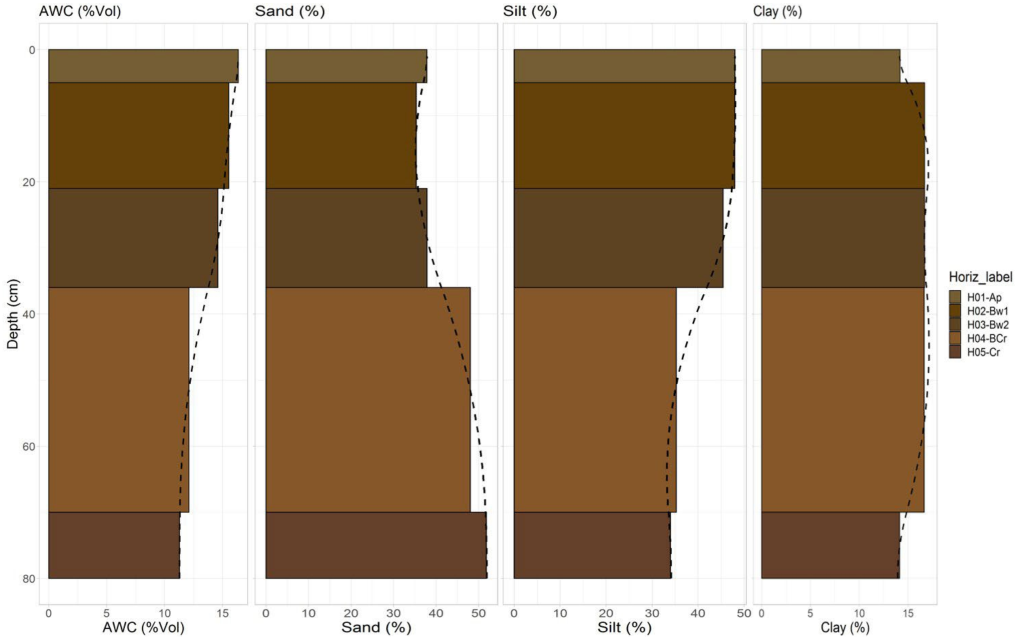

Figure 44.—Distribution of physical soil properties by depth: available water holding capacity and content of sand, silt, and clay in Santa Marta 13.

The soil organic carbon (SOC) content averages about 1.0 percent throughout the profile. It ranges from 2.2 percent in the Ap (H01) horizon to 0.2 percent in the Cr (H05) horizon (fig. 45). SOC content decreases rapidly with depth to less than 1.0 percent below 35 cm (fig. 45). The effective cation exchange capacity (ECEC) decreases slightly with depth. The mean ECEC for the first three horizons is only 12 meq/100 g soil. The ECEC increases slightly to 14 meq/100 g soil below a depth of 35 cm. Potassium content and phosphorus content decrease overall with soil depth. The potassium content ranges from 0.03 cmol/kg soil (Cr–H05) to 0.07 (Ap–H01). The phosphorus content is very low compared to the other soil profiles for this map unit. The content of phosphorus is only 2.8 mg/kg soil in the Ap (H01) horizon and decreases to 2.2 in the Bw2 (H03) and to 0.6 mg/kg soil below 35 cm. The cadmium content is 0.011 mg/kg soil in the Ap1 (H01) horizon and decreases rapidly to 0.003 in the Bw1 (H02) horizon. It is below detection limits in the Bw2 (H03) horizon. The cadmium content then increases rapidly to 0.018 mg/kg soil in the Cr (H05). The abrupt changes for cadmium and phosphorus are at the boundaries between A and B horizons and the weathered bedrock Cr horizons. Soil reaction is moderately acid. The mean soil pH is around 6.0 and varies slightly with depth compared to the other soil properties.

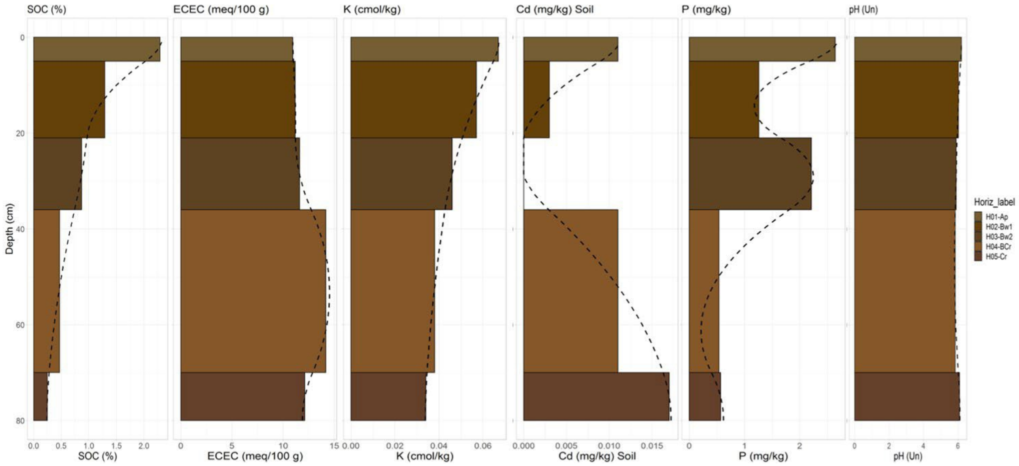

Figure 45.—Distribution of soil fertility properties by depth in Santa Marta 13.

Soil Properties in the Soil Map Unit: Distribution by Depth

The distribution of soil properties by depth varies widely within the soil map unit. This variability is shown by the width of the 90 percent confidence intervals (fig. 46). The width of the interval for AWC, soil texture, and pH increases with depth and is particularly wide below 100 cm. The interval for SOC is wider in the surface horizon than in the other horizons. Compared to the interval of other soil properties, however, the width of the interval for SOC content is small and varies only slightly with depth. This is most likely due to the limited number of measured values. Overall, the interval for most of the soil properties generally increases below a depth of 100 cm due to the limited number of observations in the subsurface horizons. The uncertainty for soil pH is high. It varies by 2.0 pH units, especially below 100 cm. The great uncertainty within the soil map unit is likely due to the soil variability and potentially due to the management of cacao biomass.

Figure 46.—The gray area is the 90 percent confidence interval for distribution by depth of physical soil properties and soil fertility properties.

203. —Santa Marta coarse-loamy, subactive, isothermic Oxyaquic Haplustepts

Site 1: On footslopes, formed in igneous and metamorphic parent materials

Soil Profile Description

A1 (H01)—0 to 2 centimeters (cut); very dark brown (10YR 2/2) sandy loam; moderate medium angular blocky structure; friable; nonsticky, nonplastic; common fine and medium and few coarse roots and few fine and medium pores throughout; moderately acid; clear smooth boundary.

Bw1 (H02)—2 to 10 centimeters (cut); brown (10YR 4/3) loam; moderate medium angular blocky structure parting to moderate medium platy; friable; slightly sticky, nonplastic; many fine and few medium and coarse roots and common fine and few medium pores throughout; strongly acid; gradual wavy boundary.

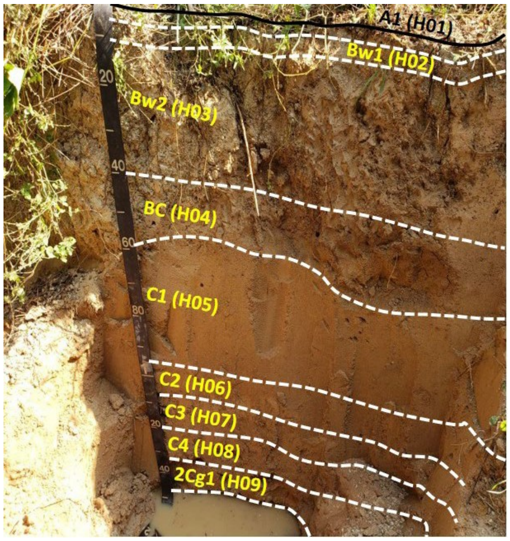

Figure 47.—Soil profile of Santa Marta Map Unit 203, Site 1.

Bw2 (H03)—10 to 40 centimeters (cut); very pale brown (10YR 4/3) loam; moderate medium subangular blocky; friable; nonsticky, nonplastic; common medium roots and common fine and few medium pores throughout; strongly acid; gradual wavy boundary.

BC (H04)—40 to 58 centimeters (cut); dark yellowish brown (10YR 4/6) sandy loam; moderate medium subangular blocky structure parting to moderate fine subangular blocky; very friable; slightly sticky, nonplastic; few medium roots throughout; moderately acid; gradual wavy boundary.

C1 (H05)—58 to 95 centimeters (cut); brown (10YR 5/3) sandy loam; weak fine subangular blocky structure parting to weak fine platy; very friable; nonsticky, nonplastic; common medium roots throughout; moderately acid; clear wavy boundary.

C2 (H06)—95 to 105 centimeters (cut); brown (10YR 5/3) sandy loam; weak fine subangular blocky structure parting to weak fine platy; very friable; slightly sticky, nonplastic; few very fine roots throughout; common medium prominent pale red (2.5YR 6/2) and common medium prominent yellowish red (5YR 4/6) masses of iron accumulation; strongly acid; clear smooth boundary.

C3 (H07)—105 to 121 centimeters (cut); yellowish brown (10YR 5/4) sandy loam; weak coarse subangular blocky structure parting to weak fine subangular blocky; very friable; slightly sticky, nonplastic; few fine roots throughout; common medium prominent yellowish red (5YR 4/6) masses of iron accumulation; moderately acid; gradual smooth boundary.

C4 (H08)—121 to 131 centimeters (cut); dark yellowish brown (10YR 4/4) sandy loam; massive; loose; nonsticky, nonplastic; common fine distinct grayish brown (10YR 5/2) masses of reduced iron; slightly acid; common fine mica flakes; gradual smooth boundary.

2Cg1 (H09)—131 to 150 centimeters (auger); 40% yellowish brown (10YR 5/4) and 60% grayish brown (10YR 5/2) sandy loam; massive; loose; nonsticky, nonplastic; moderately acid.

2Cg2 (H10)—150 to 173 centimeters (auger); light olive brown (2Y 5/3) loamy sand; massive; loose; nonsticky, nonplastic; strongly acid.

3Cg (H11)—173 to 200 centimeters (auger); greenish gray (10GY 5/1) gravelly loamy sand; massive; loose; nonsticky, nonplastic; moderately acid.

Soil Properties in the Profile: Distribution by Depth

The distribution of soil properties by depth for the representative profile is very diverse depending on the soil property. The distribution of sand, silt, and clay by depth shows abrupt changes between different horizons (fig. 48).

The average sand content for the Santa Marta 1 profile is about 50 percent. The sand content decreases with depth from about 60 percent (Ap–H01) to about 40 percent (Bw1–H02; Bw2–H03) followed by a rapid increase up to 80 percent below 40 cm that coincides with BC (H0) horizon. Silt and clay content follow an opposite trend with depth. On average, silt content is about 25 percent. The silt content is about 23 percent in the thin A (H01) horizon and 40 percent in the Bw1 (H02) and Bw2 (H03) horizons. It decreases rapidly to less than 20 percent for the subsequent subsurface horizons below 40 cm. The mean clay content is about 18 percent in surface horizons (A–H01; Bw1–H02; Bw2–H03), having an average 22 percent clay. Subsurface horizons have an average 13 percent clay. The change of AWC with depth follows that of silt content. The average AWC is about 10 percent on a per-volume basis; however, the AWC for the surface horizons (A–H01; Bw1–H02; Bw2–H03) is about 15 percent and decreases to about 8 percent below 40 cm in the subsurface horizons.

Soil organic carbon (SOC) content averages about 0.8 percent and decreases rapidly with depth to less than 0.3 percent below 40 cm. SOC content decreases with depth from 2.6 percent (A–H01) to 0.2 percent (2Cg2-H10) (fig. 49). The effective

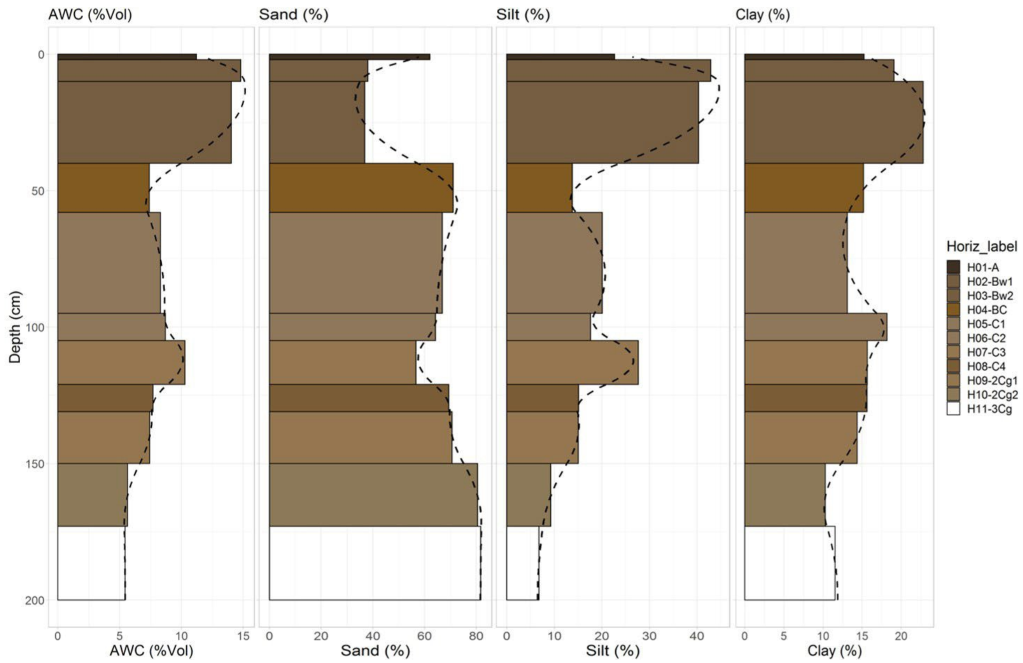

Figure 48.—Distribution of physical soil properties by depth: available water holding capacity and content of sand, silt, and clay in Santa Marta 1.

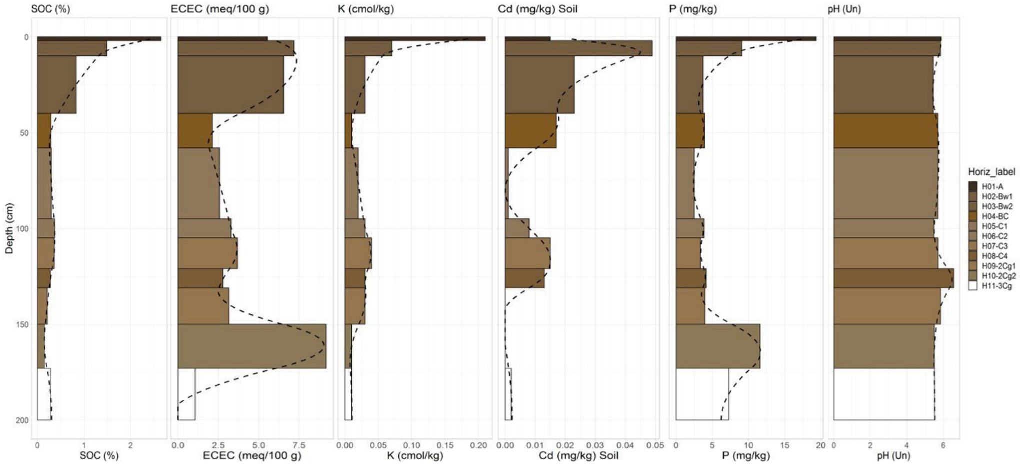

Figure 49.—Distribution of soil fertility properties by depth: soil organic carbon (%), effective cation exchange capacity (meq/100 g soil), potassium (cmol/kg soil), cadmium (mg/kg soil), phosphorus (mg/kg soil), and soil reaction (pH) in Santa Marta 1.

cation exchange capacity (ECEC) is low and decreases with depth from about 6.0 meq/10 g soil for the first three horizons (A–H01; Bw1–H02; Bw2–H03) to about 2 meq/10 g soil for the subsurface horizons. The exception is the 2Cg2 (H10) horizon, which increases to about 6.5 meq/100 g soil. Potassium content and phosphorus content decrease overall with soil depth and follow the SOC and ECEC trends. The potassium content varies from 0.22 cmol/kg soil (A–H01) to 0.025 on average for the subsurface horizons below 40 cm. The phosphorus content is very high for the thin surface layer (A–H01) at about only 18 mg/kg soil. It decreases rapidly to less than 5.0 mg/kg soil for the subsequent surface horizons, except for 2Cg2 (H10) horizon, which has 12.0 mg/kg soil. The cadmium content for the thin surface horizon (A–H01) is about 0.018 mg/kg soil. It increases rapidly to 0.048 mg/kg soil for the Bw1 (H02) horizon. The cadmium content decreases with depth to less than 0.02 mg/kg soil and follows trends similar to those of the SOC content. Soil reaction is moderately acid. The mean soil pH is around 5.9 and varies slightly with depth compared to the other soil properties.

Site 12: On toeslopes, formed in igneous parent material

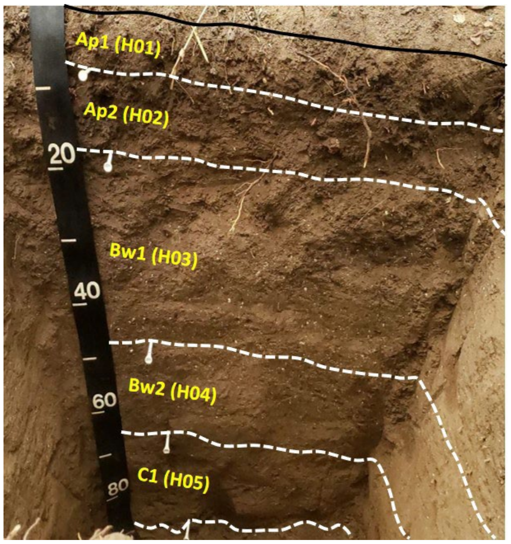

Figure 50.—Soil profile of Santa Marta Map Unit 203, Site 12.

Soil Profile Description

Ap1 (H01)—0 to 8 centimeters (pit); light black (2.5YR 2/1) sandy clay loam; moderate medium granular structure parting to moderate fine granular; friable; 5% fine gravel; slightly sticky, slightly plastic; many medium and common coarse and fine roots and common fine and few medium pores throughout; many medium and coarse wormcasts throughout; moderately acid; gradual smooth boundary.

Ap2 (H02)—8 to 18 centimeters (pit); very dark brown (10YR 2/2) loam; moderate medium subangular blocky structure; friable; 1% rich-mica-content fine gravel; slightly sticky, slightly plastic; common fine and very fine and few coarse roots and common fine and few coarse pores throughout; many medium wormcasts throughout; strongly acid; clear smooth boundary.

Bw1 (H03)—18 to 47 centimeters (pit); very dark grayish brown (10YR 3/2) fine gravelly sandy clay loam; moderate medium angular blocky structure; friable; 15% fine and 1% medium gravel; slightly sticky, nonplastic; common medium and fine roots and common medium and few coarse and fine pores throughout; few fine mica flakes; very strongly acid; clear smooth boundary.

Bw2 (H04)—47 to 66 centimeters (pit); very dark grayish brown (2.5Y 3/2) slightly stratified fine gravelly sandy loam; strong medium angular blocky structure parting to moderate medium platy; friable; 15% fine and 1% medium gravel; slightly sticky, slightly plastic; common medium and fine roots and common medium and few fine and coarse pores throughout; very strongly acid; clear smooth boundary.

C1 (H05)—66 to 89 centimeters (pit); olive brown (2.5Y 4/4) sandy loam; weak fine angular blocky structure; friable; 5% fine gravel and 3% cobbles; nonsticky, nonplastic; few very fine roots and few fine pores throughout; moderately acid; clear smooth boundary.

C2 (H06)—89 to 112 centimeters (pit); olive brown (2.5Y 4/4) sandy loam; massive; loose; 5% fine gravel; nonsticky, nonplastic; moderately acid; clear smooth boundary.

C3 (H07)—112 to 133 centimeters (auger); olive brown (2.5Y 4/4) medium gravelly sandy loam; massive; loose; 20% medium gravel; nonsticky, nonplastic; slightly acid.

C4 (H08)—133 to 169 centimeters (auger); olive brown (2.5Y 4/4) sandy loam; weak medium granular structure; very friable; 5% fine gravel; nonsticky, nonplastic; common (2%) medium mica flakes; slightly acid.

R (H09)—169+ centimeters (auger); bedrock.

Parent Material: Igneous, residuum, metamorphic. Very nearly apparent colluvial material, stones and boulders, but clearly associated with nearby channel. Anecdotal information placed site outside present flood plain, but C horizons appeared somewhat stratified with significant fragment content differences between horizons. These factors indicate alluvial deposits from flood events having different energies; i.e., different water carrying capacity.

Soil Properties in the Profile: Distribution by Depth

The distribution of soil properties by depth for the representative profile varies by the soil property. The distribution of sand, silt, and clay by depth shows abrupt changes between different horizons (fig. 51).

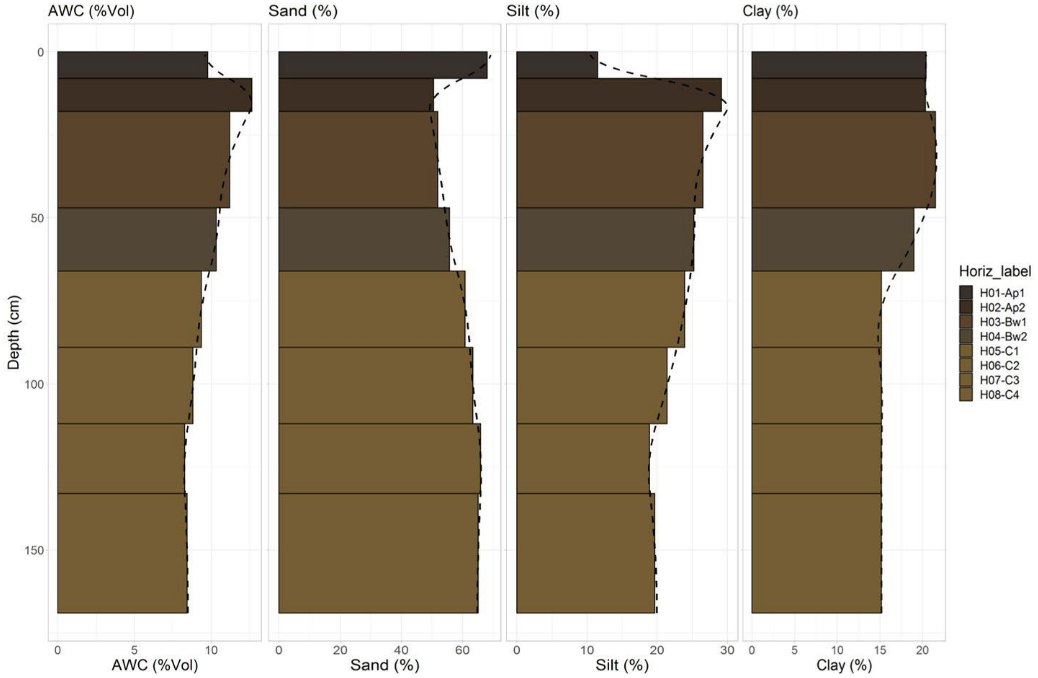

Figure 51.—Distribution of physical soil properties by depth: available water holding capacity and content of sand, silt, and clay in Santa Marta 12.

The average sand content for the Santa Marta 13 profile is about 55 percent and varies slightly with depth. The sand content is about 65 percent for the Ap1 (H01) horizon and decreases slightly to about 55 percent for the Ap2 (H02) horizon followed by steady increase above 60 percent below 66 cm. Silt and clay content follow opposite trend with depth compared to sand content. Silt content is low at about 12 percent for the Ap1 (H01) horizon but more than doubles close to 28 percent for the Ap2 (H02) horizon. The silt content decreases with depth but remains above 20 percent throughout the soil profile. The average clay content is about 16 percent and varies slightly between horizons, ranging from 15 percent for all C horizons to 20 percent for the Bw1 (H03) horizon. The average AWC is about 10 percent on a per-volume basis and decreases slightly throughout the profile, ranging from 13 percent in the Ap2 (H02) horizon to 8 percent in the C3 (H07) and C4 (H08) horizons. AWC follows the silt distribution trend with depth.

Soil organic carbon content averages about 1.2 percent and decreases rapidly with depth to less than 0.5 percent below 50 cm (fig. 52). SOC content varies from 2.8 percent in the Ap (H01) horizon to 0.2 percent in the C3 (H07) and C4 (H08) horizons. The effective cation exchange capacity (ECEC) decreases overall with depth. The mean ECEC for the profile is about 6.0 meq/100 g soil. The ECEC increases slightly to 6.4 meq/100 g soil for the Bw2 (H04) and C1 (H05) horizons followed by a slight decrease to about 4.6 meq/10 g soil for the subsequent horizons below 80 cm. Potassium content and phosphorus content decrease overall with soil depth and show a trend similar to that of ECEC. The average potassium content is about 0.045 cmol/kg soil. The potassium content is highest for the Ap1 (H01) horizon at 0.09 cmol/kg soil and lowest for the Bw1 (H02) horizon at 0.020 cmol/kg soil.

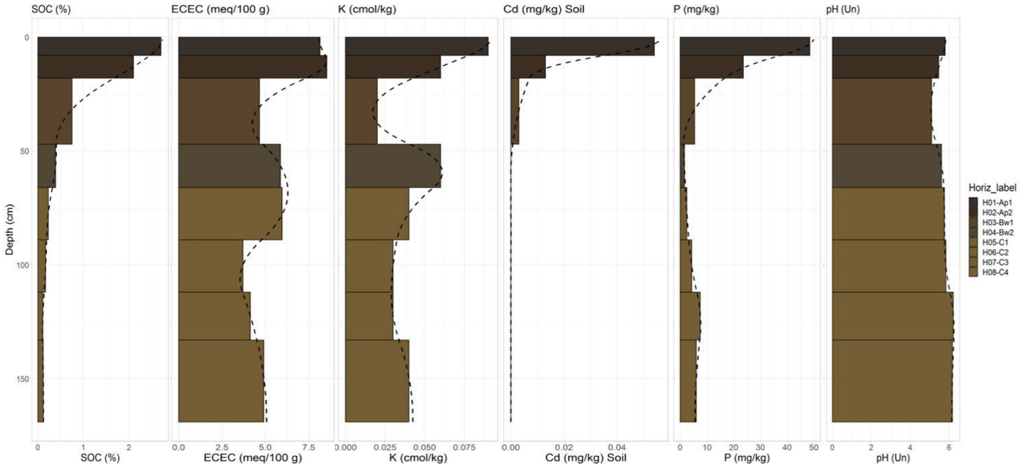

Figure 52.—Distribution of soil fertility properties by depth: soil organic carbon (%), effective cation exchange capacity (meq/100 g soil), potassium (cmol/kg soil), cadmium (mg/kg soil), phosphorus (mg/kg soil), and soil reaction (pH) in Santa Marta 12.

The mean phosphorus content is about 15.0 mg/kg soil but varies widely throughout the profile, decreasing rapidly from about 50.0 mg/kg soil (Ap1–H01) to 3.0 mg/kg soil (Bw2–H04) below 50 cm. The cadmium content is relatively higher than that of the other sites, varying from 0.06 mg/kg soil in the Ap1 (H01) horizon to below detection limits in the subsurface horizons below 50 cm. The contrasting changes of cadmium and phosphorus with depth are very similar to those of SOC, suggesting an association of the higher values for phosphorus and cadmium with SOC. The soil reaction is strongly acid or moderately acid. The mean soil pH is around 5.5 and varies slightly with depth compared to other soil properties. The soil pH decreases from 5.9 for the Ap1 (H01) horizon to about 5.2 for the Bw1 (H03) horizon followed by steady increase with depth to 6.1 in the C3 (H07) and C4 (H08) horizons.

Soil Properties in the Soil Map Unit: Distribution by Depth

The distribution of soil properties by depth varies widely within the soil map unit. This variability is shown by the width of the 90 percent confidence intervals (fig. 53). The great uncertainty within this soil map unit is likely due to the soil variability and potentially due to the management of cacao biomass.

The 90 percent confidence intervals for AWC and for sand and silt are very wide throughout the profile. The width for clay is narrow for the surface horizons and increases with depth. Overall, the uncertainty is greater for the surface horizons except for ECEC and pH. Although the overall mean values for cadmium are low, the high uncertainty associated with cadmium values throughout the soil needs to be considered in regards to the management of soils for cadmium or other soil fertility parameters. As with cadmium, the high uncertainty for AWC and pH suggests that any recommendations for managing soil water and soil reaction may need to be site specific.

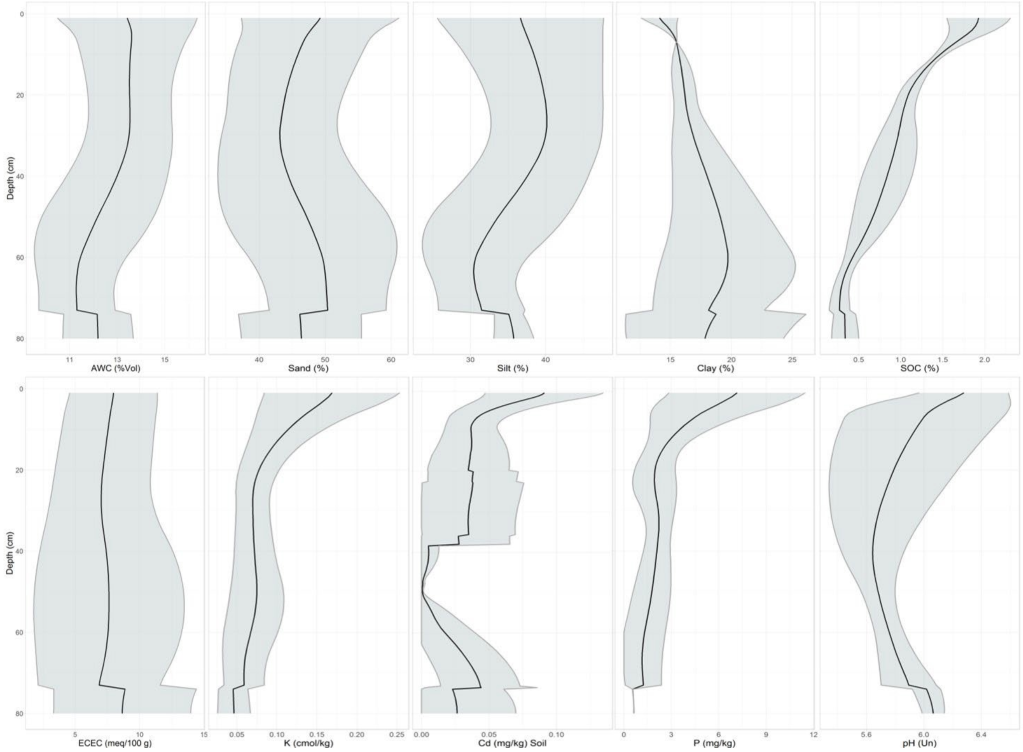

Figure 53.—The gray area is the 90 percent confidence interval for distribution by depth of physical soil properties and soil fertility properties.

205.—Santa Marta fine, mixed, subactive, isohyperthermic Oxic Haplustepts

Site 2: On summits, formed in igneous parent material

Soil Profile Description

A1 (H01)—0 to 5 centimeters (pit); dark brown (10YR 3/3) clay; weak medium granular structure; friable; 5% gravel; nonsticky, nonplastic; many fine, common very fine, and few coarse roots and few fine pores throughout; strongly acid; clear smooth boundary.

A2 (H02)—5 to 15 centimeters (pit); very dark grayish brown (10YR 3/2) clay; common medium prominent red (2.5YR 5/8) mottles; moderate fine subangular blocky structure; firm; 15% fine discontinuous clay coatings on faces of peds; slightly sticky, moderately plastic; many fine, common very fine, and few coarse roots and few fine pores throughout; very strongly acid; clear smooth boundary.

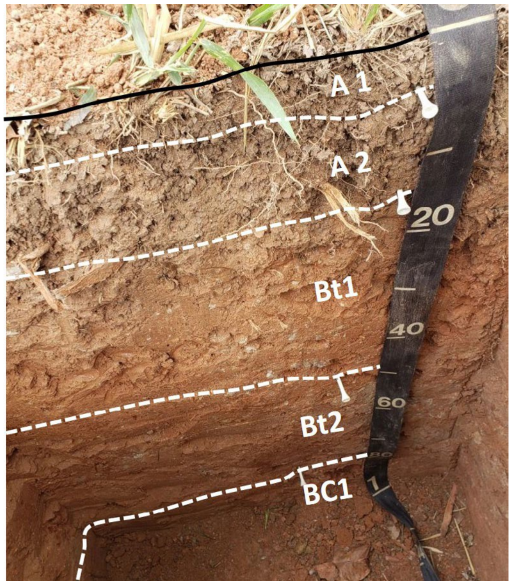

Figure 54.—Soil profile of Santa Marta Map Unit 205, Site 2.

Bt1 (H03)—15 to 47 centimeters (pit); yellowish red (5YR 5/6) silty clay; unconsolidated silty clay weathered parent materials having common fine, medium, and coarse prominent gray (2.5Y 5/1) mottles; moderate fine subangular blocky structure; firm; 25% fine discontinuous clay coatings on faces of peds; slightly sticky, moderately plastic; common very fine and few fine roots and few fine pores throughout; very strongly acid; gradual smooth boundary.

Bt2 (H04)—47 to 84 centimeters (pit); reddish yellow (7.5YR 5/6) silty clay loam; moderate fine angular blocky structure; firm; 30% continuous to discontinuous clay skins along natural breaks on ped faces; slightly sticky, slightly plastic; few fine roots and few fine pores throughout; discontinuous horizontal layers, 25 to 30 cm long and ranging from thin to medium (1 to 5 mm), of unconsolidated to weakly cemented gray (2.5Y 5/1) weathered parent materials; evidence of preferential water flow along natural breaks on ped faces; very strongly acid; gradual smooth boundary.

BC1 (H05)—84 to 130 centimeters (pit); yellowish red (5YR 4/6) clay; moderate medium subangular blocky structure parting to weak medium angular blocky; firm; 25% continuous to discontinuous clay skins along natural breaks on ped faces; nonsticky, nonplastic; few very fine roots and few fine pores throughout; very strongly acid; gradual wavy boundary.

BC2 (H06)—130 to 155 centimeters (auger); brown (10YR 4/3) clay; moderate medium subangular blocky structure; friable; 20% continuous to discontinuous clay skins along natural breaks on ped faces; nonsticky, nonplastic; few very fine roots and few fine pores throughout; very strongly acid; gradual wavy boundary.

Cr (H07)—155 to 200 centimeters (auger); 60% dark brown (7.5YR 4/4) silt loam; variegated saprolitic materials, 30% gray (2.5Y 5/1), 5% light gray (10YR 7/2), and 5% dark gray (10YR 4/1); weak medium subangular blocky structure parting to weak fine granular; friable; 1% discontinuous clay skins along natural breaks on ped faces; nonsticky, nonplastic; very strongly acid.

Soil Properties in the Profile: Distribution by Depth

The distribution of soil properties by depth for the representative profile varies by soil property. The distribution of sand, silt, and clay by depth changes between different horizons (fig. 55).

The average sand content in the Santa Marta 2 profile is about 18 percent. The sand content is the highest, about 27 percent, in the very top horizon (A1–H01) and the very bottom horizon (Cr–H07). The sand content ranges from 15 percent in the Bt1 (H03) horizon to 20 percent in the Bt2 (H04) and BC2 (H06) horizons. Silt content is the lowest, around 21 percent, in the surface horizons (A1–H01 and A2–H02) and increases to about 46 percent in the Bt1 (H03) and Bt2 (H04) horizons. The highest silt content, about 52 percent, is in the Cr (H07) horizon. The clay content averages about 35 percent and varies from 22 percent in the Cr (H07) horizon to about 57 percent in the A1–H01, A2–H02, and BC1–H05 horizons. The mean AWC is about 13 percent.

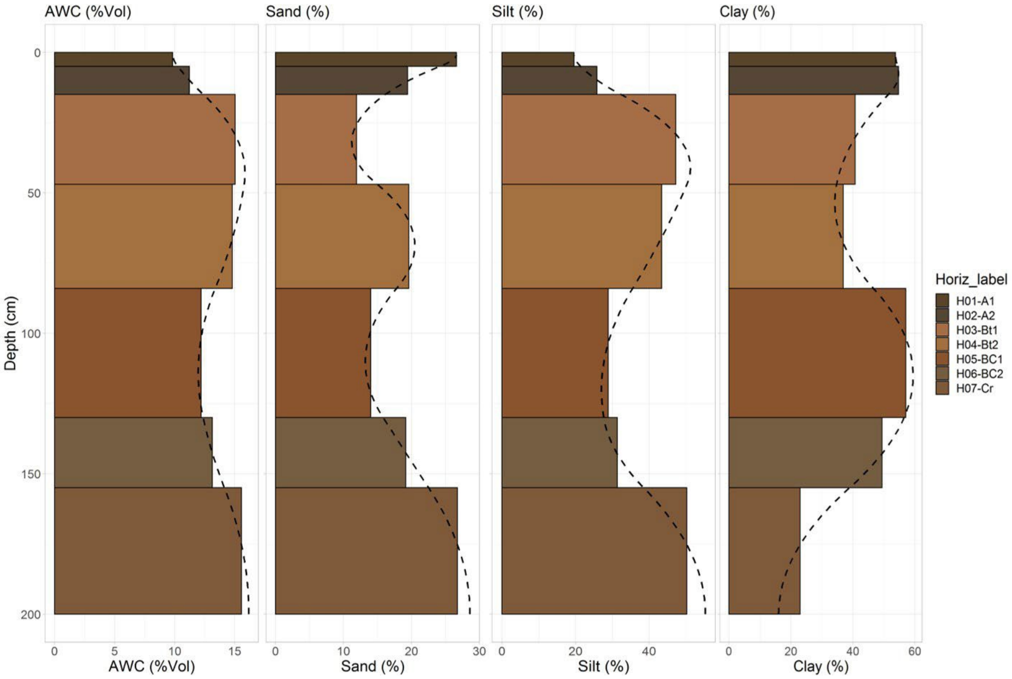

Figure 55.—Distribution of physical soil properties by depth: available water holding capacity and content of sand, silt, and clay in Santa Marta 2.

The AWC increases with depth from about 12 percent in the A1–H01 and A2–H02 horizons to about 16 percent in the Bt1–H03, Bt2–H04, and Cr–H07 horizons.

Soil organic carbon (SOC) content averages about 2.5 percent throughout the profile. It decreases rapidly with depth to less than 0.2 percent below 50 cm (fig. 56). SOC ranges from 4.6 percent in the A1 (H01) horizon to 0.1 percent in the Cr (H07) horizon. The effective cation exchange capacity (ECEC) decreases overall with depth. The mean ECEC for the profile is about 5.0 meq/100 g soil. The ECEC is the highest,

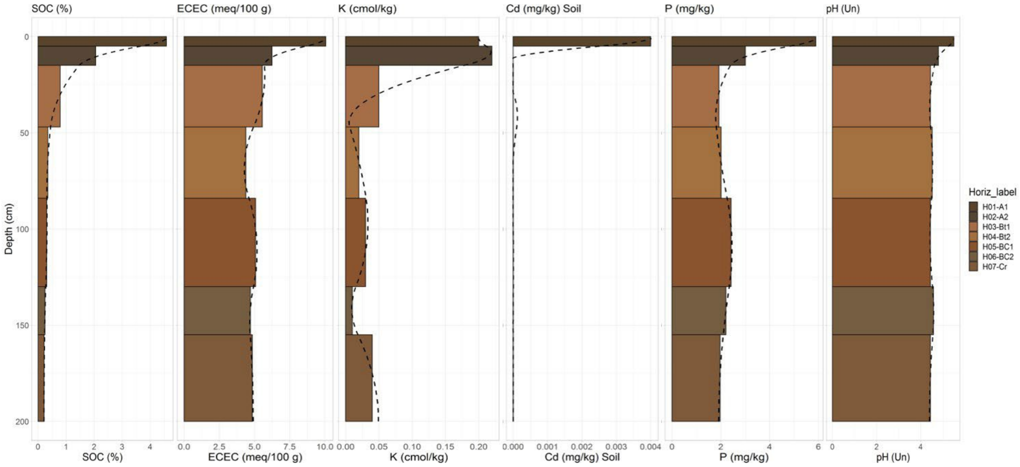

Figure 56.—Distribution of soil fertility properties by depth: soil organic carbon (%), effective cation exchange capacity (meq/100 g soil), potassium (cmol/kg soil), cadmium (mg/kg soil), phosphorus (mg/kg soil), and soil reaction (pH) in Santa Marta 2.

at about 10 meq/100 g soil, in the surface horizon (A1–H01) and the lowest, at about 5.0 meq/100 g soil, in the Bt1 (H03), BC2 (H06), and Cr (H07) horizons. The ECEC decreases below 20 cm from 10.0 to 5.0 meq/100 g soil. Overall, potassium content and phosphorous content decrease with depth in a similar fashion. The highest contents of potassium and phosphorus are measured in the surface horizons (A1–H01 and A2–H02). The potassium content is about 0.21 cmol/kg soil in the A1 (H01) and A2 (H02) horizons and decreases rapidly to about 0.05 cmol/kg soil below 20 cm. The phosphorous content decreases from about 6 mg/kg soil in the A1 (H01) horizon to about 2.0 mg/kg soil below 5 cm. Measurable amounts of cadmium (~0.004 mg/kg soil) are found only in the surface (A1–H01) horizon, indicating bioavailability accumulation from biomass decomposition. Soil reaction is very strongly acid. The mean pH is around 4.2 and varies slightly with depth compared to other soil properties.

Soil Properties in the Soil Map Unit: Distribution by Depth

The distribution of soil properties by depth varies widely within the soil map unit. This variability is shown by the width of the 90 percent confidence intervals (fig. 57). The 90 percent confidence interval shows a great variability and uncertainty for the soil properties and increases with depth, except for SOC and potassium.

The great uncertainty within this soil map unit is likely due to the soil variability and potentially due to the management of cacao biomass. Overall, the uncertainty is greater for the subsurface horizons. Site-specific management practices for liming, water, and nutrients are needed because of the high uncertainty associated with AWC, cadmium, pH values, and soil fertility properties throughout the soil.

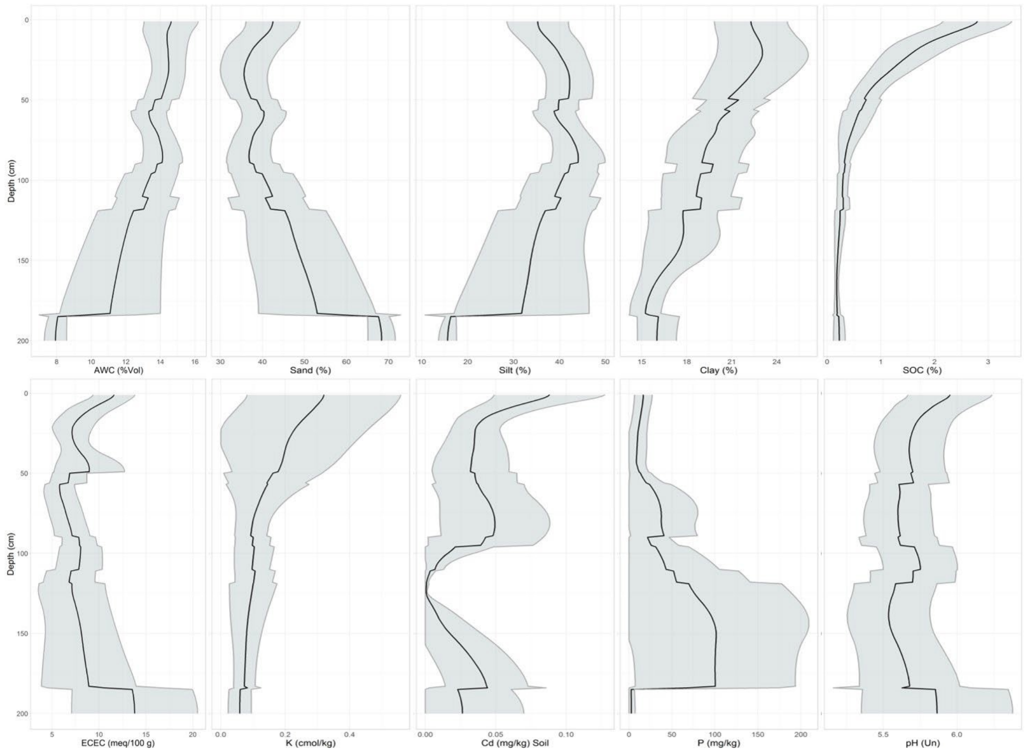

Figure 57.—The gray area is the 90 percent confidence interval for distribution by depth of physical soil properties and soil fertility properties.

304.—Santa Marta fine, mixed, subactive, isohyperthermic Oxic Haplustepts

Site 3: On wide plains, formed in sedimentary parent material

Soil Profile Description

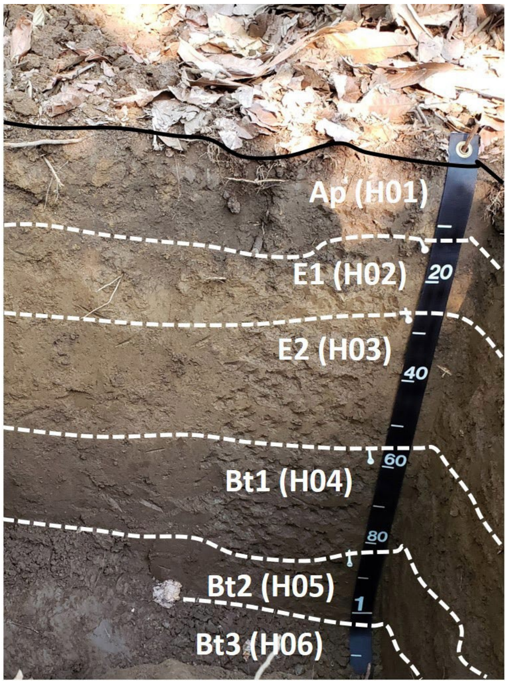

Figure 58.—Soil profile of Santa Marta Map Unit 304, Site 3.

Ap (H01)—0 to 13 centimeters (pit); very dark grayish brown (10YR 3/2) silty clay loam; moderate medium granular structure; friable; 5% gravel; nonsticky, nonplastic; common medium and coarse roots and common medium pores throughout; slightly acid; clear smooth boundary.

E1 (H02)—13 to 26 centimeters (pit); dark grayish brown (10YR 4/2) silt loam; common fine prominent dark yellowish brown (10YR 4/6) mottles; weak fine granular structure; very friable; 10% continuous and discontinuous clay skins along natural breaks on ped faces; slightly sticky, slightly plastic; common medium roots and common medium pores throughout; moderately acid; gradual smooth boundary.

E2 (H03)—26 to 57 centimeters (pit); brown (10YR 4/3) silty clay loam; weak fine subangular blocky structure parting to moderate fine granular; very friable; moderately sticky, moderately plastic; common fine roots and few medium and fine pores throughout; moderately acid; clear smooth boundary.

Bt1 (H04)—57 to 85 centimeters (pit); dark grayish brown (10YR 4/2) silty clay; moderate medium subangular blocky structure; firm; 10% continuous and discontinuous clay coatings on faces of peds; moderately sticky, moderately plastic; common fine roots and few fine and medium pores throughout; moderately acid; clear smooth boundary.

Bt2 (H05)—85 to 111 centimeters (pit); dark grayish brown (10YR 4/2) silty clay loam; weak fine subangular blocky structure; firm; 10% continuous to discontinuous clay skins along natural breaks on ped faces; moderately sticky, moderately plastic; common fine roots throughout; moderately acid; clear smooth boundary.

Bt3 (H06)—111 to 135 centimeters (pit); dark grayish brown (10YR 4/2) silty clay (field texture); common fine distinct grayish brown (10YR 5/2) mottles on interior of peds; moderate fine subangular blocky structure; firm; continuous to discontinuous clay skins along natural breaks on ped faces; moderately sticky, moderately plastic; few very fine roots throughout; clear smooth boundary.

Bt4 (H07)—135 to 200 centimeters (pit and auger); dark brown (7.5YR 3/4) silty clay (field texture); weak fine subangular blocky structure parting to massive; very firm; 5% discontinuous clay skins along ped faces; moderately sticky, moderately plastic.

Soil Properties in the Profile: Distribution by Depth

The average sand content for the Santa Marta 3 profile is about 15 percent and varies slightly with depth, ranging from 12 percent for the E2 (H03) horizon to 18 percent for the Bt2 (H05) horizon (fig. 59). The sand content decreases slightly with depth, ranging from 16 percent for the Ap (H01) horizon to 12 percent for the E2 (H03) horizon followed by an increase to about 18 percent for the subsequent horizons below 60 cm. Silt and clay content follow an opposite trend with depth. The silt content averages about 50 percent and varies slightly with soil depth. Silt content is about 55 percent for the Ap1 (H01) surface horizon and increases to about 75 percent for the E1 (H02) horizon. The silt content decreases below 30 cm and remains between 45 to 50 percent throughout the subsurface horizons. The average clay content is about 30 percent and ranges from 17 percent for the E1 (H02) horizon to 40 percent for the Bt1 (H04) horizon. Due to higher silt content at this site, the average AWC is above 15 percent on a per-volume basis. The AWC increases slightly from 17 percent in the Ap (H01) horizon to 20 percent in the E1 (H02) horizon followed by a slight decrease to 15 percent for the subsequent horizons below 30 cm.

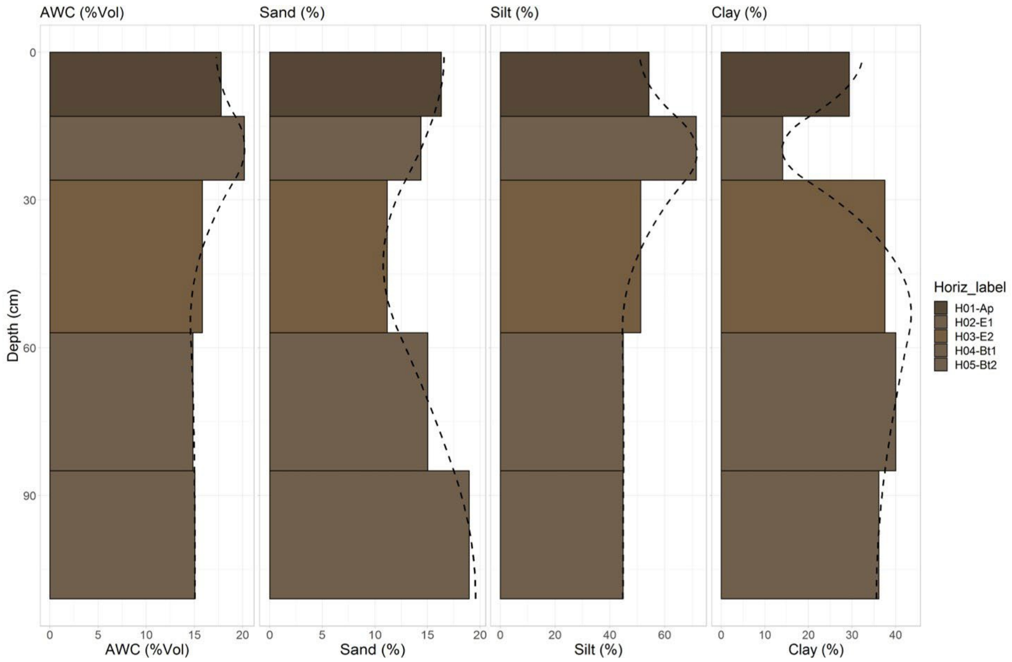

Figure 59.—Distribution of physical soil properties by depth: available water holding capacity and content of sand, silt, and clay in Santa Marta 3.

Soil organic carbon content averages about 1.5 percent and decreases rapidly with depth to less than 1 percent below 26 cm (fig. 60). SOC ranges from 3.0 percent for the Ap (H01) horizon to 0.5 percent for the E1 (H02) horizon. The effective cation exchange capacity (ECEC) decreases overall with depth in a manner similar to that of SOC. The mean ECEC for the profile is about 8.0 meq/100 g soil. The ECEC is highest for the surface horizon (Ap–H01) at about 13 meq/100 g soil and lowest for the E1 (H02) horizon at about 7.0 meq/100 g soil. The ECEC increases below 30 cm to about 13.0 meq/100 g soil for Bt1 (H04) horizon. Potassium content follows similar

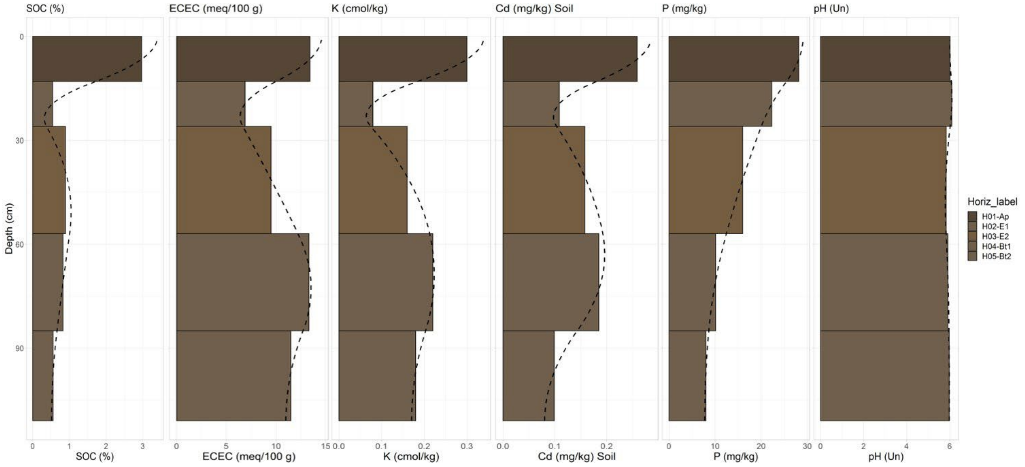

Figure 60.—Distribution of soil fertility properties by depth: soil organic carbon (%), effective cation exchange capacity (meq/100 g soil), potassium (cmol/kg soil), cadmium (mg/kg soil), phosphorus (mg/kg soil), and soil reaction (pH) in Santa Marta 3.

depth trends to those of ECEC. Potassium content is the greatest for the surface horizon (Ap–H01) at 0.3 cmol/kg soil and decreases rapidly to below 0.1 cmol/kg soil for the E1 (H02) horizon. However, below 30 cm the potassium content increases but remains at about 2.0 cmol/kg soil for the subsequent horizons. The phosphorus content decreases overall with soil depth from 28 mg/kg soil for the Ap (H01) horizon to 8.0 mg/kg soil for the Bt2 (H05) horizon. The cadmium content is higher than that of the other sites, varying from 0.01 mg/kg soil in the Bt2 (H05) horizon to as much as 0.28 mg/kg soil in the Ap (H01) horizon. The cadmium content decreases with depth, especially from the top surface horizons Ap (H01) to E1 (H02). However, it remains at about 2.0 mg/kg soil below 30 cm. The cadmium content shows a distribution by depth similar to that of ECEC and potassium. Soil reaction is moderately acid. The mean soil pH is around 6.0 and varies slightly with depth compared to other soil properties.

304.—Santa Marta loamy-skeletal, mixed, semiactive, isohyperthermic Oxic Haplustepts

Site 5: On wide plains, formed in sedimentary parent material

Soil Profile Description

Ap1 (H01)—0 to 8 centimeters (pit); gray (2.5Y 5/1) gravelly loam; strong medium granular structure; very friable; 5% medium and 10% fine gravel; nonsticky, nonplastic; common medium and few fine and coarse roots and few fine pores throughout; moderately acid; gradual smooth boundary.

Ap2 (H02)—8 to 16 centimeters (pit); dark olive brown (2.5Y 3/3) very gravelly loam; moderate medium granular structure; very friable; 15% medium, 15% fine, and 5% coarse gravel; nonsticky, nonplastic; few coarse, medium, and fine roots and few fine and common coarse and medium pores throughout; strongly acid; clear smooth boundary.

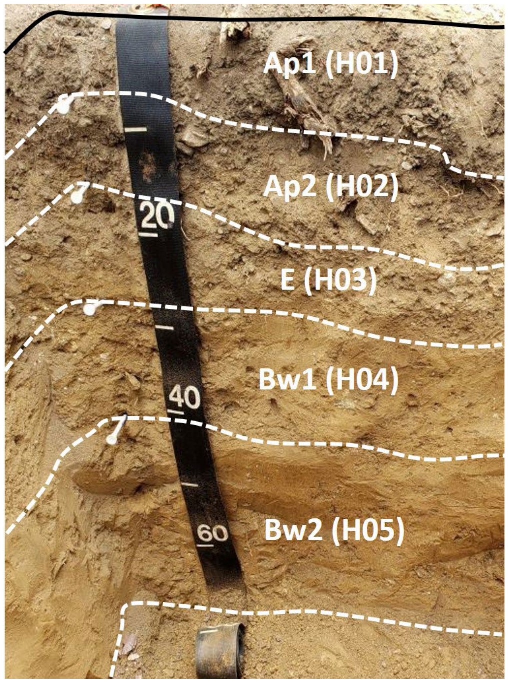

Figure 61.—Soil profile of Santa Marta Map Unit 304, Site 5.

E (H03)—16 to 27 centimeters (pit); dark yellowish brown (10YR 3/4) medium gravelly loam; moderate medium granular structure parting to moderate medium subangular; friable; 20% medium, 5% fine, and 5% coarse gravel; nonsticky, nonplastic; common fine and few very fine roots and common coarse, medium, and fine pores throughout; moderately acid; clear smooth boundary.

Bw1 (H04)—27 to 42 centimeters (pit); dark yellowish brown (10YR 4/4) coarse gravelly loam; moderate medium platy structure parting to weak medium angular blocky; firm; 20% coarse, 5% fine, and 5% medium gravel; nonsticky, nonplastic; common fine roots and few fine and medium pores throughout; slightly acid; clear smooth boundary.

Bw2 (H05)—42 to 72 centimeters (pit); brown (10YR 4/3) very gravelly loam; moderate medium and coarse subangular blocky structure; firm; 25% coarse, 5% fine, and 5% medium gravel; 4% discontinuous clay skins; slightly sticky, slightly plastic; common fine roots and common coarse, medium, and

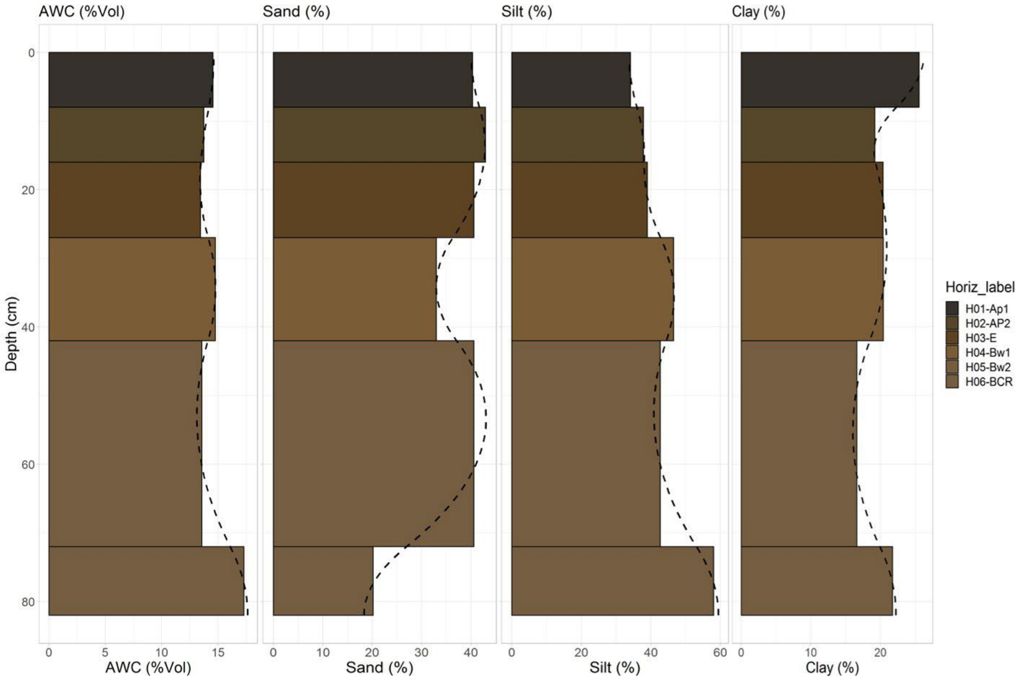

Figure 62.—Distribution of physical soil properties by depth: available water holding capacity and content of sand, silt, and clay in Santa Marta 5.

fine pores throughout; moderately acid; 2% very fine mica flakes; clear smooth boundary.

BC (H06)—72 to 83 centimeters (auger); brown (10YR 4/3) extremely gravelly silt loam; massive; friable; 30% coarse, 20% medium, and 15% fine gravel and 10% cobbles; discontinuous clay skins; slightly sticky, nonplastic; common fine roots and common coarse, medium, and fine pores throughout; moderately acid.

Soil Properties in the Profile: Distribution by Depth

The distribution of soil properties by depth for the representative profile is very diverse and is dependent on the soil property. The distribution of sand, silt, and clay by depth shows abrupt changes between different horizons (fig. 62).

The average sand content for the Santa Marta 5 profile is about 30 percent, which is twice the content of the Santa Marta 3 soil. The sand content varies slightly with depth. It ranges from 35 percent in the Bw1 (H04) horizon to 40 percent in the Bw2 (H05) horizon and decreases to 20 percent in the BCr (H06) horizon. Silt follows an opposite trend by depth as sand. Overall silt content increases with depth from 36 percent in the Ap1 (H01) horizon to about 60 percent in the BCr (H06) horizon. The average clay content is about 18 percent. It varies between 17 percent in the Bw2 (H05) horizon to about 27 percent in the Ap1 (H01) horizon. On average, the silt content is about 13 percent, which is slightly lower than in the Santa Marta 3 soil (15 percent). The AWC depth profile follows the silt trend. AWC increases slightly with depth, ranging from 14 percent in the Ap (H01) horizon to 17 percent in the BCr (H06) horizon.

Soil organic carbon content averages about 1.5 percent, which is comparable with the content in the Santa Marta 3 soil. It decreases rapidly with depth to less than 0.5 percent below 30 cm (fig. 63). SOC varies from 3.0 percent in the Ap (H01) horizon to 0.4 percent in the Bw2 (H06) horizon. The effective cation exchange capacity (ECEC) decreases overall with depth. The mean ECEC for the profile is about 8.0 meq/100 g soil, which is similar to that in the Santa Marta 3 soil. The ECEC is the highest in the surface horizon (Ap–H01) at about 12 meq/100 g soil and the lowest for the Ap2 (H02) horizon at about 5.0 meq/100 g soil. The ECEC increases below 30 cm but remains about 6.0 meq/100 g soil. Potassium follows a depth trends similar to that of ECEC. Potassium is the highest in the surface horizon (Ap–H01) at 0.22 cmol/kg soil.

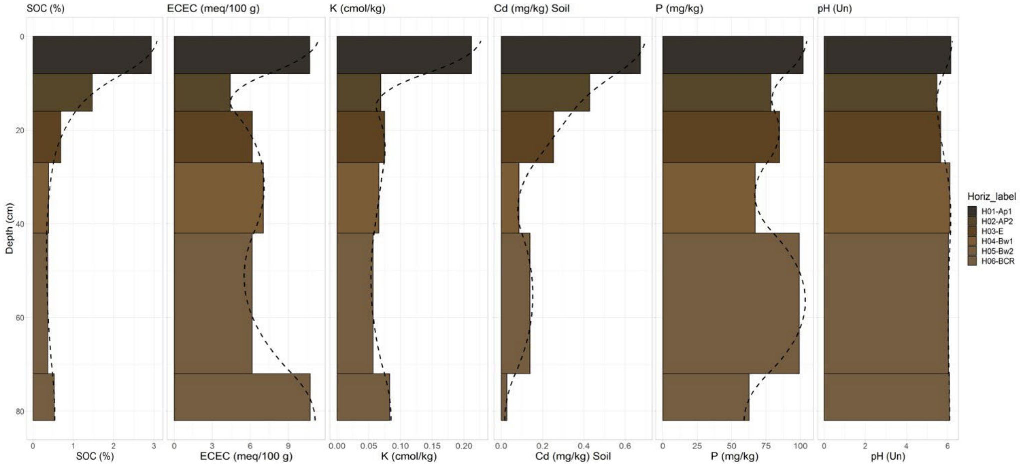

Figure 63.—Distribution of soil fertility properties by depth: soil organic carbon (%), effective cation exchange capacity (meq/100 g soil), potassium (cmol/kg soil), cadmium (mg/kg soil), phosphorus (mg/kg soil), and soil reaction (pH).

It decreases rapidly to about 0.08 cmol/kg soil below 15 cm. The cadmium content is higher than in the Santa Marta 3 soil and other sites. It ranges from 0.02 mg/kg soil in the BCr (H06) horizon to as much as 0.7 mg/kg soil in the Ap (H01) horizon. The cadmium content decreases with depth, especially below 30 cm. It is lower than 0.01 in the Bw1 (H04) horizon. Soil reaction is moderately acid to strongly acid. The mean soil pH is around 5.8 and varies slightly with depth compared to other soil properties.

Soil Properties in the Soil Map Unit: Distribution by Depth

The distribution of soil properties by depth varies widely within the soil map unit. This variability is shown by the width of the 90 percent confidence intervals (fig. 64). The 90 percent confidence interval shows a great variability and uncertainty for the soil properties with depth. The great uncertainty within this soil map unit is likely due to the soil variability and potentially due to the management of cacao biomass. The 90 percent confidence intervals for AWC, soil texture, and cadmium are very wide throughout the soil profile, decreasing only slightly below 80 cm. Overall, the uncertainty is greater in the surface horizons. Site-specific management practices for liming, water, and nutrients are needed because of the high uncertainty associated with AWC, cadmium, pH values, and soil fertility properties throughout the soil.

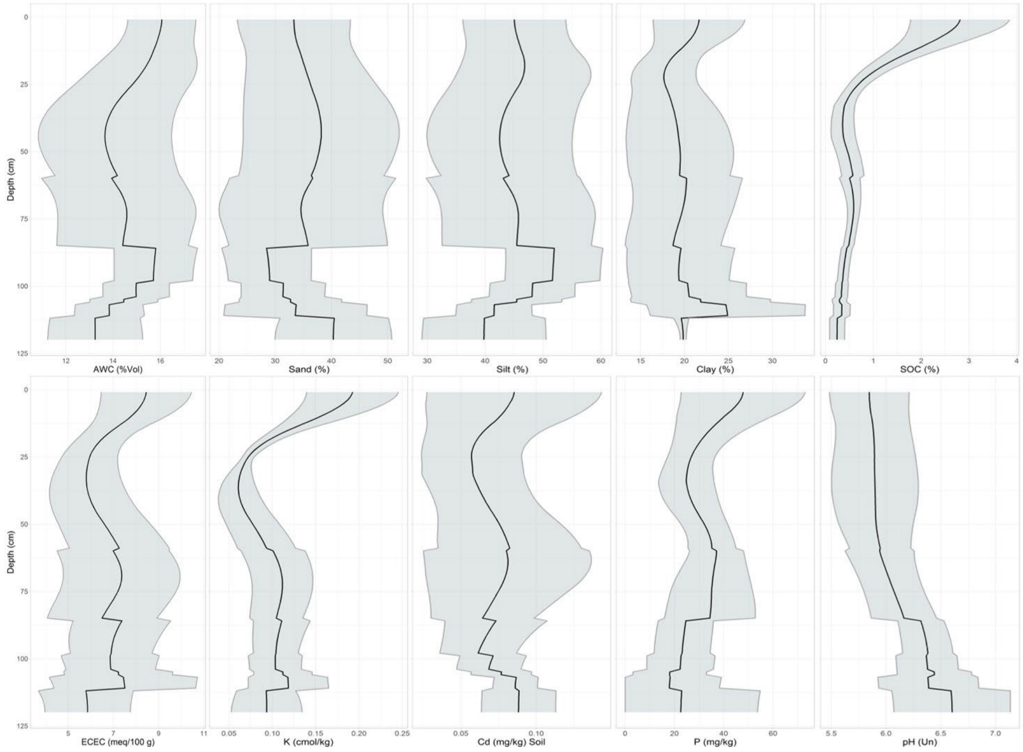

Figure 64.—The gray area is the 90 percent confidence interval for distribution by depth of physical soil properties and soil fertility properties.

Use and Management of the Soils

This soil survey is an inventory and evaluation of the soils in Sierra Nevada de Santa Marta, Colombia. In most cases, soil surveys can be broadly used to adjust land uses to the limitations and potentials of natural resources and the environment and to help prevent soil-related failures in land uses. This soil survey of Sierra Nevada de Santa Marta, Colombia, however, is instead focused on the suitability of the area for growing cacao. This focus fulfills one of the major objectives of the Cacao for Peace project.

In preparing a soil survey, soil scientists, conservationists, engineers, and others collect extensive field data about the nature and behavioral characteristics of the soils. They collect data on erosion, droughtiness, flooding, and other factors that affect various soil uses and management. Field experience and collected data on soil properties and performance are used as a basis in predicting soil behavior.

Information in this section and online (https://arcg.is/1HmGrL) can be used to plan the use and management of soils as rangeland and as sites for buildings, sanitary facilities, highways and other transportation systems, and recreational facilities. It can be used to identify the potentials and limitations of each soil for specific land uses and to help prevent construction failures caused by unfavorable soil properties. Planners and others using soil survey information can evaluate the effect of specific land uses on productivity and on the environment in all or part of the surveyed area. The survey can help planners to maintain or create a land use pattern in harmony with the natural soil. Contractors can use this survey to locate sources of sand and gravel, road fill, and topsoil. They can use it to identify areas where bedrock, wetness, or very firm soil layers can cause difficulty in excavation. Health officials, highway officials, engineers, and others may also find this survey useful. The survey can help them plan the safe disposal of wastes and locate sites for pavements, sidewalks, campgrounds, playgrounds, and trees and shrubs.

Climate-and-Soil Cacao Suitability Rating

The Colombian Government, through Instituto Geografico Agustin Codazzi (IGAC) and Unidad de Planificación Rural Agropecuaria (UPRA) (Flórez et al., 2018), has a rating for soil-use capacity and suitability for agriculture (Flórez et al., 2018). The rating of soil-use capacity is based on soil properties. The rating provides eight classes of soil-use capacity.

- Class 1—Prime arable land with no restrictions
- Class 2—Arable land with limited, easy to correct restriction(s)
- Class 3—Arable land with moderate restrictions that reduce productivity
- Class 4—Arable land with severe restrictions
- Class 5—Arable land with low erosion risk
- Class 6—Arable land with very severe restrictions and semi-permanent or permanent agroforestry or forestry system
- Class 7—Nonarable land with excessive restrictions, mostly under forest
- Class 8—Land not suitable for any agriculture activities and designated for conservation protection of water resources and recreational tourism

The cacao suitability map developed by UPRA (Flórez et al., 2018) is based on a soil map at a scale of 1:100,000. According to UPRA (Flórez et al., 2018) guidelines, the cocoa tree is generally adapted to hot weather conditions and grows below 1,300 m elevation in temperatures above 20 ºC. Optimum precipitation is between 1,000 and 2,500 mm year. Cacao is adopted to a variety of conditions, including soils that are rich in organic matter, deep soils, soil that have textures ranging to heavy clays, heavily eroded soils, newly formed volcanic sand or ash and silty soils, soils having pH of 4 to 7, good internal and external drainage, and slopes ranging from 12 to 75 percent. Slopes exceeding 75 percent are excluded due to difficulties related to sustainable management.

The cacao suitability rating according to UPRA (Flórez et al., 2018) is developed based on several hierarchical conditions, including (1) physical characteristics, (2) social ecosystem, and (3) social economic conditions. However, only physical characteristics were used to develop the suitability rating. The major physical characteristics or factors are climate, soil, and their respective criteria.

Climate Criteria

- Elevation (m)
- Precipitation (mm/year)
- Temperature (°C)
- Precipitation deficit (months with precipitation of 100 mm or less)

Soil Criteria

- Tillage capacity: Slope (%), soil texture, and surface rocks/coarse fragments (%)
- Plant root conditions: Effective soil depth (cm), stoniness (%), and soil texture (medium, fine, and very fine)
- Moisture availability: Moisture regime (available water capacity and soil texture)
- Oxygen availability: Natural drainage and flooding frequency
- Nutrient availability: Soil pH (reaction); base saturation (%); sum of Ca, Mg, K, and Na and interchangeable acidity (Al and H)(% of CEC); CEC: Ca, Mg, K, Cu, Zn, Fe, Mn, and NH_4 (cmol(+) kg/soil); organic matter (%OC)
- Soil toxicity: Salinity (soluble salts via electric conductivity and/or sodicity (exchangeable Na) and Al^{+3} saturation as a percentage ratio between the Al^{+} in the exchange complex and total acidity
- Soil conservation: Slope (%), erosion, landslide susceptibility

The cacao suitability maps developed by UPRA (Flórez et al., 2018) at 1:100,000 scale classify the suitability in 6 groups. The first four suitability groups (A1: high, A2: medium, A3: low, and N1: not suitable) are based on hierarchical criteria, such as physical characteristics, social ecosystem, and social-economic conditions. The last two suitability groups are based on legal considerations (N2) and legal and technical conditions (C1).

To provide a useful cacao suitability map, the analytical hierarchical process (AHP) implemented by UPRA (Flórez et al., 2018) for developing the 1;100,000 scale cacao suitability map is used with adaptations to suit the data. The AHP determines the priority of criteria based on their importance for cacao growth (Siraj et al., 2015). The hierarchy divides the importance of the factors into three broad groups: very important, equally important, and less important. Within the very important group there are 4 subgroups (extremely important, strongly important, important, and moderately important). The same subgroups are used for the less important group but in reverse order (moderately less important, strongly less important, very strongly less important and extremely not important). The PriEsT (Priority Estimation Tool) (Siraj et al., 2015) requires the number of factors and the weight of each factor add to 100 percent to develop a priority vector for defining the suitability zones (tables 4 and 5).

Table 4.— Cacao Suitability by Soil and Climate Factors.

[Multicriteria matrix for cacao suitability rating for soil and climate factors only (Flórez et al., 2018) based on the PriEsT software (Siraj et al., 2015). Detailed descriptions and definitions for the factors are provided in Flórez (2018).]

Factor	Climate	Nutrient availability	Soil toxicity	Water availability	Oxygen availability	Plant root conditions	Tillage capacity	Plant disease risks	Soil conser-vation
Climate	1								
Nutrient availability	1/7	1							
Soil toxicity	1/7	1/3	1						
Water availability	1/3	5	5	1					
Oxygen availability	1/5	3	3	1/3	1				
Plant root conditions	1/3	5	5	3	5	1			
Tillage capacity	1/7	1/3	1	1/5	1/3	1/7	1		
Plant disease risks	1/5	1/5	1/3	1/5	1/3	1/7	1/3	1	
Soil conser-vation	1/5	3	5	1/3	1/3	1/5	5	3	1

Table 5.—Weighing of the Factors for Cacao Suitability Rating (Flórez et al., 2018).

No.	Component	Factor	Weight (%)
1	Physical Environment	Climate conditions	15.5
2	Physical Environment	Plant root conditions	14.3
3	Physical Environment	Water availability	10.9
4	Social Economic	Labor market	8.2
5	Social Economic	Economic indicators	6.7
6	Physical Environment	Oxygen availability	5.6
7	Social Economic	Infrastructure and logistics	5.1
8	Social Economic	Institutions and associations	5.1
9	Social Economic	Price of rural land	3.8
10	Physical Environment	Soil conservation	3.1
11	Physical Environment	Nutrient availability	2.8
12	Social Ecosystem	Ecological integrity	2.6

No.	Component	Factor	Weight (%)
13	Physical Environment	Tillage capacity	2.4
14	Physical Environment	Plant disease risks	2.3
15	Physical Environment	Soil toxicity	2.3
16	Social Ecosystem	Land use change	2.1
17	Social Economic	Public safety and security	1.9
18	Social Ecosystem	Water appropriation	1.6
19	Social Ecosystem	SOC evaluation variability	1.1
20	Social Ecosystem	Fire risks	0.9
21	Social Economic	Farm size	0.9
22	Social Economic	Living conditions	0.8

The weighing schema used by UPRA is based on a combination of expert opinion regarding the importance of each factor and the PriEsT software. According to the weighing schema, 59.5 percent of the weight is related to physical environment, 32.2 percent is social-economic conditions, and 8.3 percent is social-ecosystem conditions. Because the soil survey only considers the physical environment conditions, the cacao suitability ratings in this survey are based only on climate and soil factors—Climate-and-Soil Cacao Suitability Rating (CSCSR). The ratings combine existing climate data with newly collected soil data.

For purposes of rating cacao suitability, there are limiting threshold values that make cultivation of cacao not a viable option. These limiting threshold values are summarized in table 6.

Table 6.—Criteria Threshold Limits and Units.

[Criteria threshold limits and units for the climate and soil factors used for cacao suitability ratings (Flórez et al., 2018.]

Criteria	Limiting threshold	Units
Climate		
Temperature	<20	°C
Precipitation	<500	mm
Precipitation Deficit		Months with precip <100 mm
Nutrient Availability		
Soil pH (reaction)	≤4.0 and ≥7.8	Log H+
Base Saturation	Rated based on soil pH	%
CEC	Rated based on soil pH	cmol(+)/kg soil
SOC	Rated based on soil pH	%
Soil Toxicity		
Salinity	>4	dS/m
Al Saturation	>90	%

Criteria	Limiting threshold	Units
Soil Conservation		
Slope	>75	%
Actual Erosion	Severe to very severe	Categorical
Landslide Susceptibility		
Oxygen Availability		
Drainage	Very poor	Categorical
Flooding Frequency	>30 days (very frequent)	Categorical
Moisture Availability		
Moisture Regime		Aridic and Peraquic
Soil Texture		Categorical
Tillage Capacity		
Slope	>75	%
Soil Texture		Categorical
Stoniness	≥90	%
Plant Root Conditions		
Effective Soil Depth	<50 (shallow and very shallow)	cm
Stoniness	≥90	%
Soil Texture		Categorical

The UPRA procedure for cacao suitability rating was used with modifications to accommodate the data type and availability. The maps for the cacao suitability are generated by the sum of the rating values for each factor. Spatial analysis tools combine all the criteria within each factor, typically in a raster format, to produce the map of cacao suitability for each factor.

Initially, maps are compiled for each criterion. Each map is then classified in four suitability groups (0: not suitable; 1: low suitability; 2: medium suitability; and 3: high suitability) (fig. 65). To simplify the interpretation, the suitability classes assigned were such that a higher score translates into higher suitability. The assignment was the opposite of the classes used by UPRA (Flórez et al., 2018). Spatial layers are created for each criterion based on suitability (0 through 3) and by depth where appropriate. The process creates maps for each criteria suitability rating. Some areas, however, have mixed rating for various properties (criteria). For example, depending on the criteria or soil property, an area may have suitability 1 for soil pH, suitability 2 for soil depth, suitability 3 for clay, and so on. In order to provide information about the most limiting criteria within each factor for each grid cell, individual layers of each criteria are also generated and available. This supports specific management practices tailored to specific limitations and order of priority in addressing them.

Factor	Criteria	Criteria Threshold	Criteria Suitability Rating	Factor Suitability Rating
Climate	Mean Annual Temperature	< 20^{0}C	0 Not Suitable	0 1 2 3 4 5 6 7 8
		≥ 22^{0}C to < 22^{0}C	1 Low	
		≥ 22^{0}C to < 24^{0}C and ≥ 28^{0}C	2 Medium	
		≥ 24^{0}C to ≤ 28^{0}C	3 High	
	Total Precipitation	< 500 mm	0 Not Suitable	
		500 - 1000 and > 4000 mm	1 Low	
		1000 - 1500 and > 2500 - 4000 mm	2 Medium	
		1500 - 2500 mm	3 High	
	Precipitation Deficit	≥ 4	0 Not Suitable	
		≥ 2 to < 4	1 Low	
		< 2	2 Medium	

Figure 65.—Criteria, thresholds, and suitability rating for the climate factor. Criteria are mean annual temperature, total annual precipitation, and precipitation deficit, which is the number of months that have less than 100 mm precipitation. Criteria suitability ratings are combined to create the factor suitability rating. The highest possible score for the climate factor suitability rating is 8 (3 + 3 + 2).

Climate Suitability Rating

Climate suitability rating is developed based on three criteria: (i) mean annual temperature, (ii) total annual precipitation, and (iii) precipitation deficit (number of months with less than 100 mm precipitation).

Suitability Rating Based on Mean Annual Temperature

Mean annual temperature was classified based on temperature thresholds as specified by UPRA (Flórez et al., 2018).

Suitability Rating Based on Total Annual Precipitation

Total annual precipitation for the 2007–2019 period was classified based on precipitation thresholds as specified by UPRA (Flórez et al., 2018).

Suitability Rating Based on Precipitation Deficit

For each month, the precipitation was first classified based on the 100 mm threshold. Unsuitable areas with less than 100 mm were classified as 0, and areas with more than 100 mm precipitation were classified as 1 (suitable). However, the suitability rating is based on the number of months with less than 100 mm precipitation, thus suitability ratings were added together.

- Areas that were classified as 0 are considered not suitable throughout the year because more than 4 months out of 12 have precipitation less than 100 mm.
- Areas with values from 1 to 8 are rated as medium suitability because they have between 2 and 4 months with precipitation below 100 mm to be considered highly suitable.
- The presence of values 11 and 12 would have been an indication of high suitability rating, meaning areas having one or no months with less than 100 mm precipitation.

All three factor suitability ratings (mean annual temperature, total annual precipitation, and precipitation deficit) were added, resulting in a map showing the areas with the highest combined suitability rating for all three criteria (fig. 66). The highest suitability rating, which occurs where all the criteria are high, is eight. Conceptually, the lowest suitability rating is zero. In practice, however, because of the multiple criteria, the smallest value in the survey area is two. This should be interpreted as an area that has at least one limiting criterion rated as not suitable or low suitability. About 75% of the area is rated as highly suitable for cacao based on climate (fig. 67).

Temperature, total precipitation, and precipitation deficit suitability rating by hectares and as a percent of the survey area are provided in the appendix (fig. A–1).

Soil Fertility Suitability Rating (Nutrient Availability)

Soil fertility suitability rating is based on four criteria: (i) soil pH, (ii) base saturation (%), (iii) cation exchange capacity CEC (cmol(+)/kg soil), and (iv) soil organic carbon (%) (fig. 68). The ratings are developed for 4 major soil layers (0–20, 20–60, 60–100, and 100–200 cm) (fig. 69). Conceptually, the potential maximum rating based on the addition of the four criteria is 36. In practice, however, the suitability ratings range from 6 to 19. This range indicates that in all locations at least one limiting criterion is rated as not suitable or low suitability.

Distribution and percent area of suitability classes for (i) soil pH, (ii) base saturation (%), (iii) cation exchange capacity CEC (cmol(+)/kg soil), and (iv) soil organic carbon (%) are shown in the appendix (fig. A–2).

Soil Toxicity Suitability Rating

Soil toxicity suitability rating is developed based on (i) salinity (dS/m) and (ii) Aluminum (Al) saturation (%) (fig. 70). The rating is based only on Al saturation (fig. 71).

Soil Conservation Suitability Rating

Soil conservation suitability rating is developed based on (i) slope, (ii) actual erosion, and (iii) landslide susceptibility (fig. 72). The actual erosion was not determined in the field. The landslide susceptibility is based on slope. It is considered low or very low for slopes of less than 25 percent, medium for slopes between 25 and 50 percent, and high or very high for slopes greater than 75 percent. Soil thickness and texture also play a significant role; therefore, soil thickness and texture were combined with slope to provide a soil conservation suitability rating (Sharma et al., 2012) (fig. 73). The ratings for thickness are as follows: shallow soils (<50 cm deep) are least stable, soils between 50 and 100 cm in depth are low to medium, and deep soils (>100 cm depth) are considered most stable. Regarding texture, finer soil textures are considered least stable for landslide susceptibility, and coarser soils are considered most stable.

Suitability classes for (i) soil depth; (ii) slope; and (iii) soil texture class suitability rating are shown by hectares and as a percent of the survey area in the appendix (fig. A–3).

Moisture Availability Suitability Rating

Soil moisture availability rating is developed based on (i) soil moisture regime and (ii) soil texture. However, available water holding capacity (AWC) was used for the rating based on the classification developed by USDA-NRCS (1998). The moisture regime for the entire area is Ustic, which is rated as medium suitability. AWC values of less than 0.1 (that is, 10%) on volume basis are rated as low suitability, values between 0.1 to 0.25 are medium suitability, and values greater than 0.25 are high suitability (fig. 74). Soil moisture regime was combined with AWC classes to generate the final moisture availability suitability rating (fig. 75).

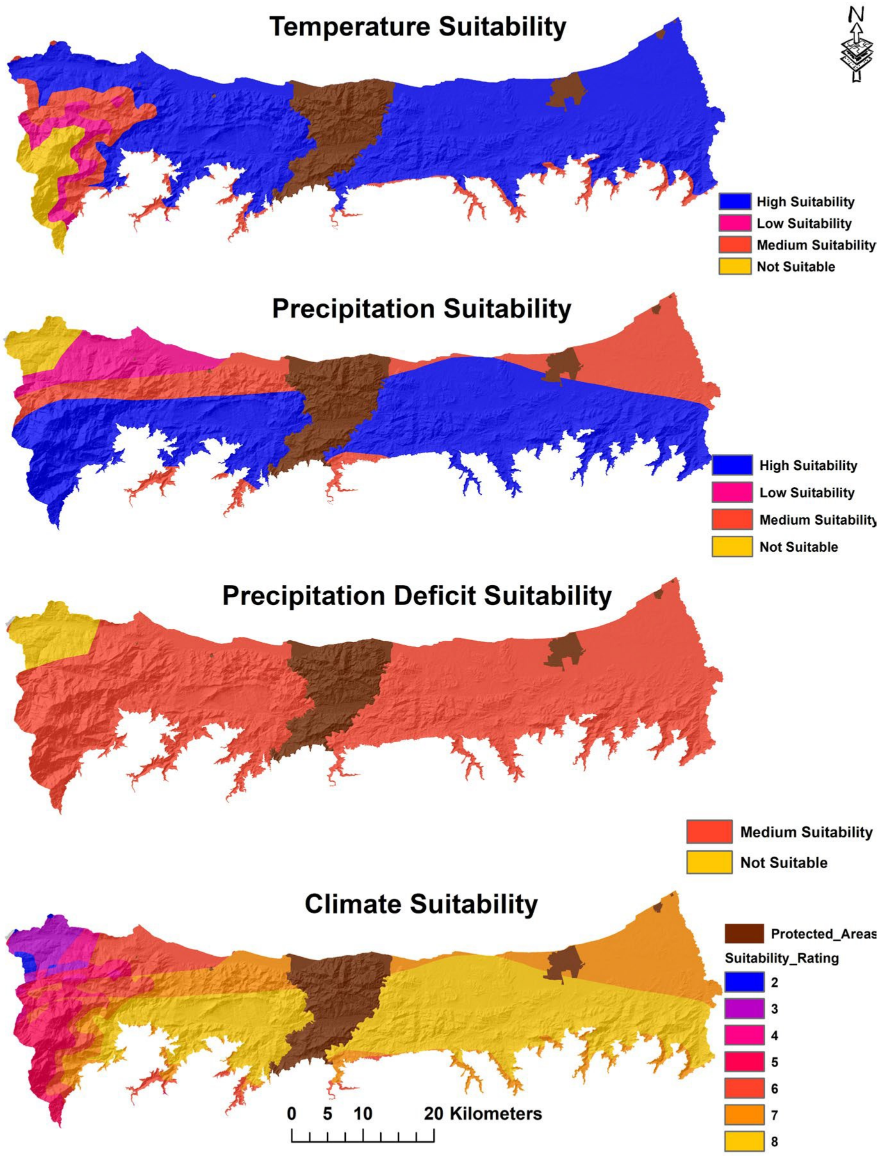

Figure 66.—Distribution of suitability classes for mean annual temperature, total annual precipitation, precipitation deficit, and climate.

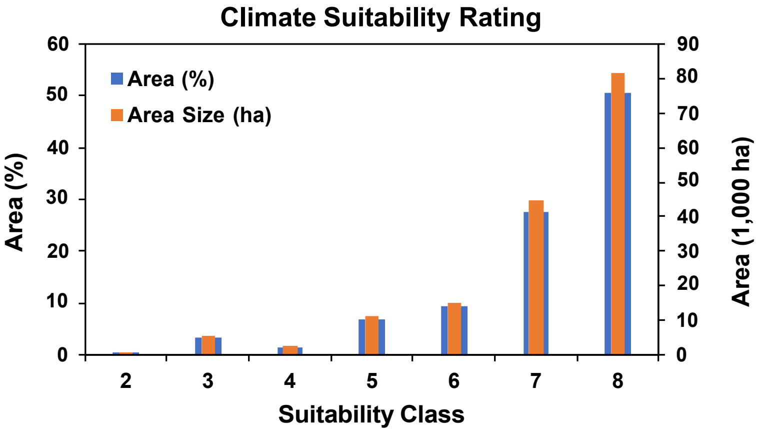

Figure 67.—Climate suitability ratings by hectares and as a percent of the survey area.

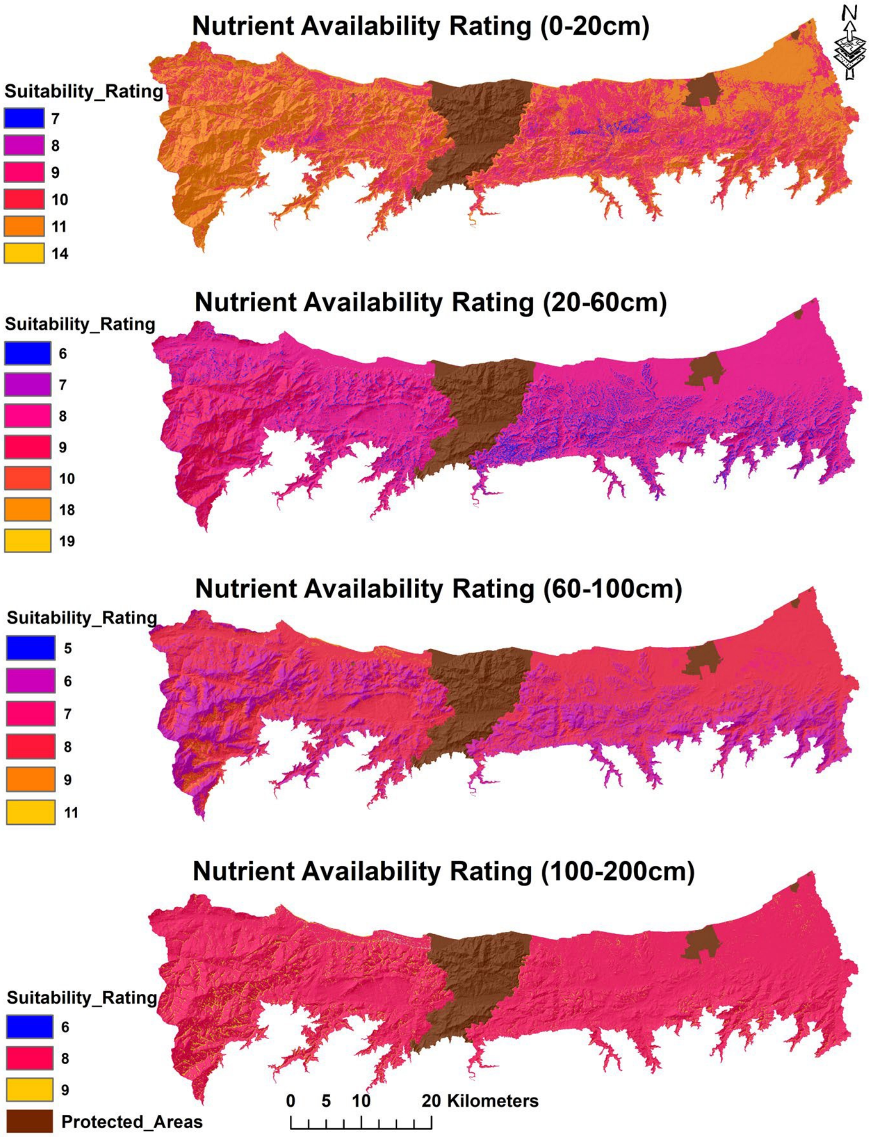

Figure 68.—Distribution of suitability classes for soil fertility (nutrient availability) by soil depth.

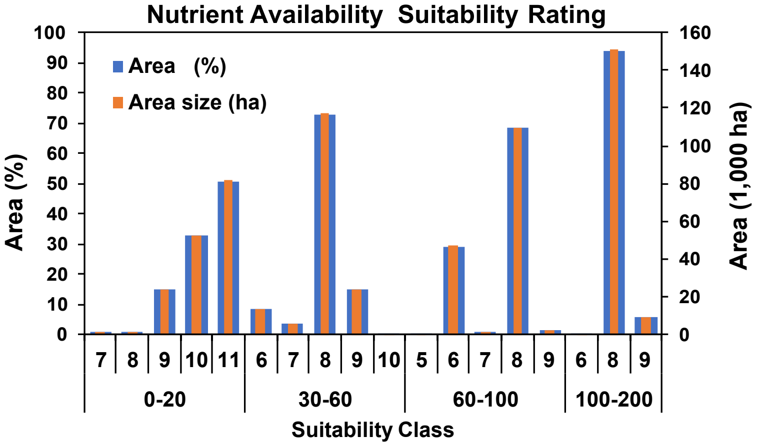

Figure 69.—Soil fertility suitability rating by hectares and as a percent of the survey area.

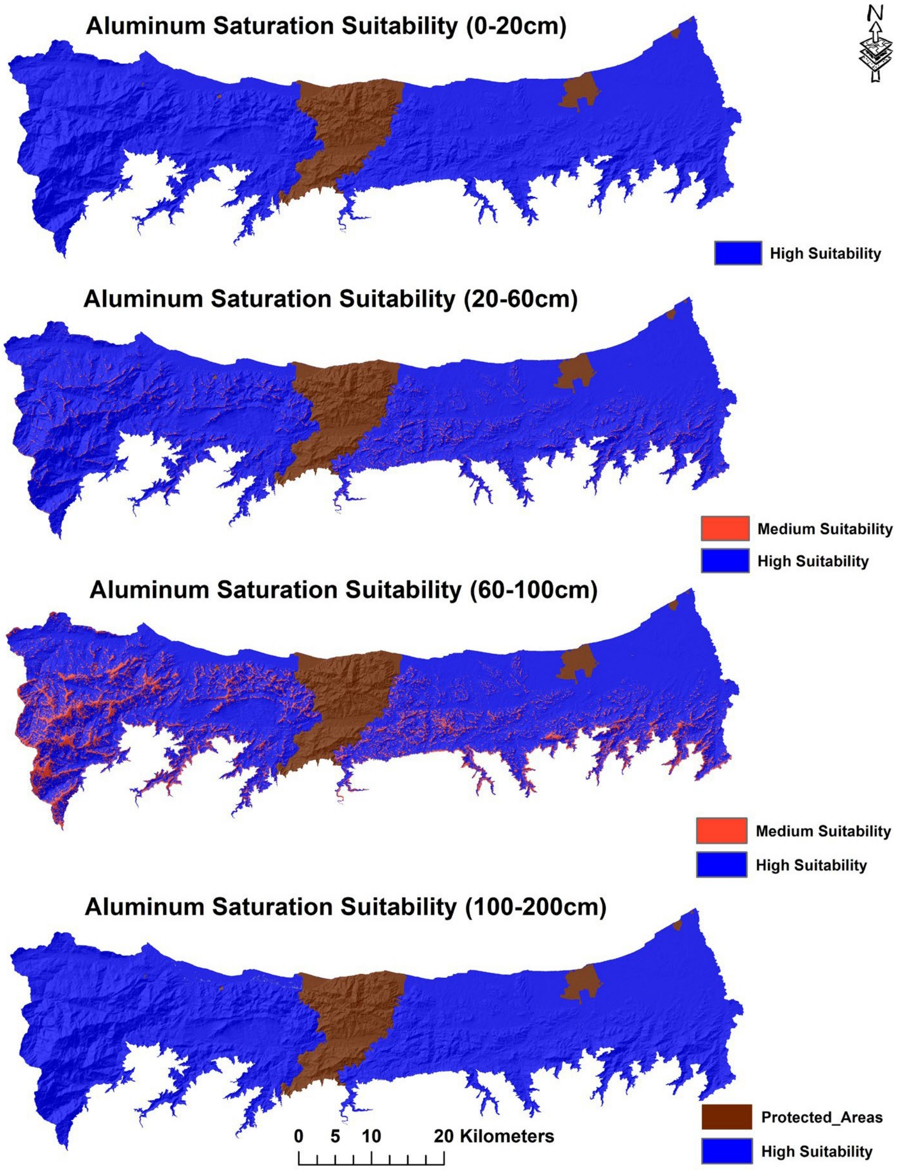

Figure 70.—Distribution of suitability classes for soil toxicity suitability rating.

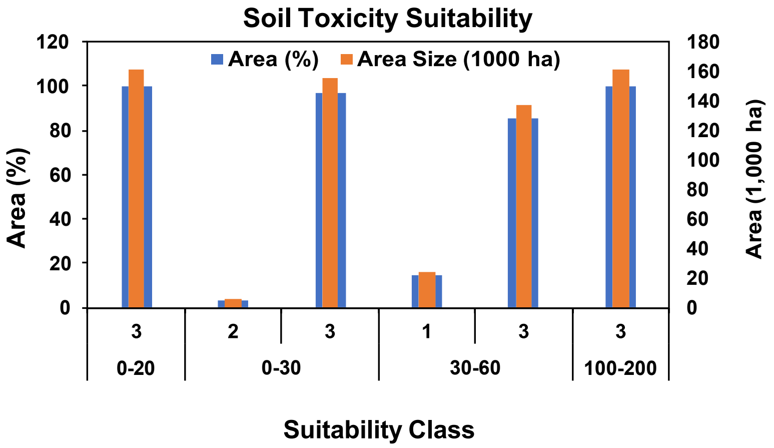

Figure 71.—Soil toxicity suitability rating by hectares and as a percent of the survey area.

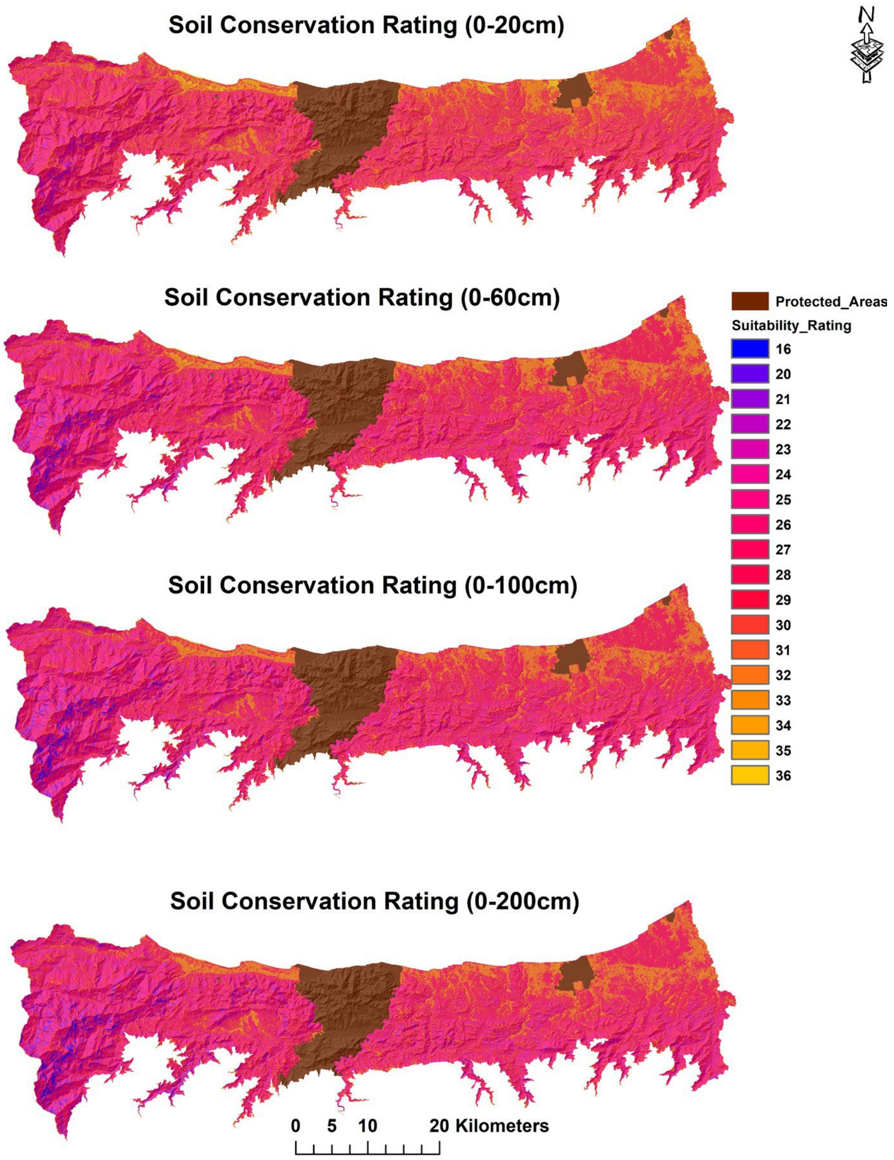

Figure 72.—Distribution of soil conservation suitability rating by soil depth.

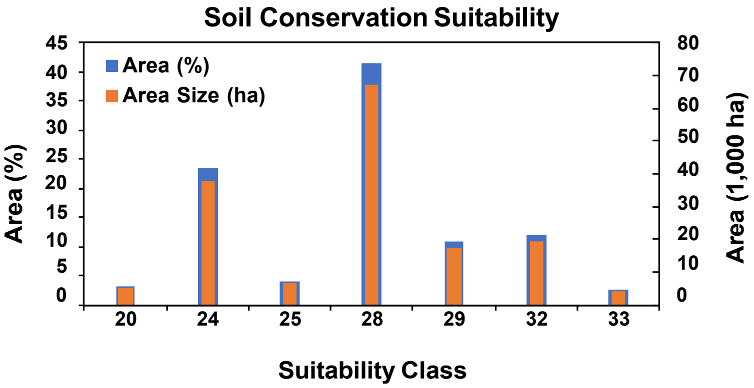

Figure 73.—Soil conservation suitability rating by hectares and percent of the survey area. Areas less than 1% of the total area are not included in the graph.

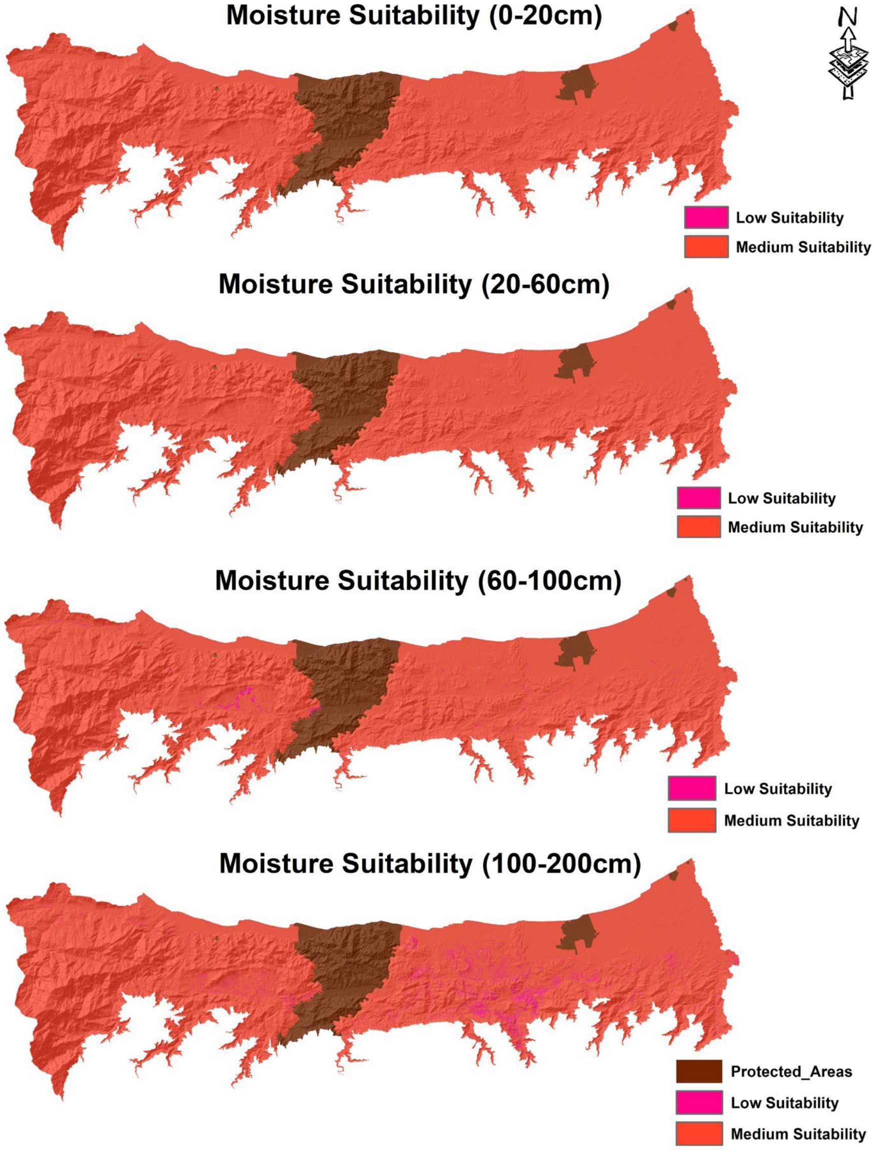

Figure 74.—Distribution of moisture availability suitability rating by soil depths (0–20, 20–60, 60–100, and 100–200 cm).

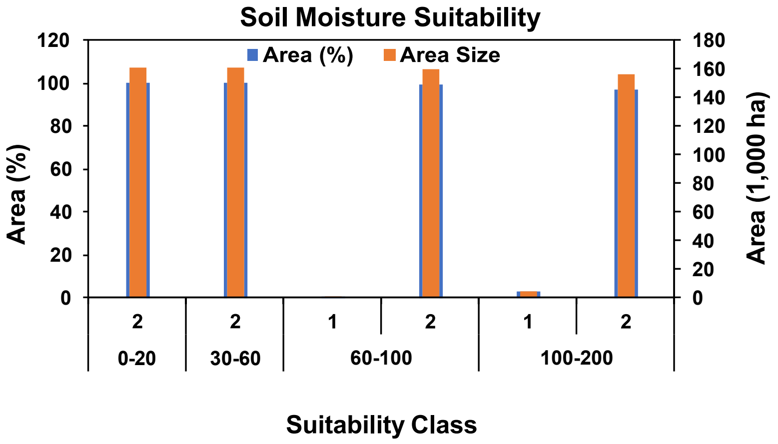

Figure 75.—Moisture availability suitability rating by hectares and as a percent of the survey area.

Tillage Capacity Suitability Rating

Tillage capacity rating is developed based on (i) slope, (ii) texture, and (iii) stoniness or coarse fragments. The stoniness or coarse fragments were not measured; thus, only slope and texture are actually included in these ratings. The tillage capacity is developed only for the 0–20 cm soil depth (fig. 76). About 75% of the area is rated as highly suitable for tillage (fig. 77).

Suitability classes for (i) slope and (ii) soil texture are shown by hectares and as a percent of the survey area in the appendix (fig. A–4).

Plant Root Conditions Suitability Rating

The suitability rating for plant root conditions is developed based on three criteria: (i) effective soil depth; (ii) stoniness or coarse fragments; and (iii) soil texture. Stoniness and coarse fragments were not measured; thus, only effective soil depth and texture are actually included in these ratings (fig. 78). The rating for effective soil depth was first developed based on the depth criteria provided by UPRA (Flórez et al., 2018). This rating was combined with soil texture class rating to generate the plant root conditions suitability rating (fig. 79).

Suitability classes for (i) soil texture and (ii) soil depth are shown by hectares and as a percent of the survey area in the appendix (fig. A–5).

The actual suitability ranges from 2 to 6. The higher the number, the more suitable the soil. However, the proportion of classes varied by soil depth.

Overall Suitability Rating

The suitability ratings for all 7 factors (climate, nutrient availability, soil toxicity, soil conservation, moisture availability, tillage capacity, and plant root conditions) are added together for the final suitability rating. The overall suitability ratings range from 40 to 80 (fig. 80). This overall rating, however, does not identify what criteria within each factor has the lowest rating. For each area, the factors can be: not suitable (0), low (1), moderate (2), or high (3). The individual rating for each criterion within each factor (table 5) are provided as grids. They can be identified easily for each pixel area using GIS based spatial analysis tools and GIS platforms on websites.

The overall rating is also adjusted based on the weighs for each factor as shown in table 5. Because the rating is based only on the physical environmental conditions (soils and climate factors), the weights for each factor were adjusted accordingly. The weights for the physical environment conditions were added together. Their sum was considered as 100, and all the weights were prorated based only on the factors for the physical environment conditions (fig. 81).

Cacao Irrigation Suitability Rating

This rating was developed based on the interpretation guidelines of U.S. Soil Survey. Soils are rated based on their degree of limitation. The degrees are: not limited (degree of limitation = 0), somewhat limited (degree of limitation >0 and <1.0), or very limited (degree of limitation = 1.0). Only slope, soil depth, and soil reaction criteria were used for this rating because the other criteria were not measured or estimated (figs. 82 and 83). A full description of the irrigation rating rules and guidelines is provided in the appendix.

Suitability classes for (i) slope and (ii) soil depth are shown by hectares and as a percent of the survey area in the appendix (fig. A–6).

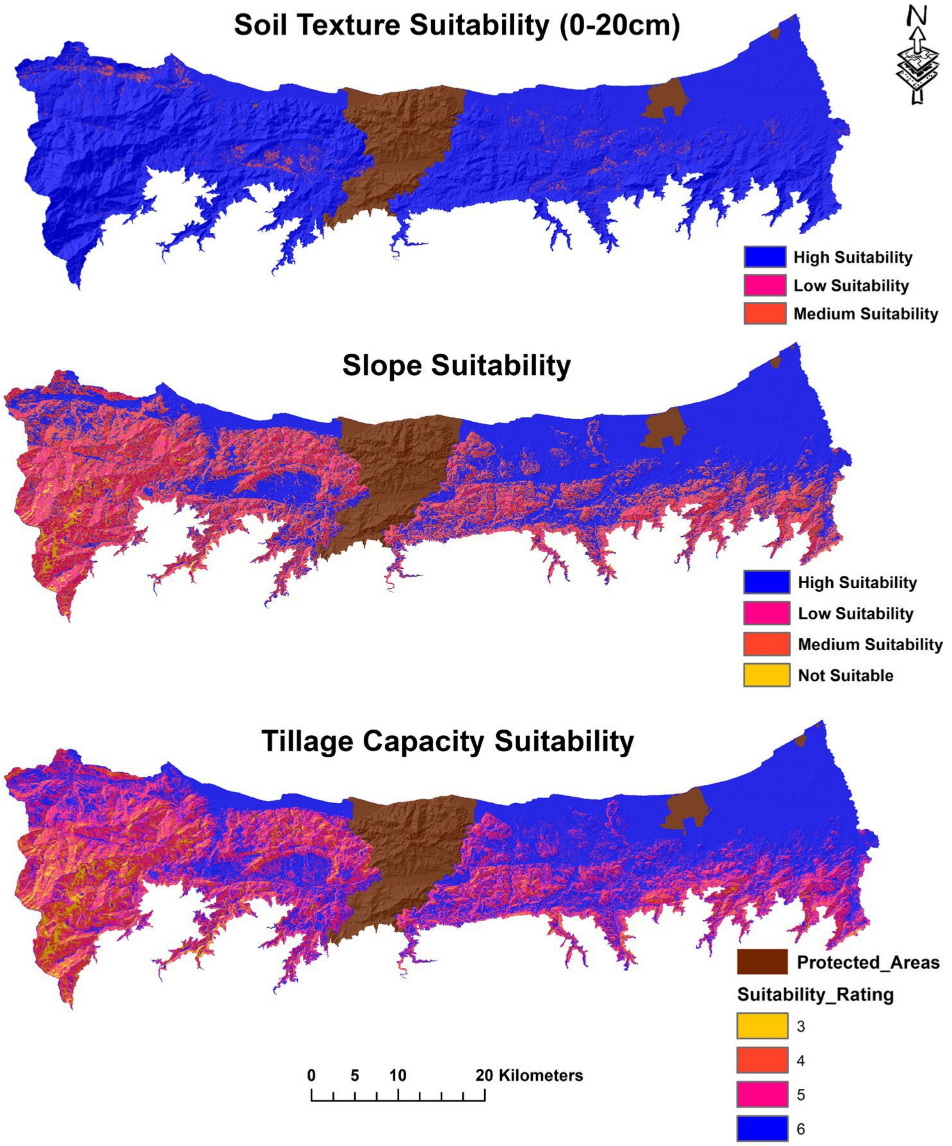

Figure 76.—Distribution of suitability classes for texture, slope, and tillage capacity at 0–30 cm.

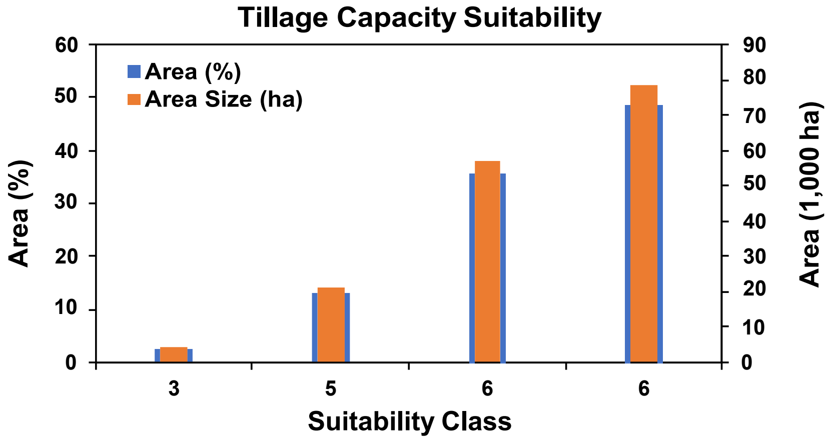

Figure 77.—Tillage capacity suitability rating by hectares and as a percent of the survey area.

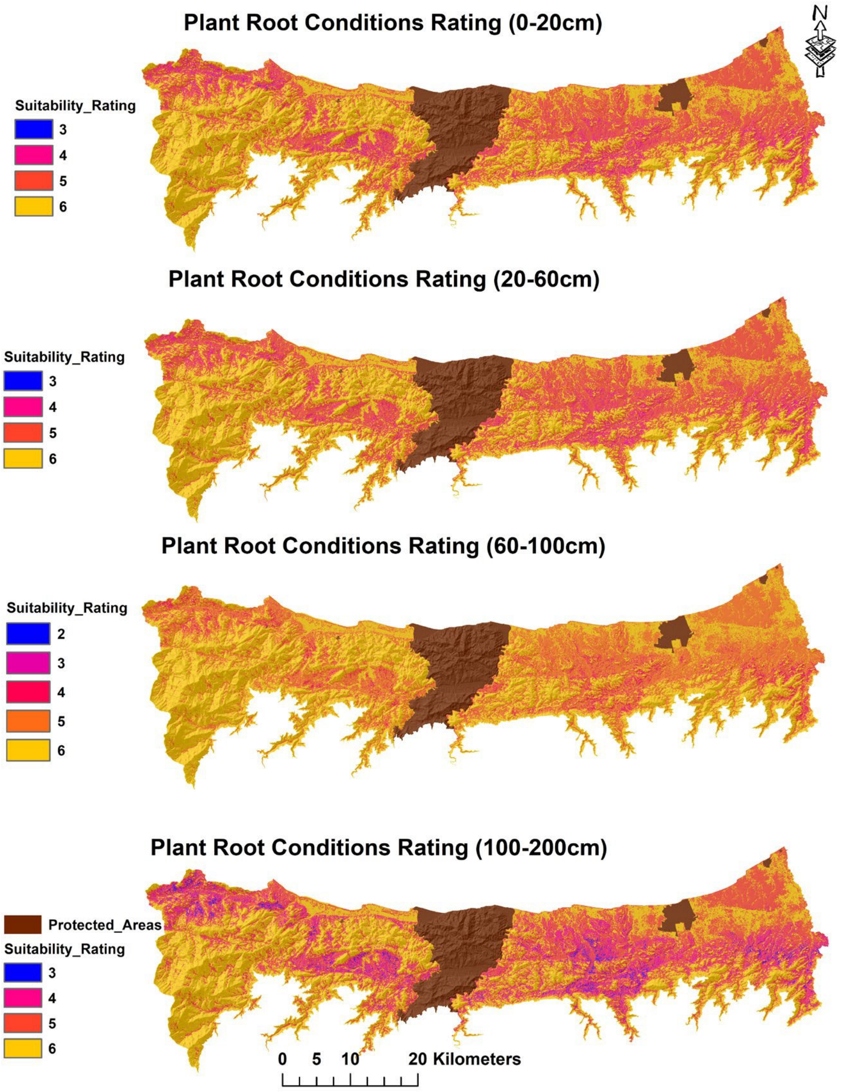

Figure 78.—Distribution of plant root conditions suitability rating by soil depths (0–20, 20–60, 60–100, and 100–200 cm).

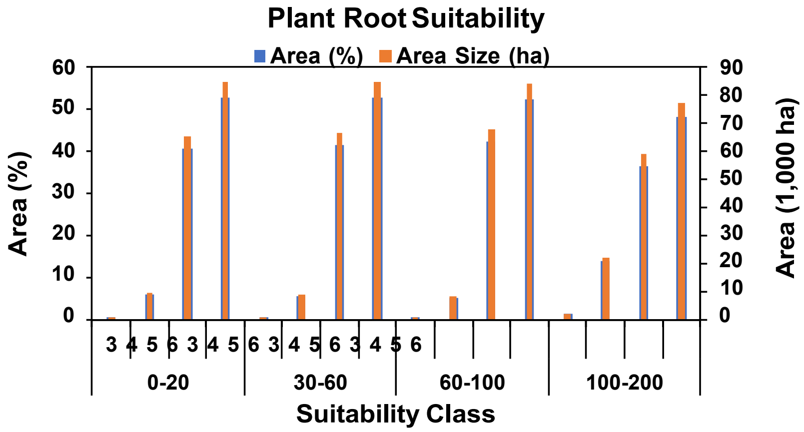

Figure 79.—Plant root conditions suitability rating by hectares and as a percent of the survey area at soil depths 0–20, 20–60, 60–100, and 100–200 cm.

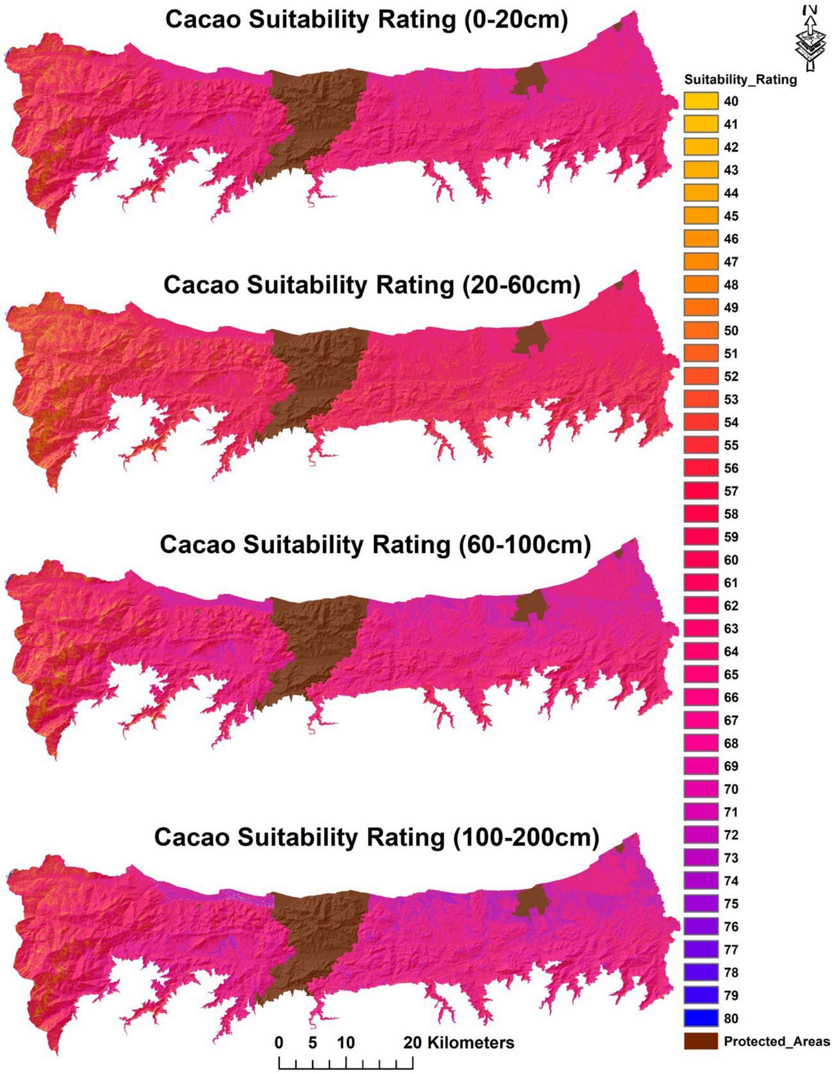

Figure 80.—Cacao suitability rating based on the physical environment conditions without adjusting for the weights of each factor.

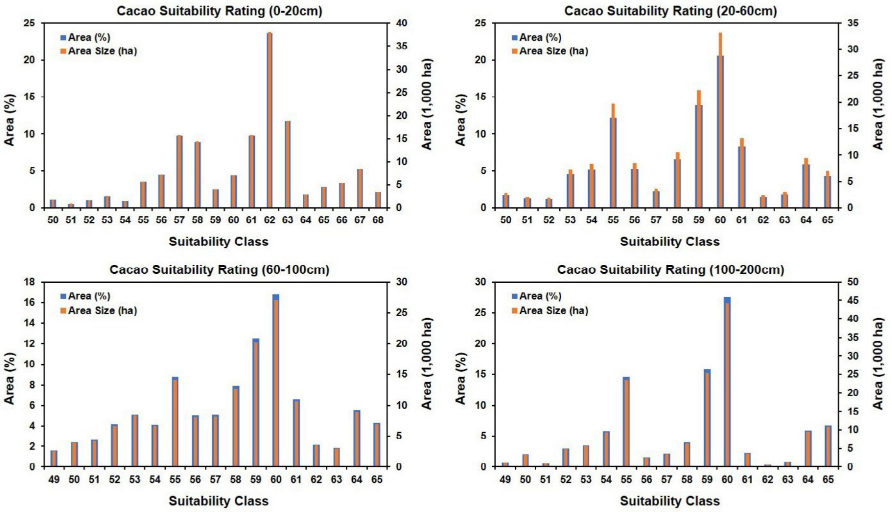

Figure 81.—Cacao suitability rating by hectares and as a percent of the survey area without adjusting for the weights of each criterion by soil depths (0–20, 20–60, 60–100, and 100–200 cm).

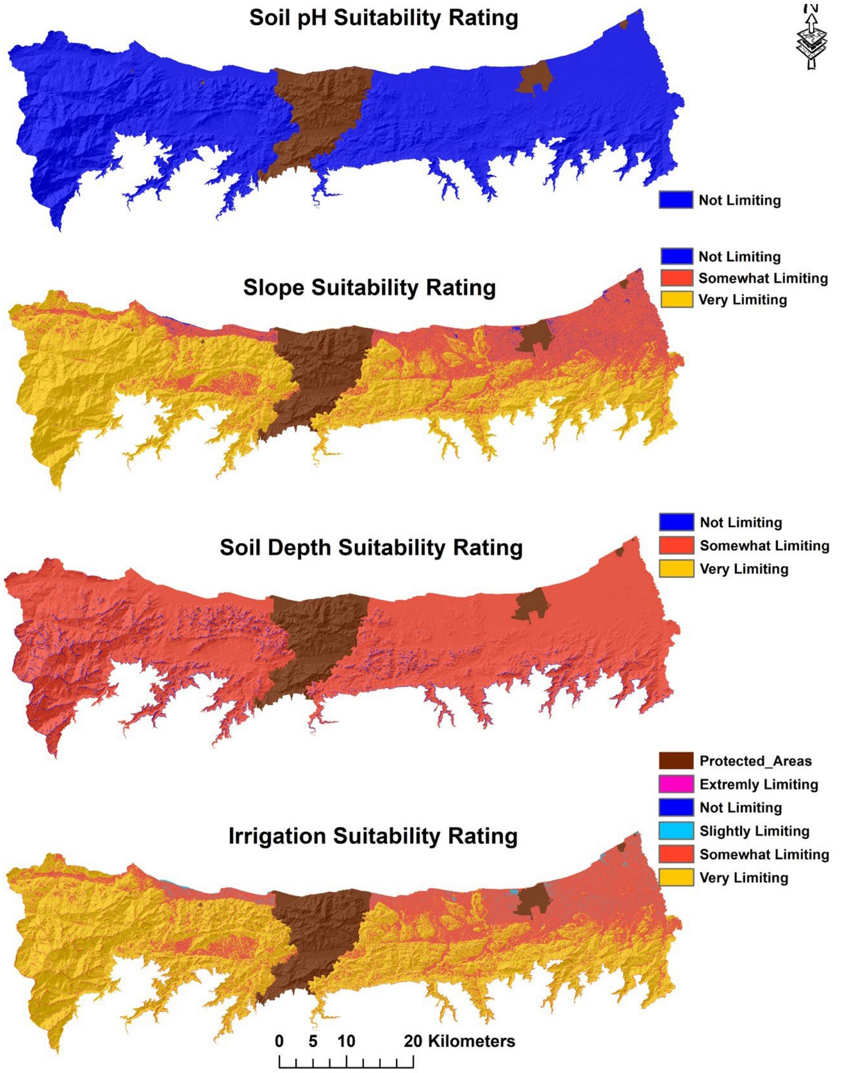

Figure 82.—Cacao suitability rating for irrigation.

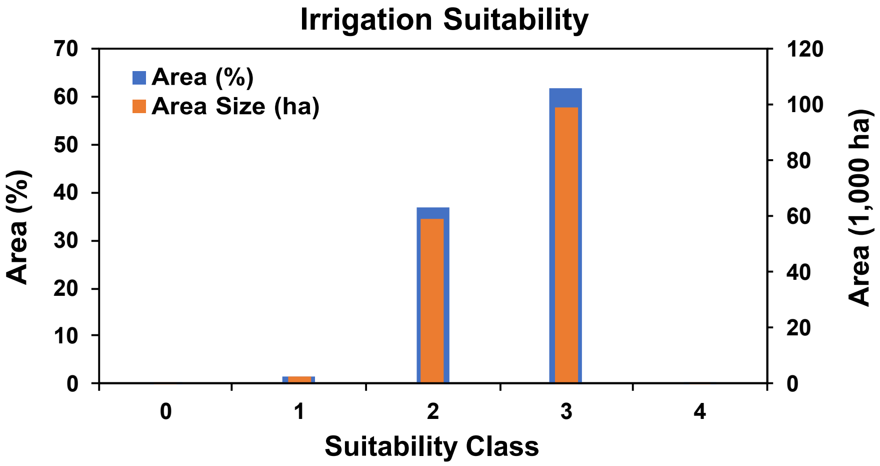

Figure 83.—Irrigation suitability rating by hectares and as a percent of the survey area.

Cacao Potential Erosion Suitability Rating

Estimating soil loss in the study area is difficult because of insufficient accurate climate data, soil data, and site characteristics for the locations visited. The following rating uses assumptions and local data (where available) to give the reader some ability to pick from the data presented to estimate the erosion on some of the visited sites. The erosion model used is the Revised Universal Soil Loss Equation version 2 (RUSLE2). RUSLE2 is an improvement and update of the Revised Universal Soil Loss Equation (RUSLE), which is an improvement and update of the Universal Soil Loss Equation (USLE). All of these models were developed by the United Stated Department of Agriculture, Agriculture Research Service (USDA-ARS). The basic premise of the models is that erosion can be estimated by the following equation.

$A = RKLSCP$

Where:

A = average annual erosion rate (mass/area/year) for the slope length λ,
R = erosivity factor (erosivity unit/area/year),
K = soil erodibility factor (mass/erosivity unit),
L = slope length factor (dimensionless),
S = slope steepness factor (dimensionless),
C = cover-management factor (dimensionless), and
P = support practice factor (dimensionless).

More than one version of RUSLE2 is in use. NRCS version 2.6.11.1 was used for this survey. More information about RUSLE2 can be found in the ARS RUSLE2 Science Documentation (USDA–ARS, 2013). More information about USLE can be found in ARS Agriculture Handbook 537 (USDA–ARS, 1981). The reader is referred to these documents for in-depth discussions of each factor and their respective subfactors.

The reader is reminded that RUSLE2 estimates sheet and rill erosion. It does not estimate concentrated flow erosion, also known as gully erosion (ephemeral and classic). In many cases, concentrated flow erosion from a field can be on the same order of magnitude as sheet and rill erosion. Often, concentrated flow erosion is the main type of erosion in a field. Because of the evidence of gullying in the more sloping cacao stands in Colombia, the reader should keep in mind that the estimates below may be only a small portion of the active erosion in many cacao farms.

Soil Erosivity Factor (R)

A lot of information is required to generate a climate record in RUSLE2. Most of the needed information was not available in the study area. Therefore, an alternative method was used for creating climate records in RUSLE2 to set the R factors. First, average monthly climate data were downloaded from the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM, 2020). Specifically, the 1971–2000 averages were used. Precipitation averages for towns close to the work sites were used to estimate the monthly precipitation pattern. Once the pattern was identified, a climate record with a similar pattern was found among the established U.S. climate records. The U.S. climate record most resembling the study sites was associated with the Ponce area of Puerto Rico (fig. 84).

The total annual precipitation varied between the four Colombian towns, ranging from 1,307.8 mm (51.49 inches) at Dibulla to 2,010.3 mm (79.15 inches) at Buritaca. Therefore, climate records were created for 1,090 mm, 1,290 mm, 1,490 mm, 1,690 mm, 1,900 mm, 2,160 mm, and 2,400 mm precipitation. The process first found a similar climate data set for comparison. Figure 85 below shows a Santa Marta

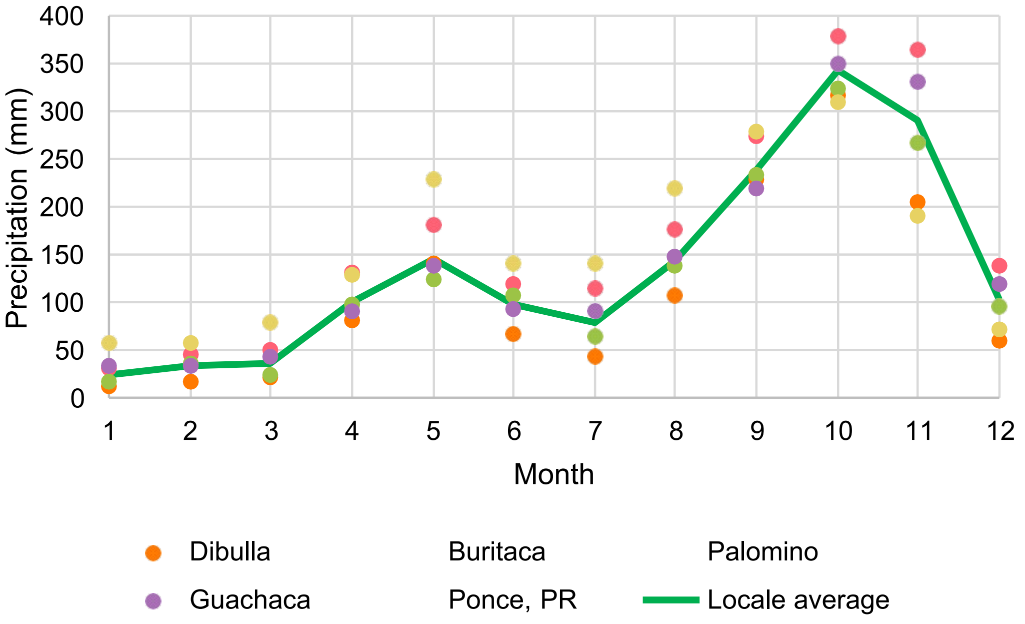

Figure 84.—Precipitation patterns of towns near the study sites, the average among those sites, and a similar U.S. record (Ponce, Puerto Rico) that was used to make multiple climate records for Colombia.

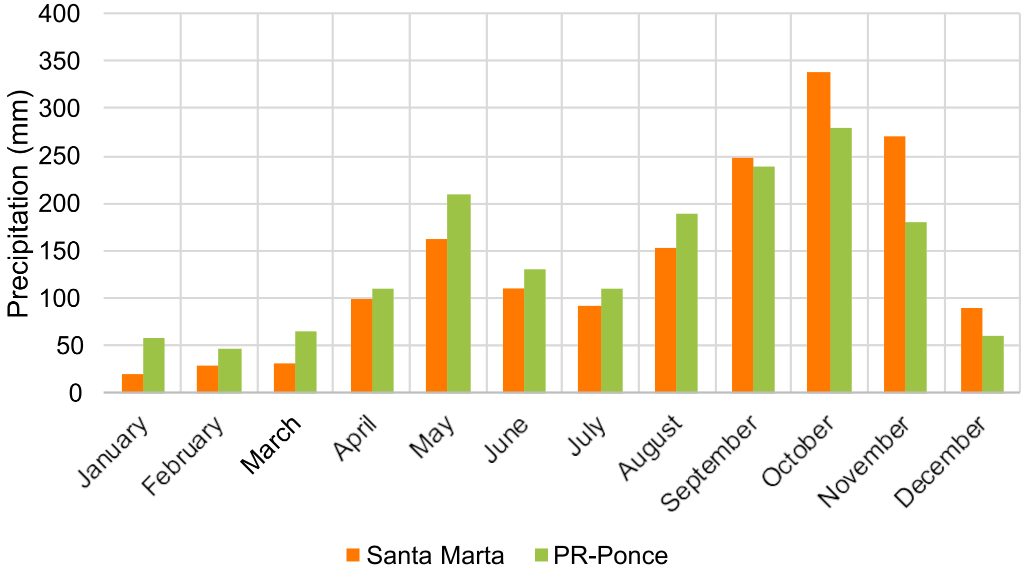

Figure 85.—Average monthly precipitation totals for Santa Marta, Colombia (1,645 mm), and Ponce, Puerto Rico, U.S. (1,681 mm).

precipitation record, with an annual total of 1,645 mm, compared to Puerto Rico record, with an annual total of 1,681 mm.

Using the precipitation totals, a monthly difference was calculated from a reference point so that records of different annual totals could be generated. September was arbitrarily chosen as a reference month because the totals were very similar for both locations. From that, the corresponding climate record for Ponce, Puerto Rico, was opened in RUSLE2 and edited with the generated monthly totals. For example, the 2,360 mm annual total record created for Colombia is shown in figure 85. Notice that the shape and relative differences of figure 85 and figure 86 are similar, only their magnitudes (i.e., Y-axis values) differ.

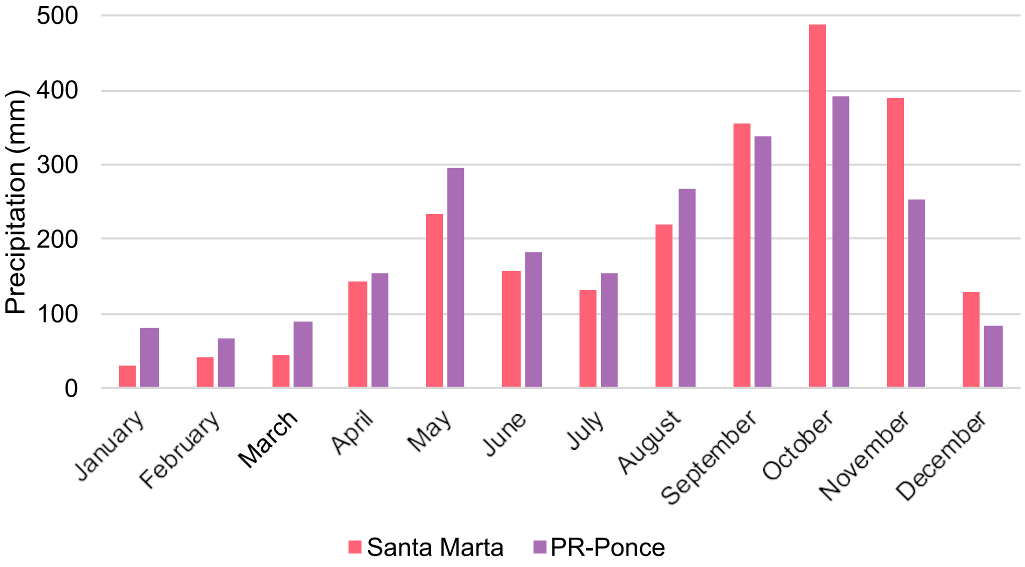

Figure 86.—Generated average monthly precipitation totals for Santa Marta, Colombia (1,645 mm), compared to the source Ponce, Puerto Rico, U.S. (1,681mm) data.

Temperature has a significant effect on residue composition. However, the precise manner in which temperature changes with elevation and precipitation could not be discerned from the climate data provided from IDEAM. That is, it was not possible to get both precipitation and temperature from the same station location. Therefore, only one average monthly climate data set was used for all the climate records in the RUSLE2 analysis (fig. 87). It is important to note that as the temperature is reduced, the decomposition of residue is reduced. This reduction in decomposition can significantly affect soil loss reduction by resulting in more soil that is covered with leaf residues on the surface. To improve the estimates, the user should adjust for the local temperature in the climate record.

By selecting a reference set of parameters and varying only the total annual precipitation, the expected results displayed in figure 87 are produced. The conditions used for this analysis are 100-m slope length, 50% slope grade, loamy soil, and sparse forest cover management. Slope effects are discussed in the Slope Factor section; the soil details are discussed in the Soil Erodibility Factor section; and the management details are discussed in the Cover Management Factor section. The records all have one temperature regime. Typically, the higher the elevation, the higher the precipitation but the lower the temperatures. Because this holds true for Colombia, as is indicated by the limited data in figure 87, then the slope of the best fit line in figure 88 is expected to be reduced. Because of more accurate local climate data, RUSLE2 climate records can be created that are more accurate than the records used for this analysis. Ideally, high-quality, serially complete climate data would be used in the Rainfall Intensity Summarization Tool (RIST) (USDA–ARS, 2019) to generate the correct RUSLE2 climate record for each identifiable area where modeling of soil loss is desired.

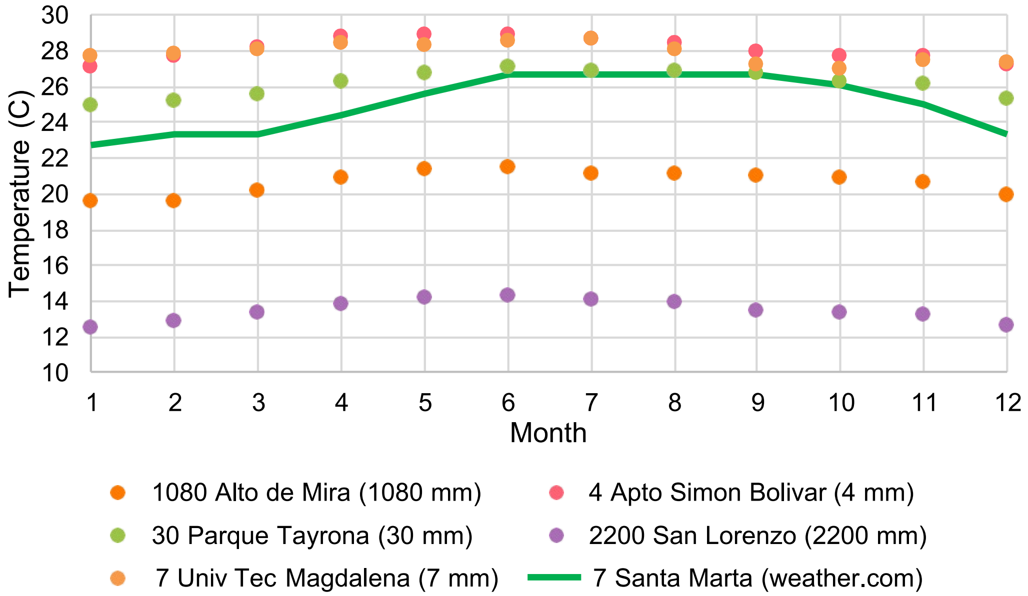

Figure 87.—Average monthly temperatures at selected locations in Santa Marta, Magdalena, Colombia (from IDEAM). The green line indicates the data used for setting the temperatures in the RUSLE2 climate records.

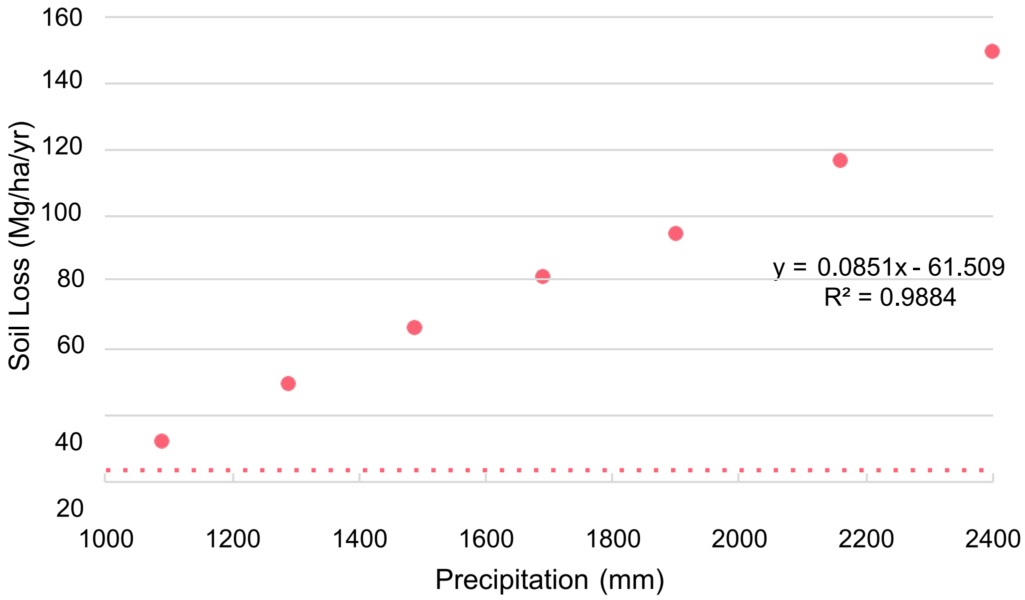

Figure 88.—Soil loss as a function of varying the amount of precipitation in RUSLE2.

Soil Erodibility Factor (K)

The parameters needed to calculate soil erodibility are percent sand, percent silt, percent clay, percent very fine sand, percent organic matter, structure, permeability, and coarse fragments. Not all of this information was available for the soil profiles described in this survey. The actual data available are summarized in table 7. The locations of the soil profiles used for the calculations are shown in figure 89.

Table 7.—Selected surface-horizon properties of the 10 profiles described during the 2019 field work trip. Profiles 01, 02, 07, 09, and 10 were used for calculating soil erodibility factor (K).

Surface horizon properties					
Profile ID	**Texture classification**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**SOC (%)**
P01	Sandy loam	62.08	22.66	15.26	2.65
P02	Clay	26.64	19.61	53.75	4.58
P03	Sandy clay loam	16.33	54.29	29.38	2.97
P04	Sandy clay loam	68.18	8.96	22.86	1.72
P05	Loam	40.32	34.13	25.56	2.93
P06	Clay loam	36.17	35.85	27.98	2.25
P07	Clay loam	38.93	32.93	28.14	2.96
P08	Loam	32.40	43.42	24.18	1.59
P09	Sandy clay loam	68.07	11.52	20.41	2.70
P10	Loam	37.79	48.03	14.18	2.29

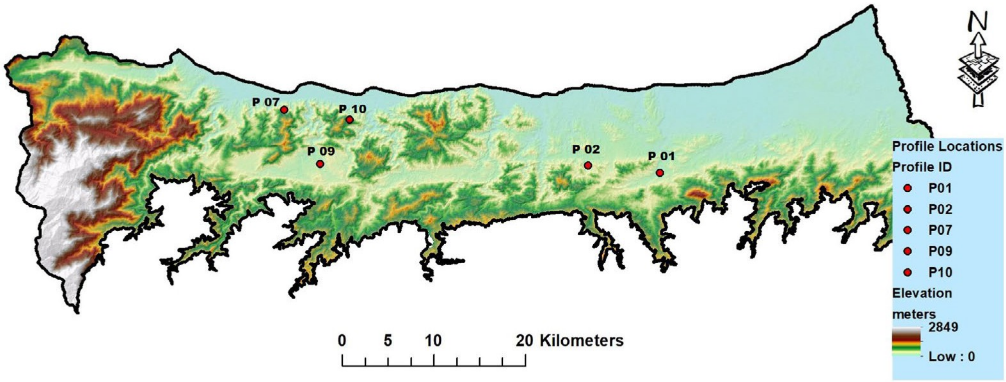

Figure 89.—Soil profiles used in developing the soil records in RUSLE2 for estimating soil loss.

Once the soil texture was determined, a corresponding "generic soils" record was created. Typically, the low-moderate organic matter option was used. The values for percent sand, percent silt, and percent clay were updated; very fine sand was calculated based on texture; percent recalcitrant organic matter was entered from the percent SOC values; coarse fragments were left at zero; and the default values in the generic soils record were used for missing values for structure and permeability. Next, the ARS nomograph was used to calculate the erodibility of the soil. The resulting Kf values for the soil records created for this analysis are summarized in table 8.

The climate records were saved in a Colombia folder in the RUSLE2 database. The effect of soil erodibility is seen in figure 90. The conditions used for this analysis are 100-m slope length, 50% slope grade, 1,690 mm climate record, and sparse forest cover management (tables 9-A through 9-G).

Table 8.—Erodibility Factors (Kf) calculated by the ARS nomograph in the RUSLE2 program. Calculations were based on selected data from 5 distinctly different top horizons of the original 10 described profiles.

Calculated Kf values		
Profile ID	**Texture classification**	**Kf (SI units)**
P01	Sandy loam	0.03533
P02	Clay	0.02019
P07	Clay loam	0.03735
P09	Sandy clay loam	0.02803
P10	Loam	0.05958

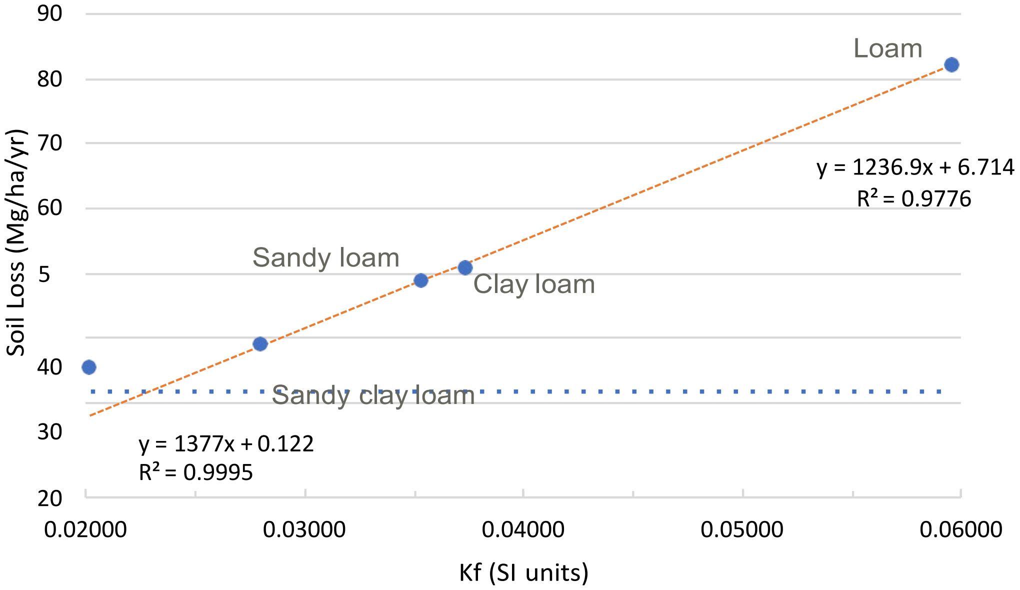

Figure 90.—Soil loss as a function of soil erodibility. The dotted trendline uses all the data. The regression data for this trendline is in the upper right corner of the figure. The dashed trendline leaves out the clay texture to create a better fit for textures that are not clay. The regression data for the dashed trendline is in the lower left corner of the figure.

Table 9-A.—Soil loss in Mg/ha/yr for average annual precipitation of 1,090 mm. Data are for loamy soil and a sparse forest cover management.

Average annual precipitation 1,090 mm						
		Slope length (meters)				
		10	**25**	**50**	**75**	**100**
Percent slope	1	0.795	0.807	0.821	0.831	0.84
	2	1.24	1.28	1.33	1.36	1.39
	5	2.13	2.28	2.45	2.58	2.7
	10	3.43	3.83	4.3	4.69	5.02
	20	6.92	8.17	9.72	11	12.1
	30	10	12.3	15.2	17.5	19.4
	50	15.4	19.8	25.3	29.4	32.5

Table 9-B.—Soil loss in Mg/ha/yr for average annual precipitation of 1,290 mm. Data are for loamy soil and a sparse forest cover management.

Average annual precipitation 1,290 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	1.14	1.16	1.18	1.19	1.2
	2	1.8	1.86	1.92	1.97	2.01
	5	3.22	3.44	3.7	3.91	4.09
	10	5.21	5.81	6.54	7.12	7.63
	20	10.6	12.5	14.8	16.7	18.4
	30	15.3	18.8	23.1	26.6	29.5
	50	23.6	30.2	38.5	44.8	49.6

Table 9-C.—Soil loss in Mg/ha/yr for average annual precipitation of 1,490 mm. Data are for loamy soil and a sparse forest cover management.

Average annual precipitation 1,490 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	1.49	1.52	1.54	1.56	1.58
	2	2.37	2.45	2.53	2.6	2.65
	5	4.28	4.59	4.94	5.21	5.45
	10	6.97	7.79	8.75	9.53	10.2
	20	14.2	16.7	19.9	22.5	24.7
	30	20.6	25.3	31.1	35.7	39.6
	50	31.7	40.6	51.7	60.2	66.6

Table 9-D.—Soil loss in Mg/ha/yr for average annual precipitation of 1,690 mm. Data are for loamy soil and a sparse forest cover management.

Average annual precipitation 1,690 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	1.8	1.83	1.87	1.89	1.91
	2	2.88	2.97	3.08	3.16	3.22
	5	5.26	5.64	6.06	6.4	6.69
	10	8.59	9.6	10.8	11.7	12.6
	20	17.5	20.7	24.6	27.7	30.4
	30	25.5	31.3	38.4	44.2	48.9
	50	39.2	50.3	64	74.4	82.3

Table 9-E.—Soil loss in Mg/ha/yr for average annual precipitation of 1,900 mm. Data are for loamy soil and a sparse forest cover management.

Average annual precipitation 1,900 mm						
		Slope length (meters)				
		10	**25**	**50**	**75**	**100**
Percent slope	1	2.15	2.18	2.22	2.25	2.28
	2	3.43	3.55	3.68	3.77	3.85
	5	6.31	6.77	7.28	7.69	8.03
	10	10.3	11.6	13	14.1	15.1
	20	21.1	25	29.6	33.4	36.7
	30	30.8	37.7	46.3	53.2	58.9
	50	47.3	60.6	77.1	89.6	99.2

Table 9-F.—Soil loss in Mg/ha/yr for average annual precipitation of 2,160 mm. Data are for loamy soil and a sparse forest cover management.

Average annual precipitation 2,160 mm						
		Slope length (meters)				
		10	**25**	**50**	**75**	**100**
Percent slope	1	2.48	2.52	2.57	2.6	2.63
	2	3.98	4.12	4.27	4.38	4.47
	5	7.38	7.93	8.53	9	9.41
	10	12.1	13.6	15.3	16.6	17.8
	20	24.8	29.4	34.9	39.4	43.2
	30	36.2	44.5	54.6	62.8	69.5
	50	55.6	71.4	90.9	106	117

Table 9-G.—Soil loss in Mg/ha/yr for average annual precipitation of 2,400 mm. Data are for loamy soil and a sparse forest cover management.

Average annual precipitation 2,400 mm						
		Slope length (meters)				
		10	**25**	**50**	**75**	**100**
Percent slope	1	2.97	3.03	3.08	3.12	3.16
	2	4.84	5.02	5.21	5.35	5.47
	5	9.15	9.87	10.7	11.3	11.8
	10	15.1	17.1	19.3	21	22.4
	20	31.1	37.2	44.4	50.2	55.1
	30	45.2	56.3	69.6	80.2	89.0
	50	69.3	90.3	116	135	150.0

Soil Factors (L, S)

Slope factors can have a large impact on the soil loss estimates. It is difficult to correctly link the actual onsite slope conditions for all sites visited with the climate and management. Therefore, this section discusses the effects of slope length and slope steepness in general and provides a comprehensive analysis of slope factor effects.

Slope Length (L)

The equation for average annual erosion rate shows that as slope length increases, the erosion increases. Figure 91 displays soil loss as a function of increasing slope length. The conditions used for this analysis are 50% slope grade, loamy soil, 1,690 mm climate record, and a sparse forest cover management (tables 9-A through 9-G).

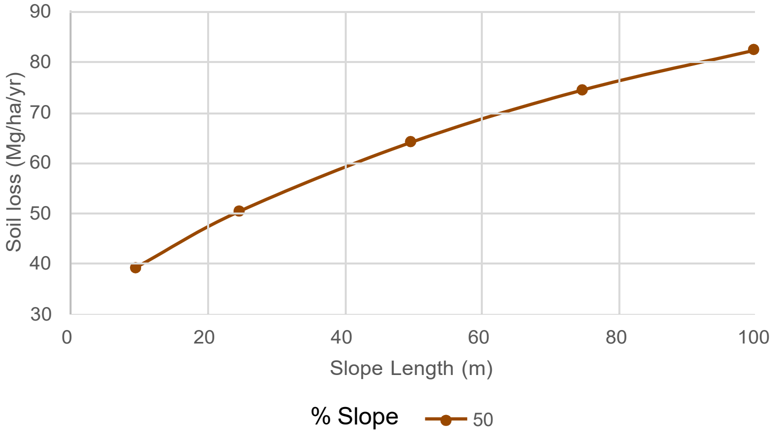

Figure 91.—Soil loss as a function of varying the slope length in RUSLE2.

Slope Steepness (S)

As with slope length, as slope steepness increases, the erosion increases. Figure 92 displays soil loss as a function of increasing slope length. The conditions used for this analysis are 100-m slope length, loamy soil, 1,690 mm climate record, and a sparse forest cover management (tables 9-A through 9-G).

Combined Slope Length and Steepness Analysis Across Multiple Climate Zones

This section provides a more comprehensive analysis of the effects of the slope factors across several precipitation ranges, starting from a low of 1,090 mm/year to a high of 2,400 mm/year. The conditions used for these analyses are variable climate records, variable slope lengths, variable slope grades, loamy soil, and a sparse forest cover management (tables 9-A through 9-G).

Tables 9-A through 9-G report soil loss values for specific combinations of slope length, slope steepness, and annual precipitation. If the average annual precipitation total is known for a location, the soil loss can be estimated by finding the closest slope length and slope steepness in the table. If the soil texture is different than loam, the soil loss can generally be closely estimated by dividing the soil loss estimates in tables 9-A through 9-G by the Kf for loam and then multiplying by the Kf for the soil of interest. The exception is for clay. See the soil erodibility section for details regarding clay. The temperature issue (see Erosivity Factor section) should be considered when these corrections are made. The data are represented with surface graphs in figure 93 and with scatter plots in figure 94. Evident in figure 93 is the repeating pattern of

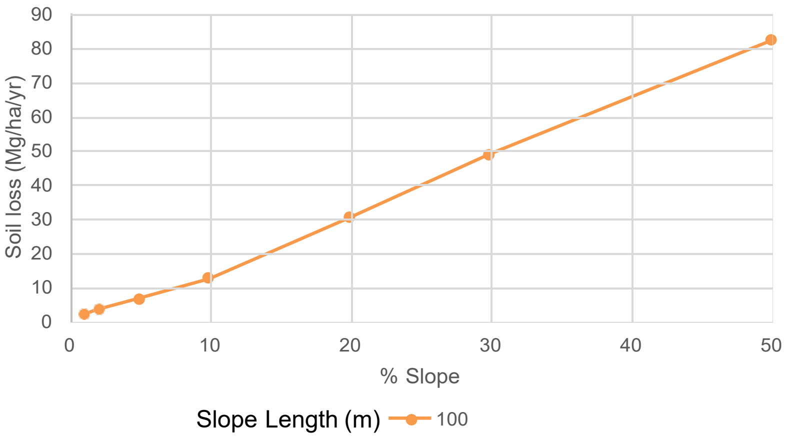

Figure 92.—Soil loss as a function of varying the slope steepness in RUSLE2.

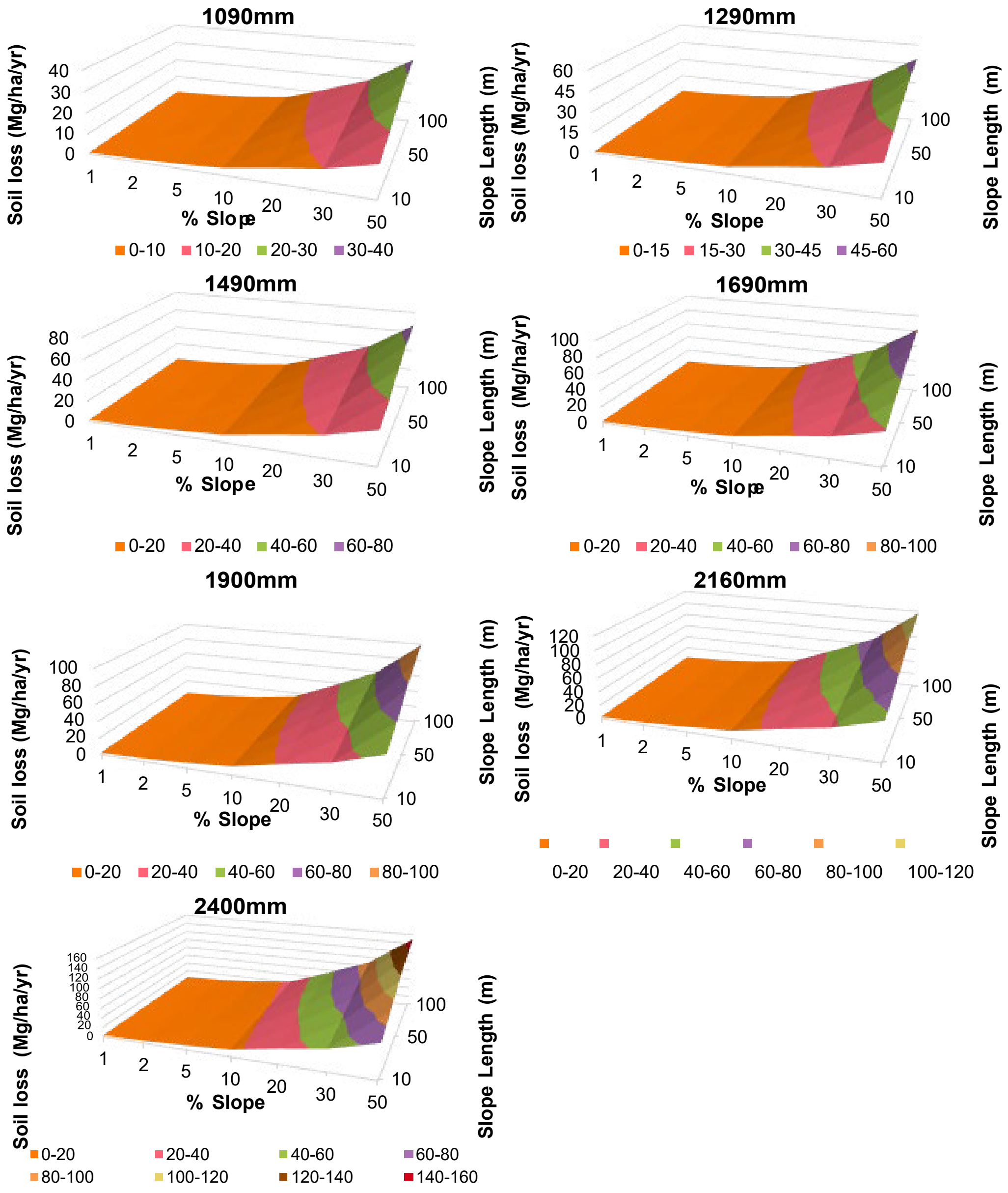

Figure 93.—Surface plots of soil loss in Mg/ha/yr. Variables are slope length, slope grade, and average annual precipitation. Soil texture (loamy) and forest cover management (sparse) are constants.

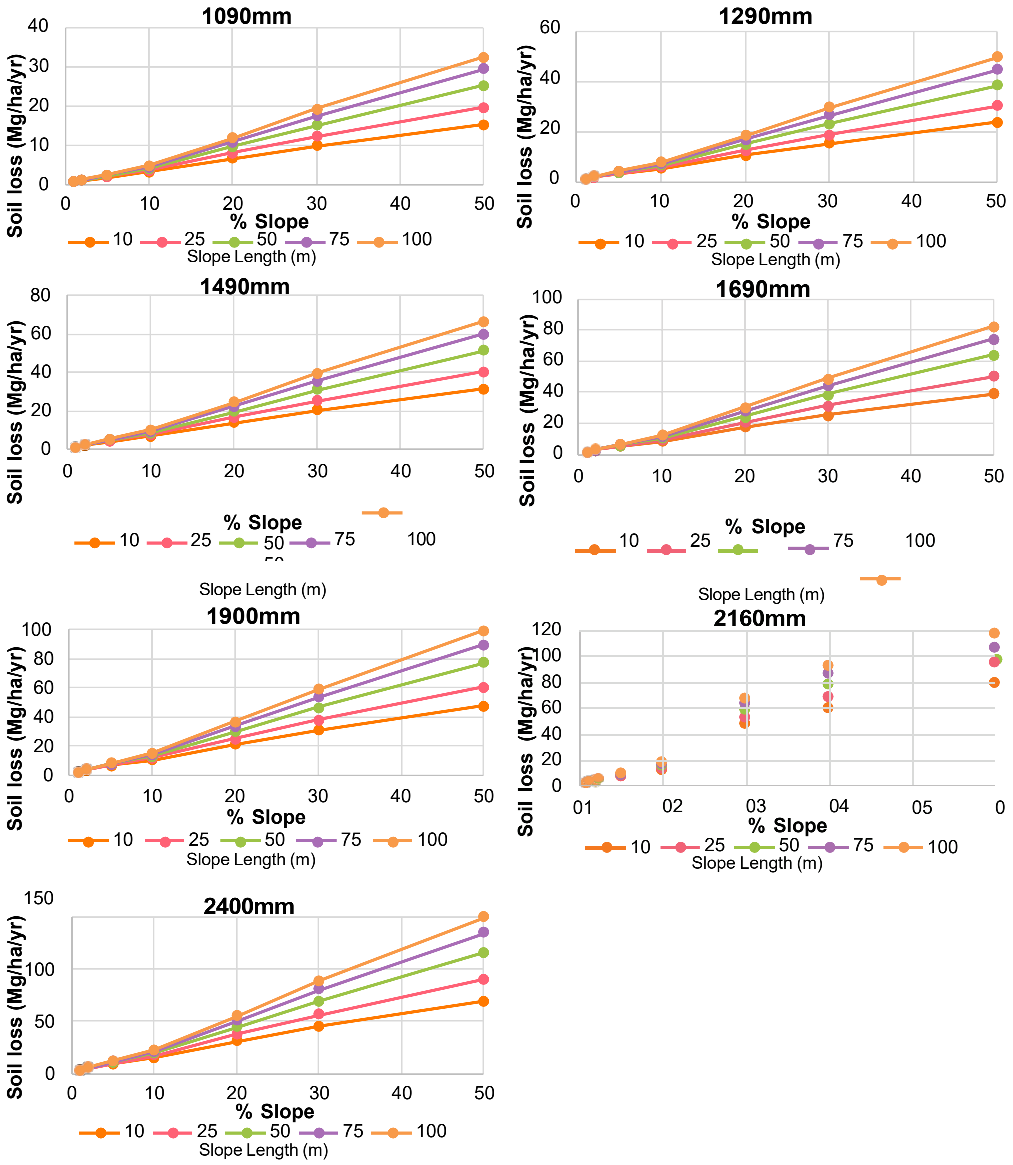

Figure 94.—Scatter plots of soil loss in Mg/ha/yr. Variables are slope length, slope grade, and average annual precipitation. Soil texture (loamy) and forest cover management (sparse) are constants.

erosion increasing as slope length and slope steepness increase. The graphs are also all similarly shaped; only the magnitude of the vertical axis changes between the figures. This pattern is also evident in figure 94.

Cover Management Factor (C)

Cover management is the main factor that is controlled directly by the farm manager. Type and timing of soil-disturbing activities, management of the plant biomass, and harvest activities can all significantly affect the erosion estimates. To model the situations at the visited sites, three different management scenarios were developed. The main differences in the managements are the amount of biomass being generated and the percent canopy cover of the soil, namely “moderate,” “sparse,” and “very sparse” canopy cover. The details of the management records are listed in tables 10, 11, and12.

Table 10.—Management parameters used to model the cover management factor for established forest with moderate cover.

Date (m/d/y)	Operation	Vegetation	Yield (kg/ha)	Type of cover material	Biomass generated (kg/ha)
2/1/2000	Add mulch			Leaves, deciduous tree	392
3/1/2000	Add mulch			Leaves, deciduous tree	392
4/1/2000	Add mulch			Leaves, deciduous tree	392
5/1/2000	Begin growth	Pecan, walnut; bare ground	2,353		
6/1/2000	Add mulch			Leaves, deciduous tree	392
7/1/2000	Add mulch			Leaves, deciduous tree	392
8/1/2000	Add mulch			Leaves, deciduous tree	392
9/1/2000	Add mulch			Leaves, deciduous tree	392
10/1/2000	Add mulch			Leaves, deciduous tree	392
10/15/2000	Harvest, orchard and nut crops				
11/1/2000	Add mulch			Leaves, deciduous tree	392
12/1/2000	Add mulch			Leaves, deciduous tree	392

Table 11.—Management parameters used to model the cover management factor for forest with sparse canopy cover.

Date (m/d/y)	Operation	Vegetation	Yield (kg/ha)	Type of cover material	Biomass generated (kg/ha)
2/1/2000	Add mulch			Leaves, deciduous tree	280
3/1/2000	Add mulch			Leaves, deciduous tree	280
4/1/2000	Add mulch			Leaves, deciduous tree	280
5/1/2000	Begin growth	Pecan, walnut; bare ground; young	1,000		
6/1/2000	Add mulch			Leaves, deciduous tree	280
7/1/2000	Add mulch			Leaves, deciduous tree	280
8/1/2000	Add mulch			Leaves, deciduous tree	280
9/1/2000	Add mulch			Leaves, deciduous tree	280
10/1/2000	Add mulch			Leaves, deciduous tree	280
10/15/2000	Harvest, orchard and nut crops				
11/1/2000	Add mulch			Leaves, deciduous tree	280
12/1/2000	Add mulch			Leaves, deciduous tree	280

Table 12.—Management parameters used to model the cover management factor in relatively bare area with very sparse canopy cover.

Date (m/d/y)	Operation	Vegetation	Yield (kg/ha)	Type of cover material	Biomass generated (kg/ha)
2/1/2000	Add mulch			Leaves, deciduous tree	168
3/1/2000	Add mulch			Leaves, deciduous tree	168
4/1/2000	Add mulch			Leaves, deciduous tree	168
5/1/2000	Begin growth	Pecan, walnut; bare ground; very young	500		
6/1/2000	Add mulch			Leaves, deciduous tree	168
7/1/2000	Add mulch			Leaves, deciduous tree	168
8/1/2000	Add mulch			Leaves, deciduous tree	168
9/1/2000	Add mulch			Leaves, deciduous tree	168
10/1/2000	Add mulch			Leaves, deciduous tree	168
10/15/2000	Harvest, orchard and nut crops				
11/1/2000	Add mulch			Leaves, deciduous tree	168
12/1/2000	Add mulch			Leaves, deciduous tree	168

The main difference between the management scenarios are the amount of leaf-fall that is modeled (last two columns in tables 10–12) and the vegetation records used to model the leaf canopy (third column in tables 10–12). For the most mature canopy cover, the vegetation record used was the existing “Pecan, walnut; bare ground.” For the other two management scenarios, the vegetation record was modified from this existing record to reflect a lower canopy value. As modeled in a RUSLE2, the effects on canopy and surface residue of the vegetation record by management can be seen in figure 95. The conditions used for these analyses are 100-m slope length, 50% slope steepness, loamy soil, 1,690-mm climate record, and the three managements scenarios described above. Note that as the biomass of the trees and leaf drop increases, the respective amount of soil cover (percent surface and canopy cover) also increases (figures 95 A, B, and C). The biomass is modeled as an “add mulch” operation in the above tables, second column. All the data in tables 9-A through 9-G and figures 93 and 94 were generated with the management described in table 11.

The “Moderate” scenario for canopy management is described in table 10 and figure 95-A. It maintains a leave canopy cover of 50% to 75% and a forest floor residue cover of greater than 75% (2,500–3,000 kg/ha of residue). The “Sparse” scenario for canopy management is described in table 11 and figure 95-B. It maintains a leave canopy cover of 35% to 50% and a forest floor residue cover of greater than 65% (about 1,800 kg/ha of residue). The “Very Sparse” scenario for canopy management is described in table 12 and figure 95-C. It maintains a leave canopy cover of 15% to 25% and a forest floor residue cover of about 50% (about 1,250 kg/ha of residue).

The effect of the cover-management factor, as noted earlier, can be significant. For comparison, a RUSLE2 analyses was conducted varying the three managements scenarios described above for 100-m slope length, 50% slope steepness, loamy soil, and 1,690-mm precipitation climate record. The results were 40.3 T/ha/yr for the moderate canopy, 82.3 T/ha/yr for the sparse canopy, and 405 T/ha/yr for the very sparse canopy. The actual erosion events from each run are compiled in figure 96.

Even on slopes as steep as 50%, the prevalence of a high amount of surface cover (greater than 75%), kept the erosion rate at about 40.3 T/ha/yr. Reducing the surface

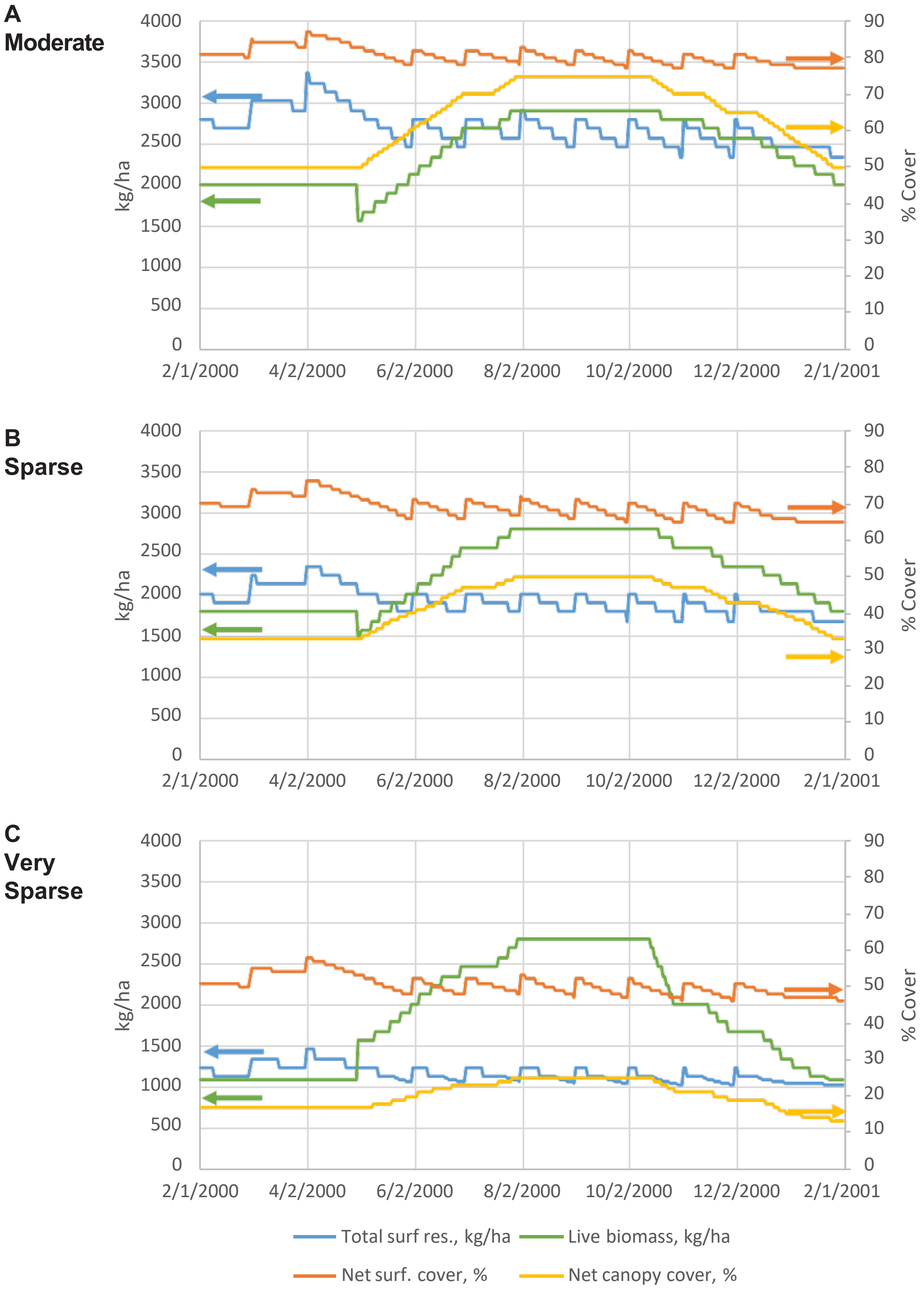

Figure 95.—The amounts of biomass generated by the tree (Live biomass) and leaf drop (Total surf res) and the percent cover from the tree canopy (net canopy cover) and the leaves on the surface of the soil (Net surf. cover). These data correspond to the (A) moderate (table 10), (B) sparse (table 11) and (C) very sparse (table 12) canopy cover; 100-m slope length; 50% slope steepness; loamy soil; and the 1,690 mm precipitation climate record.

cover by 10%, roughly doubled the erosion rate to 82.3 T/ha/yr. A further reduction to about 50% produced an erosion rate of 405 T/ha/yr, which is about an order of magnitude higher than the rate on the moderate forest canopy management at greater than 75% cover.

Of course, this is only one example comparing different management. To better understand the effect of this parameter on soil loss, a series of RUSLE2 runs were performed similar to those in tables 9-A through 9-G and in figures 93 and 94. All the variations of slope length (i.e., 10, 25, 50, 75, and 100 m) and steepness (i.e., 1, 2, 5, 10, 20, 30, and 50%) were run. Three climates (i.e., 1,090 mm, 1,690 mm, and 2,400 mm) and one soil texture (loamy) were analyzed for the moderate and very sparse canopy management scenarios as shown in tables 13-A through 13-F and in figure 97. The data associated with the sparse forest canopy management scenario are in tables 9-A through 9-G and in figures 93 and 94.

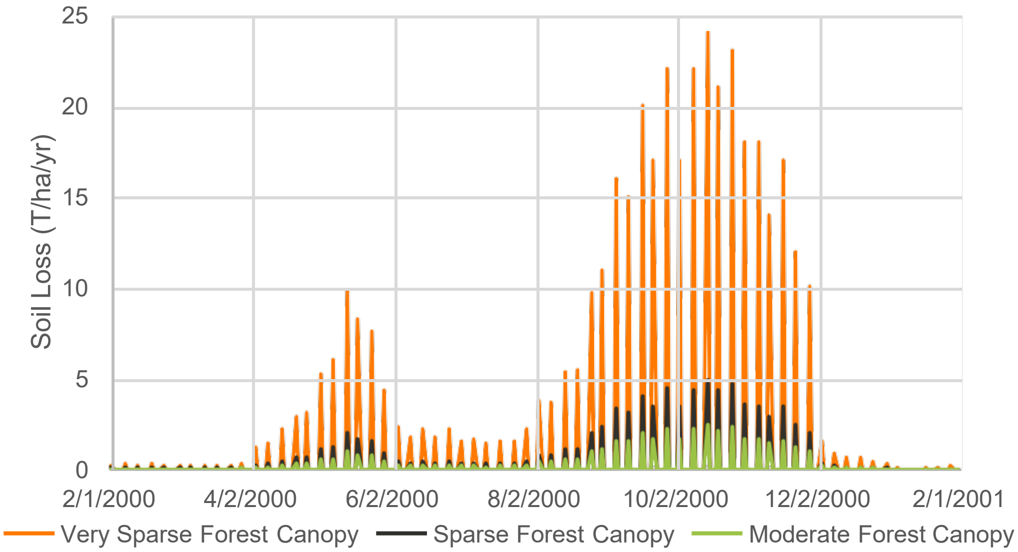

Figure 96.—Soil loss varying the three managements scenarios described in tables 10, 11, and 12 for 100-m slope length, 50% slope steepness, loamy soil, and 1,690-mm precipitation climate record.

Table 13-A.—Soil loss in Mg/ha/yr for average annual precipitation of 1,090 mm. Data are for loamy soil and a moderate forest cover management.

Average annual precipitation 1,090 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	0.489	0.495	0.503	0.509	0.514
	2	0.749	0.77	0.794	0.813	0.829
	5	1.21	1.29	1.38	1.45	1.51
	10	1.91	2.11	2.35	2.55	2.71
	20	3.78	4.4	5.15	5.75	6.24
	30	5.44	6.55	7.88	8.9	9.7
	50	8.27	10.4	12.8	14.5	15.7

Table 13-B.—Soil loss in Mg/ha/yr for average annual precipitation of 1,690 mm. Data are for loamy soil and a moderate forest cover management.

Average annual precipitation 1,690 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	1.14	1.16	1.17	1.19	1.2
	2	1.78	1.83	1.89	1.93	1.97
	5	3.05	3.25	3.47	3.65	3.8
	10	4.86	5.38	5.99	6.47	6.89
	20	9.7	11.3	13.2	14.7	15.9
	30	14	16.8	20.2	22.8	24.8
	50	21.3	26.6	32.8	37.2	40.3

Table 13-C.—Soil loss in Mg/ha/yr for average annual precipitation of 2,400 mm. Data are for loamy soil and a moderate forest cover management.

Average annual precipitation 2,400 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	1.84	1.87	1.9	1.92	1.94
	2	2.9	2.98	3.08	3.15	3.21
	5	5.08	5.41	5.78	6.08	6.3
	10	8.15	9.02	10	10.8	11.5
	20	16.4	19	22.2	24.7	26.8
	30	23.6	28.4	34.1	38.4	41.8
	50	36	45	55.4	62.7	68.0

Table 13-D.—Soil loss in Mg/ha/yr for average annual precipitation of 1,090 mm. Data are for loamy soil and a very sparse forest cover management.

Average annual precipitation 1,090 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	1.96	2.01	2.06	2.09	2.11
	2	3.32	3.49	3.65	3.76	3.85
	5	6.5	7.2	7.92	8.44	8.88
	10	11	12.9	15	16.7	18
	20	22.7	28.8	36	41.9	47
	30	33.1	44.1	57.8	69.1	78.7
	50	50.3	71.5	98.7	121	139

Table 13-E.—Soil loss in Mg/ha/yr for average annual precipitation of 1,690 mm. Data are for loamy soil and a very sparse forest cover management.

Average annual precipitation 1,690 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	4.6	4.75	4.88	4.97	5.03
	2	8.14	8.65	9.11	9.43	9.67
	5	17.2	19.5	21.8	23.4	24.7
	10	29.5	35.9	42.6	47.7	51.9
	20	61.4	81.3	104	122	138
	30	89.2	125	167	202	231
	50	135	200	283	350	405

Table 13-F.—Soil loss in Mg/ha/yr for average annual precipitation of 2,400 mm. Data are for loamy soil and a very sparse forest cover management.

Average annual precipitation 2,400 mm						
		Slope length (meters)				
		10	25	50	75	100
Percent slope	1	7.31	7.58	7.81	7.95	8.08
	2	13.2	14.1	14.9	15.5	15.90
	5	28.5	32.8	36.9	39.7	42.0
	10	49.6	61.4	73.7	82.8	90.4
	20	103	140	181	214	242.0
	30	150	215	291	353	405.0
	50	226	344	492	610	708.0

Support Practice Factor (P)

The support practice factor is associated with adjusting the predicted erosion results by the implementation of such practices as planting on the contour, tile drainage, irrigation, buffer strips, and diversions. Because none of these were modeled, the reader is referred to the previously mentioned RUSLE2 documentation for further discussions about this factor.

Summary

The quantitative effects of the variables involved in estimating soil loss were demonstrated. Results were provided for over 450 RUSLE2 runs, capturing some of the variability in the study area. These runs represent only a very limited number of situations that may be found. The RUSLE2 database that was created, however, can be used to adjust any of the records created for the study to fit any particular location of interest. This effort can help with the initial quantification of erosion results in the study areas and help with identification of the data necessary to improve accuracy of the estimates.

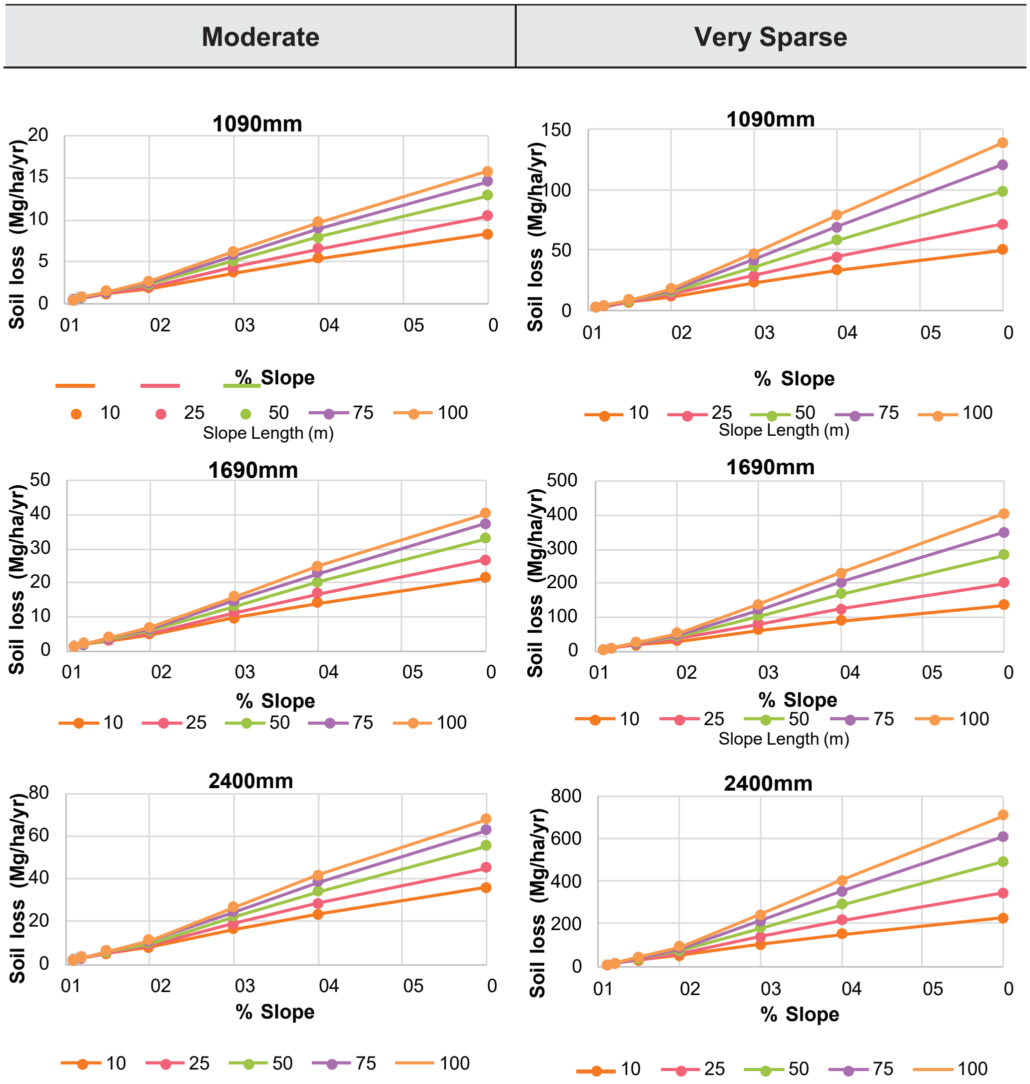

Figure 97.—Soil loss in Mg/ha/yr for a loamy soil by slope length, slope grade, and average annual precipitation (1,090 mm, 1,690 mm, and 2,400 mm). Graphs on the left show results for a moderate forest canopy cover management scenario. Graphs on the right show results for a very sparse forest canopy cover management scenario.

Soil Properties

Data relating to soil properties are collected during the survey.

Soil properties are determined by field examination of the soils and by laboratory index testing of some benchmark soils. Established standard procedures are followed. During the survey, many shallow borings are made and examined to identify and classify the soils and to delineate them on the soil maps. Samples are taken from some typical profiles and tested in the laboratory to determine particle-size distribution. A summary of the measured major soil properties that affect soil behavior for the entire survey area are shown in table 14.

Table 14.—Statistical Summary of Major Soil Properties

[Biological, physical, and chemical soil properties measured in Sierra Nevada de Santa Marta.]

Soil property	Samples	Mean	Median	Min	Max	Range	StDev	StError
Bulk density (g/cm^3)	176	1.31	1.30	0.82	1.75	0.93	0.14	0.01
Sand (%)*	389	46.19	46.74	11.18	81.71	70.53	14.84	0.75
Silt (%)*	389	33.14	32.16	6.76	71.78	65.03	12.56	0.64
Clay (%)*	389	20.67	17.81	10.29	58.71	48.43	8.36	0.42
AWC (%Vol)*	389	12.51	12.46	5.43	20.91	15.48	2.83	0.14
Soil organic carbon (%)**	389	1.08	0.69	0.07	6.65	6.58	1.03	0.05
Organic matter (%)	389	1.82	1.17	0.12	11.33	11.21	1.71	0.09
pH (Un)**	389	5.83	5.88	4.39	7.07	2.68	0.50	0.03
P (mg/kg)**	389	26.71	7.75	0.04	354	353	46.19	2.34
Ca (cmol/kg)	389	5.13	4.75	0.18	32.38	32.20	3.27	0.17
Mg (cmol/kg)	389	2.09	1.69	0.03	15.76	15.73	1.76	0.09
K (cmol/kg)**	389	0.11	0.08	0.00	1.58	1.58	0.13	0.01
Al (cmol/kg)	90	1.10	0.65	0.02	6.98	6.96	1.26	0.13
Na (cmol/kg)	299	0.12	0.09	0.02	2.75	2.73	0.17	0.01
ECEC (meq/100 g)**	389	7.68	7.15	1.05	48.94	47.89	4.44	0.23
Fe (mg/kg)	389	29.32	23.06	2.21	255	252	24.78	1.26
Mn (mg/kg)	389	28.91	19.30	0.21	156	156	27.73	1.41
Cu (mg/kg)	389	0.63	0.34	0.05	2.69	2.64	0.63	0.03
Zn (mg/kg)	389	1.47	0.79	0.04	24.91	24.86	1.97	0.10
B (mg/kg)	389	0.39	0.25	0.00	5.36	5.36	0.48	0.02
S (mg/kg)	389	17.96	15.82	2.91	92	89	9.97	0.51
Zn (mg/kg)	389	70.94	66.51	8.53	215	206	33.57	1.70
Cd (mg/kg) Soil	389	0.06	0.03	0.00	1.12	1.12	0.10	0.01

* Major physical properties.

** Major characteristics for soil fertility.

The distribution of soil property estimates is shown in figures 98–106. They include biological, physical, and chemical properties and pertinent soil and water features. The soil properties are given for the soil layers at four depths (0–20, 20–60, 60–100, and 100–200 cm).

Biological Properties

Soil organic carbon (SOC) is an important property. As the content of SOC increases, soil structure and stability, water holding capacity, and fertility all improve. Measurements of the distribution of SOC by depth show that the majority of SOC is concentrated in the upper 20 cm (fig. 98). The soils that have the highest content of SOC (between 2 and 3.5 percent) in the survey area are at the higher elevations and on summits. These high concentrations are expected in forest ecosystems. The content of SOC ranged between 1.8 and 2.2 percent on the wide plains in the northeastern part of the survey area and on most of the backslopes at lower elevations. The content of SOC for the rest of the survey area, especially at the lower elevations, ranged between 0.5 and 1.5 percent.

Across the survey area, the content of SOC decreases rapidly between depths of 20 and 60 cm. The soils that have the highest concentration at these depths are on the higher-elevation summits and have a content of about 0.5 percent. The content of SOC at depths of 60–100 cm and 100–200 cm is very low (about 0.2 percent).

Physical Properties

Available water capacity (AWC) refers to the quantity of water that the soil is capable of storing for use by plants. The capacity for water storage is given as percent of water per volume basis. The capacity varies, depending on soil properties that affect water retention. The most important properties are the content of organic matter, soil texture, bulk density, and soil structure. Available water capacity is an important factor in the choice of plants or crops to be grown and in the design and management of irrigation systems. Available water capacity is not an estimate of the quantity of water actually available to plants at any given time.

AWC distribution decreases overall with depth (fig. 99). The soils on the wide plains and the higher elevation summits have higher AWC for all depths compared to the rest of the area. AWC in these areas ranges between 10 and 16 percent. The 0–20 cm soil layer has higher AWC than the other soil depths. AWC ranges between 16 and 23 percent. The high AWC in the upper layer is especially notable on the wide plains. The AWC for the soils on the wide plains is higher at all depths than the other soils in the survey area.

With the exception of soils on the wide plains, the sand content is higher on footslopes than in other positions for all soil layers (fig. 100). The highest sand content is at the 100–200 cm depth. In contrast, silt content varies with depth throughout the survey area (fig. 101). Silt content is high, especially for soils on the wide plains, at 40 to 54 percent and remains higher with depth than in other areas. Silt content increases with depth into the second layer (20–60 cm) but only on summits and throughout the area where summits occur. Clay content decreases initially with depth at 0–20 cm and 20–60 cm but increases at 60–100 cm (fig. 102). The highest clay content for the first three layers is on summits and backslopes. The highest clay content for the deepest soil layer (100–200 cm) is on footslopes.

Chemical Soil Properties

Cation-exchange capacity is the total amount of exchangeable cations that can be held by the soil, expressed in terms of milliequivalents per 100 grams of soil at neutrality (pH 7.0) or at some other stated pH value. Soils having a low cation-exchange capacity hold fewer cations and may require more frequent applications of fertilizer than soils having a high cation-exchange capacity. The ability to retain cations reduces the hazard of ground-water pollution. However, because of low soil reaction values (pH), the effective cation exchange capacity (ECEC) is a more suitable indicator of the ability of the soil to hold cations. ECEC accounts for aluminum in the exchange sites in addition to calcium, magnesium, potassium, and sodium. The ECEC concentration is the highest for the surface layer (0–20 cm), especially for soils on the wide plains and in the mountainous southwest portion of the survey area (fig. 103). ECEC in these areas ranges from 7 to 11 meq/100 g soil. Also, the concentration of ECEC (3 to 5 meq/100 g soil) in the deeper soil horizons in these two areas is higher than in other parts of the survey area. The distribution of higher concentrations in the survey area changes with soil depth, especially in the hilly and mountainous areas. The ECEC concentrations are higher on footslopes and toeslopes (4 to 6 meq/100 g soil) than on summits, shoulder slopes, and backslopes (3 to 4 meq/100 g soil).

The concentration of *soil potassium* is higher in the surface layer than in the subsurface layer (fig. 104). However, the concentration of potassium in the surface layer is also more variable than in the deeper soil layers, varying from 0.03 to 0.8 cmol/kg soil. In the surface layer, the highest concentration of potassium is on summits, shoulders, and backslopes, particularity at higher elevations. The wide plains, footslopes, and toeslopes have the lowest concentrations. Similar distribution patterns are also observed for the deeper layers.

Cadmium in soils can originate from weathering of parent materials and can bioaccumulate from plants. Large amounts of cadmium (above a certain threshold) can lead to increased concentrations in plant biomass and fruits. The highest cadmium concentration and variation (0.05 to 0.33 mg/kg soil) are in the surface layer (0–20 cm). Cadmium concentrations in the subsurface layers are below 0.05 mg/kg soil. The wide plains and higher elevation areas have higher concentrations of cadmium throughout the area and for all soil depths. This suggests bioaccumulation and perhaps sedimentation origins of cadmium in the surface for the wide plains, which are over sedimentary rocks, and parent material origin of cadmium on summits, shoulders, and backslopes at the higher elevations, which are over metamorphic rocks.

Soil phosphorus (P) increases with depth, especially in the 100–200 cm layer in the mountainous and hilly areas that are most likely associated with metamorphic rocks (fig. 105). The wide plains have higher concentrations of phosphorus in the first three layers, ranging from 40 to 120 mg/kg soil, but not in the deepest layer, which ranges between 20 and 40 mg/kg soil. The highest concentrations of phosphorus, especially at the 20–60 cm depth, are likely associated with erosional deposits. Although higher concentrations of phosphorous would be expected in the depositional areas, lower concentrations are actually encountered because of plant uptake and, in some places, fertilizer application.

Soil reaction is a measure of acidity or alkalinity. The pH of each soil horizon is based on many field tests. For many soils, values have been verified by laboratory analyses. Soil reaction is important in selecting crops and other plants, in evaluating soil amendments for fertility and stabilization, and in determining the risk of corrosion. Soil pH decreases with soil depth, especially for the first three layers (0–20; 20–60; and 60–100 cm) (fig. 106). For the surface layer (0–20 cm), the highest soil pH values are on the wide plains and range from 5.8 to 6.2. The pH decreases in the 30–60 cm layer, ranging between 5.3 and 5.5 on the mountainous and hilly landscapes and between 5.5 and 5.8 on the wide plains. The highest variability of soil pH by soil depths is in the 60–100 cm layer. The wide plains have the highest values, ranging from 6 to 6.7, and the mountainous and hilly areas have the lowest values, ranging from 5.2 to 5.6.

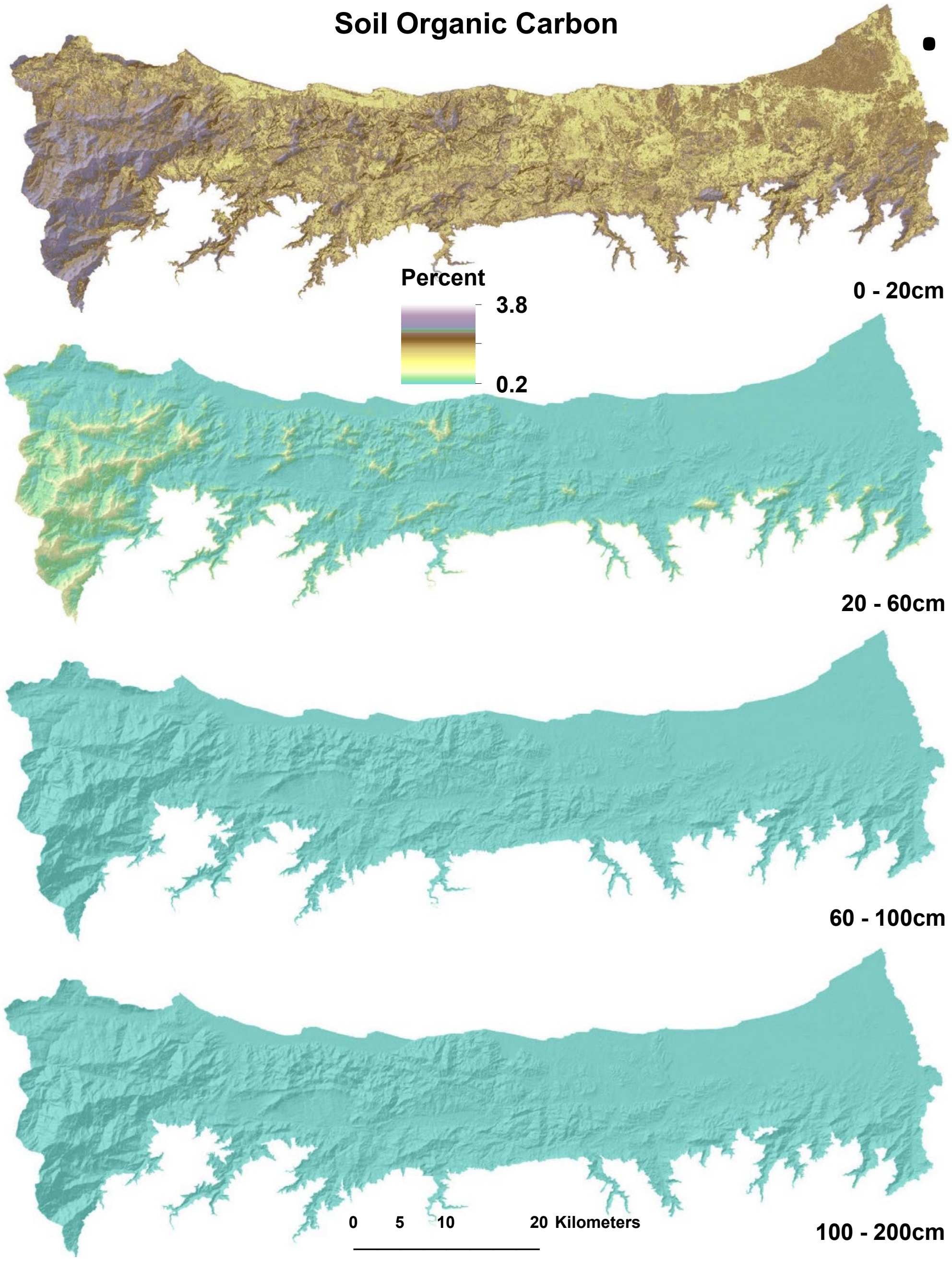

Figure 98.—Soil organic carbon distribution of Sierra Nevada de Santa Marta for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

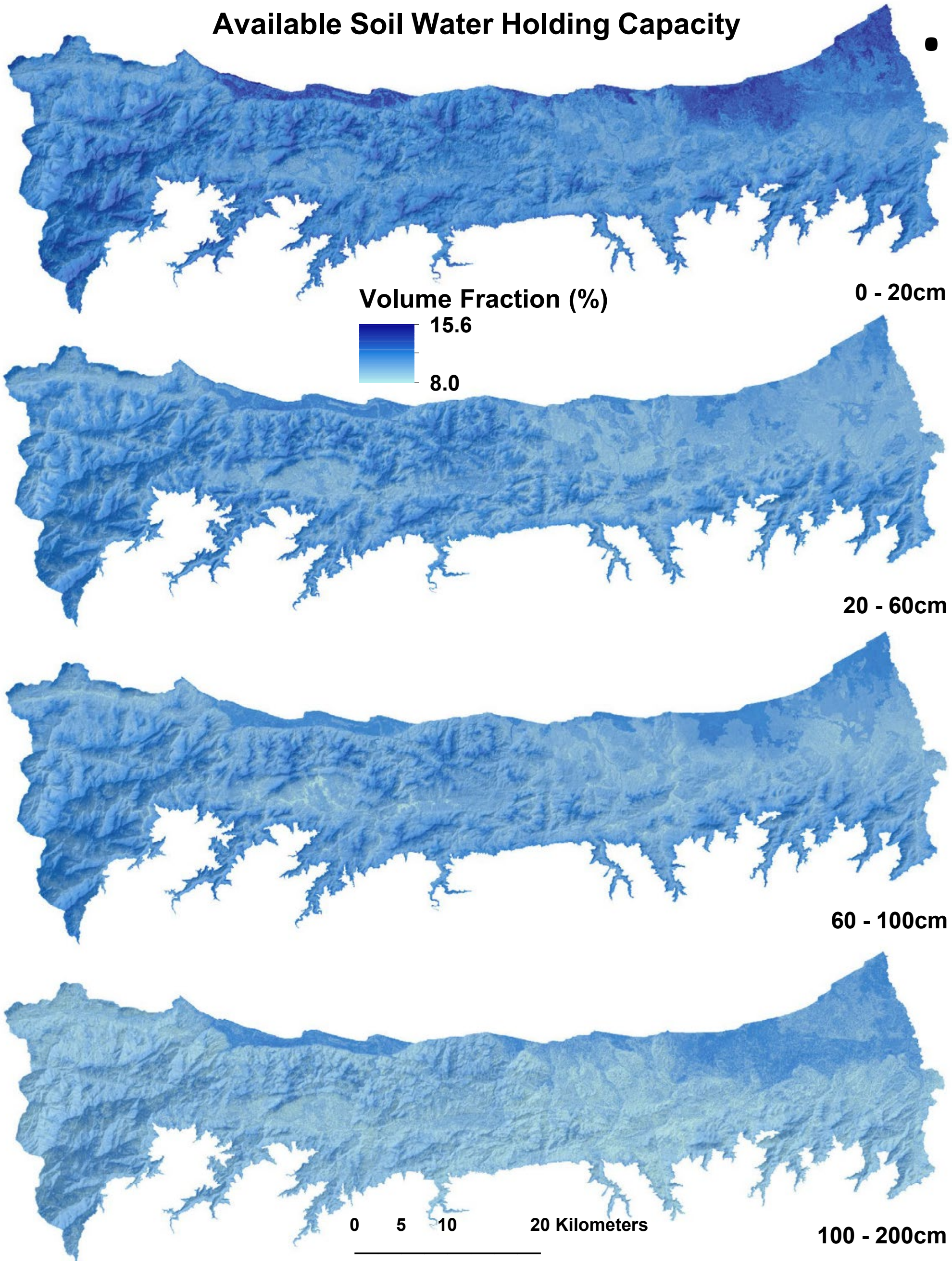

Figure 99.—Available water holding capacity (AWC) distribution for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

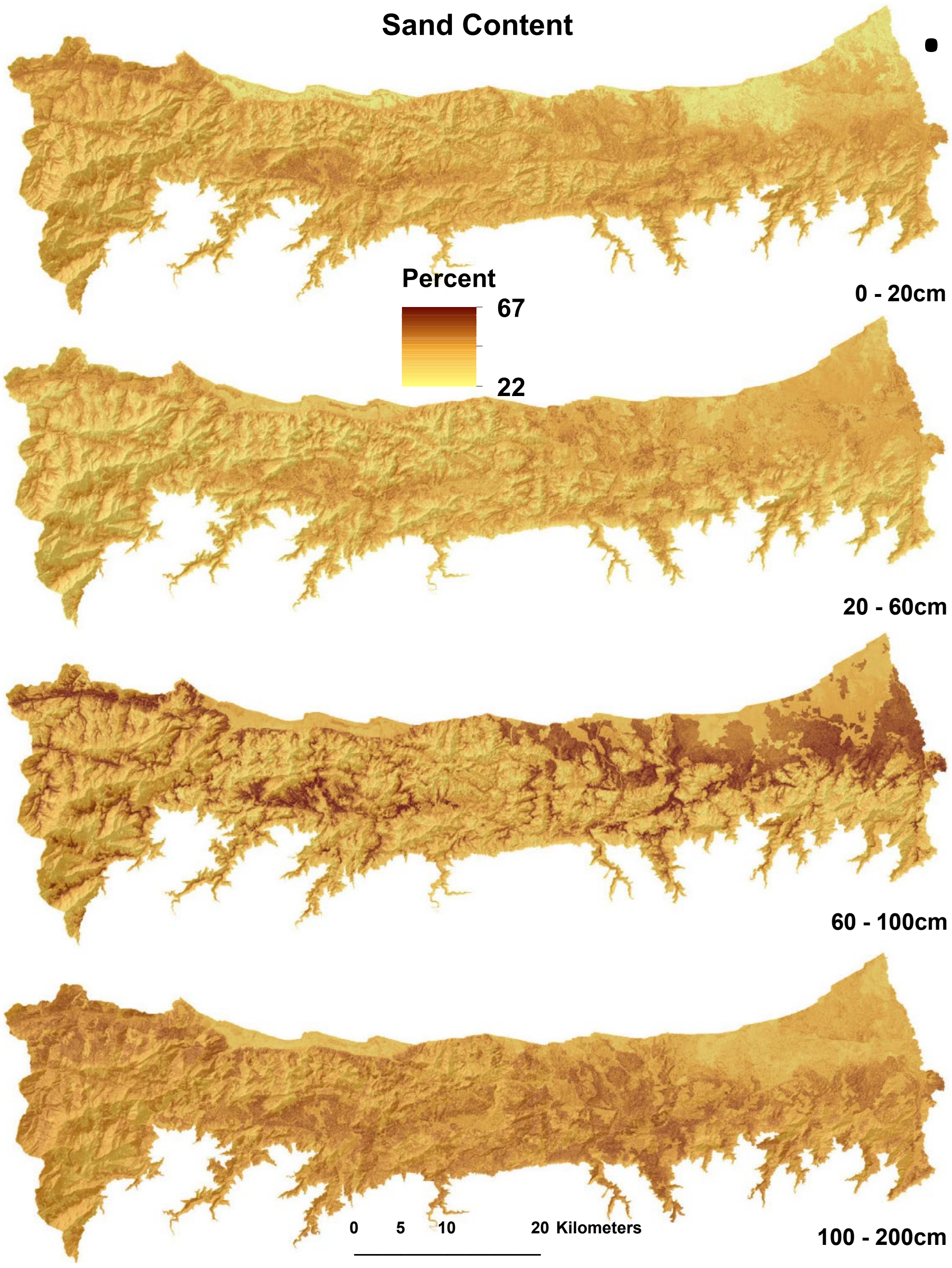

Figure 100.—Sand content distribution for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

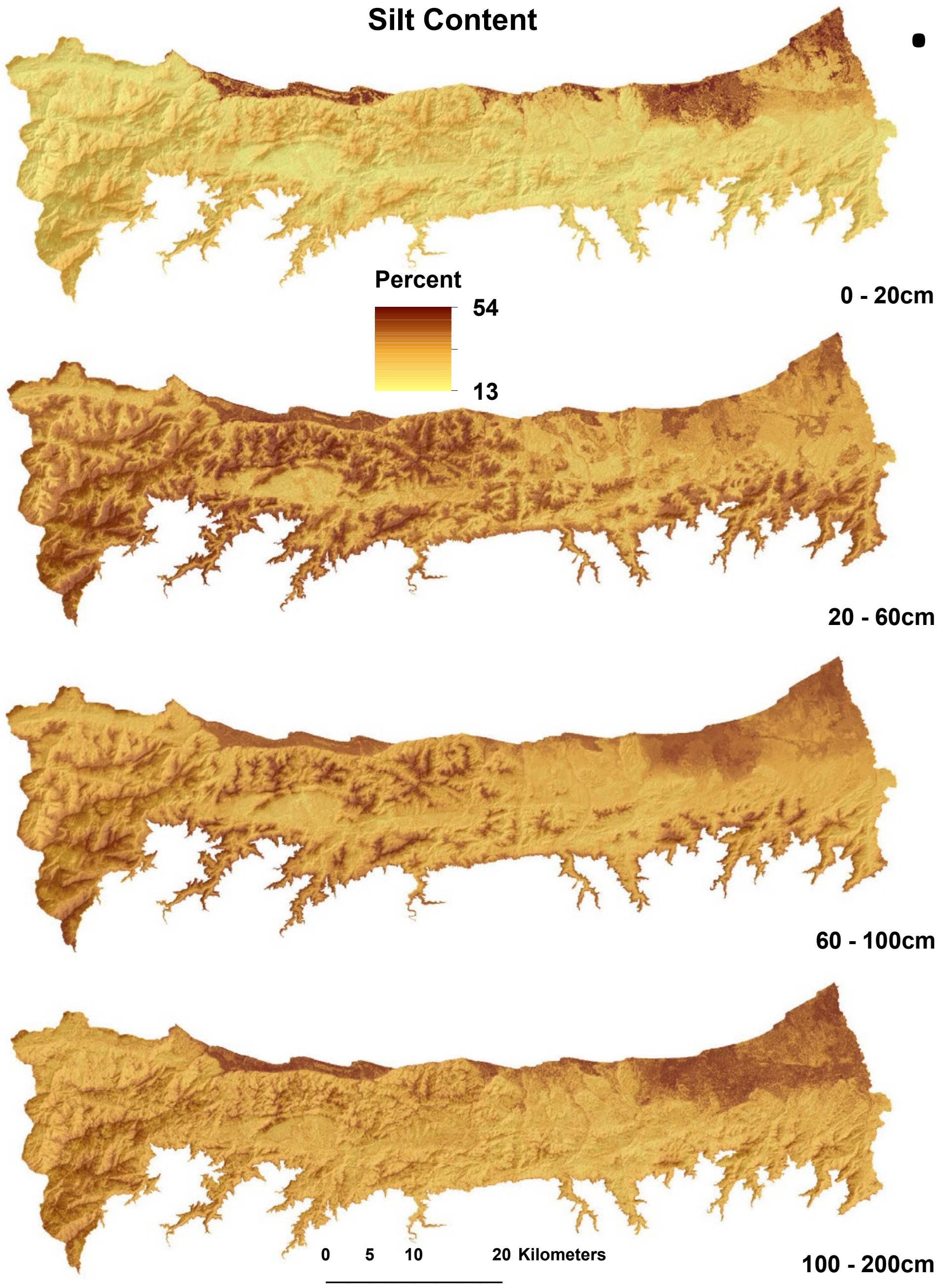

Figure 101.—Silt content distribution for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

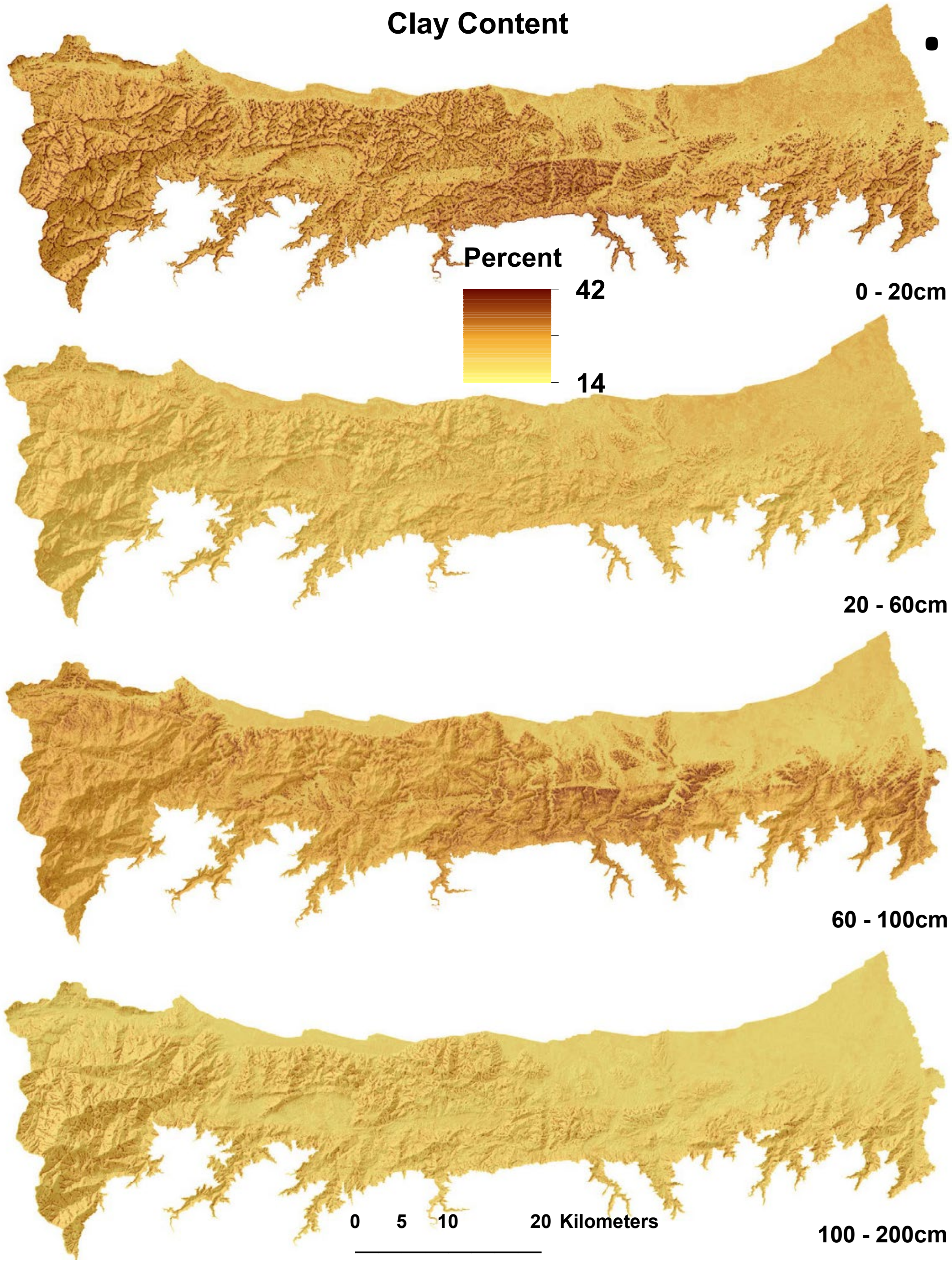

Figure 102.—Clay content distribution for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

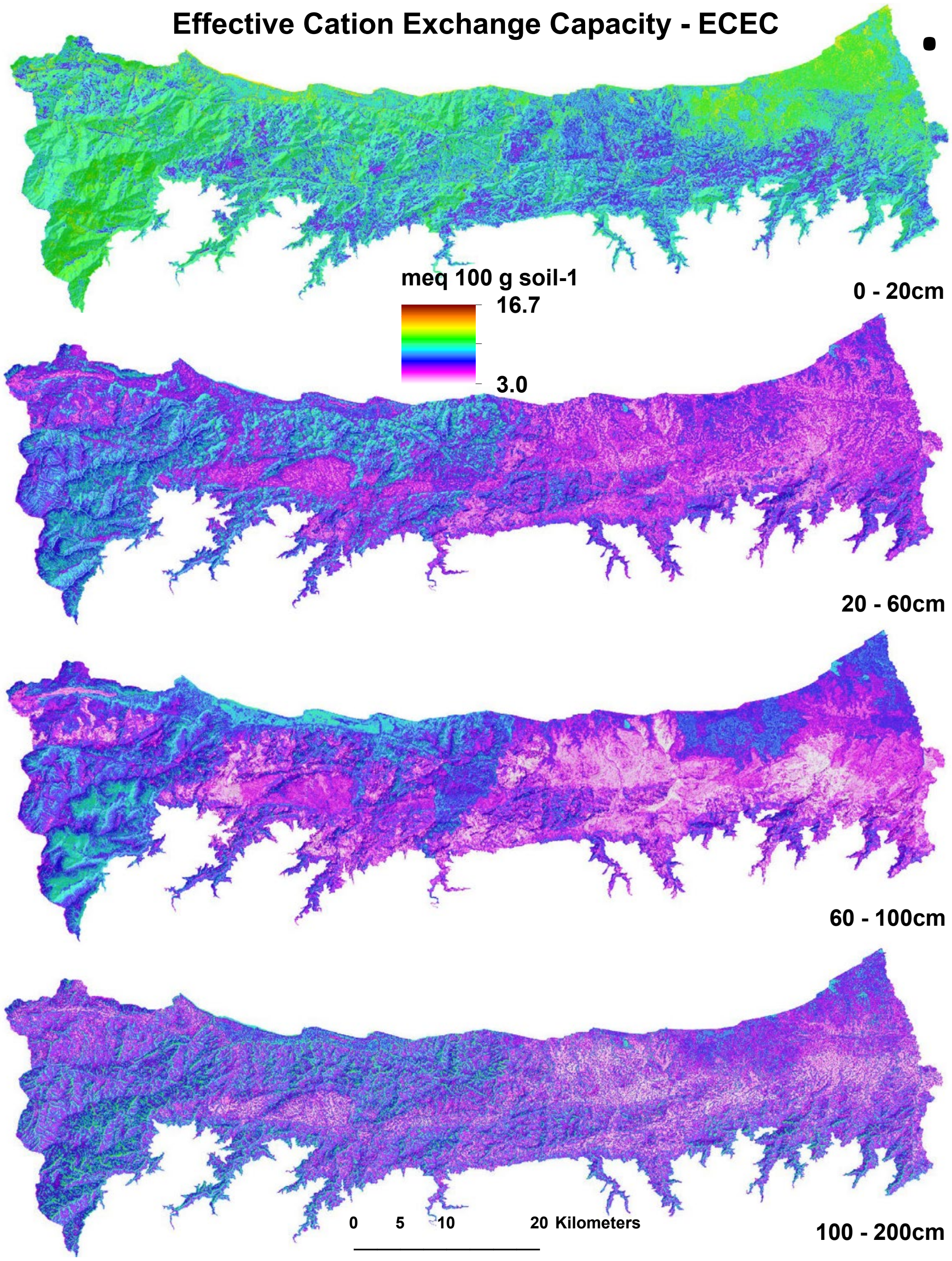

Figure 103.—Effective Cation Exchange Capacity (ECEC) distribution for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

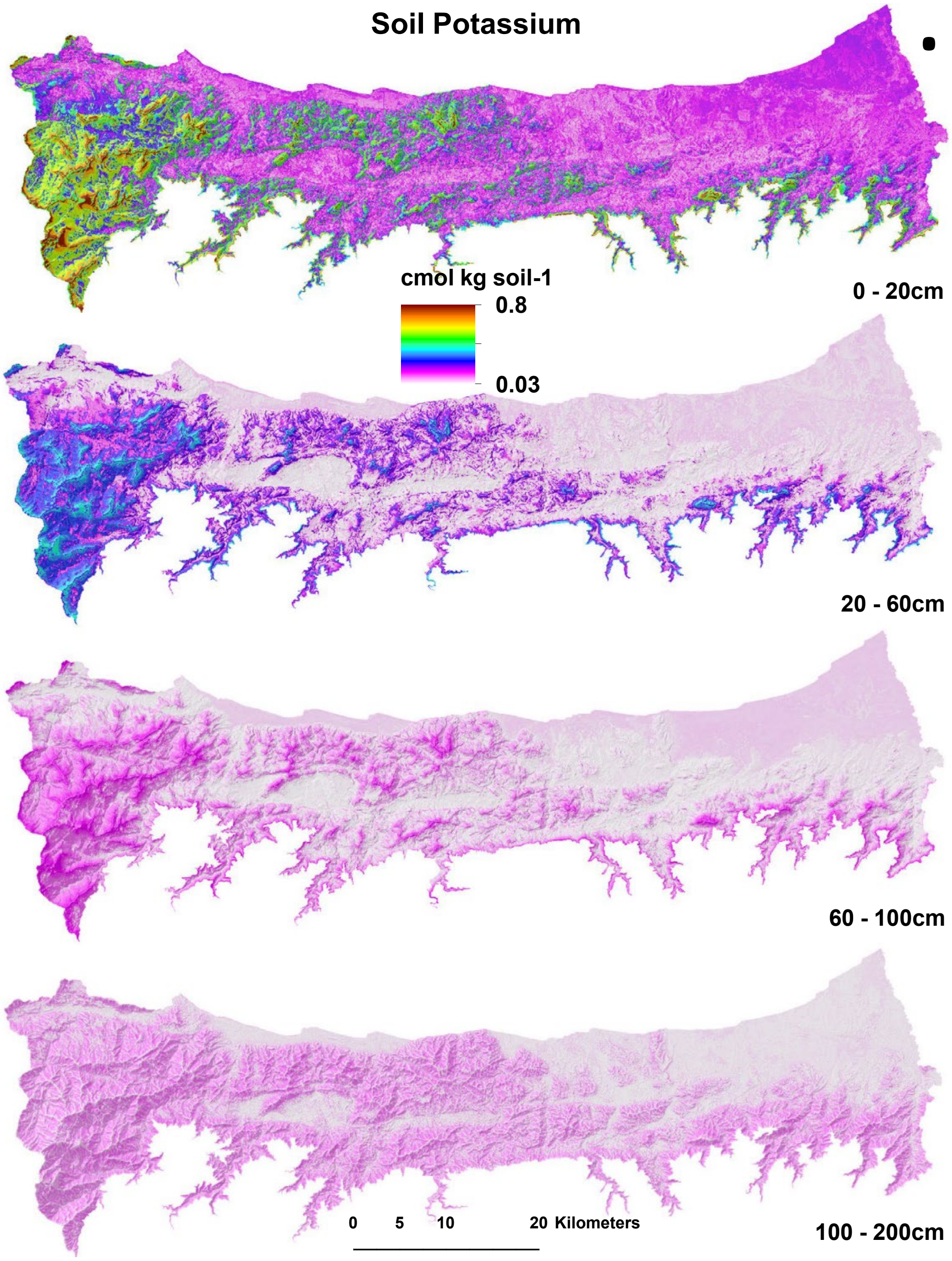

Figure 104.—Potassium (K) content distribution for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

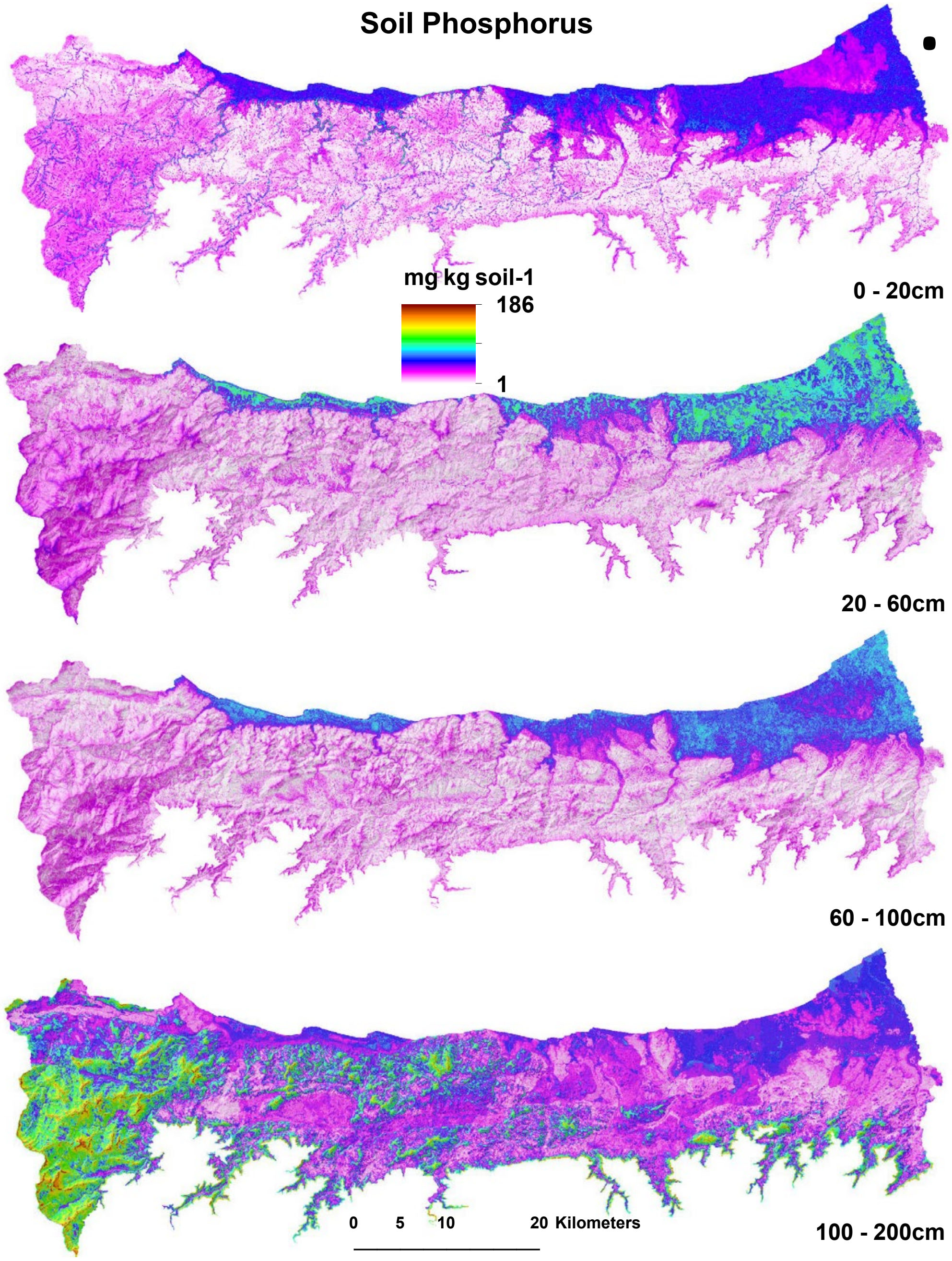

Figure 105.—Phosphorous (P) content distribution for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

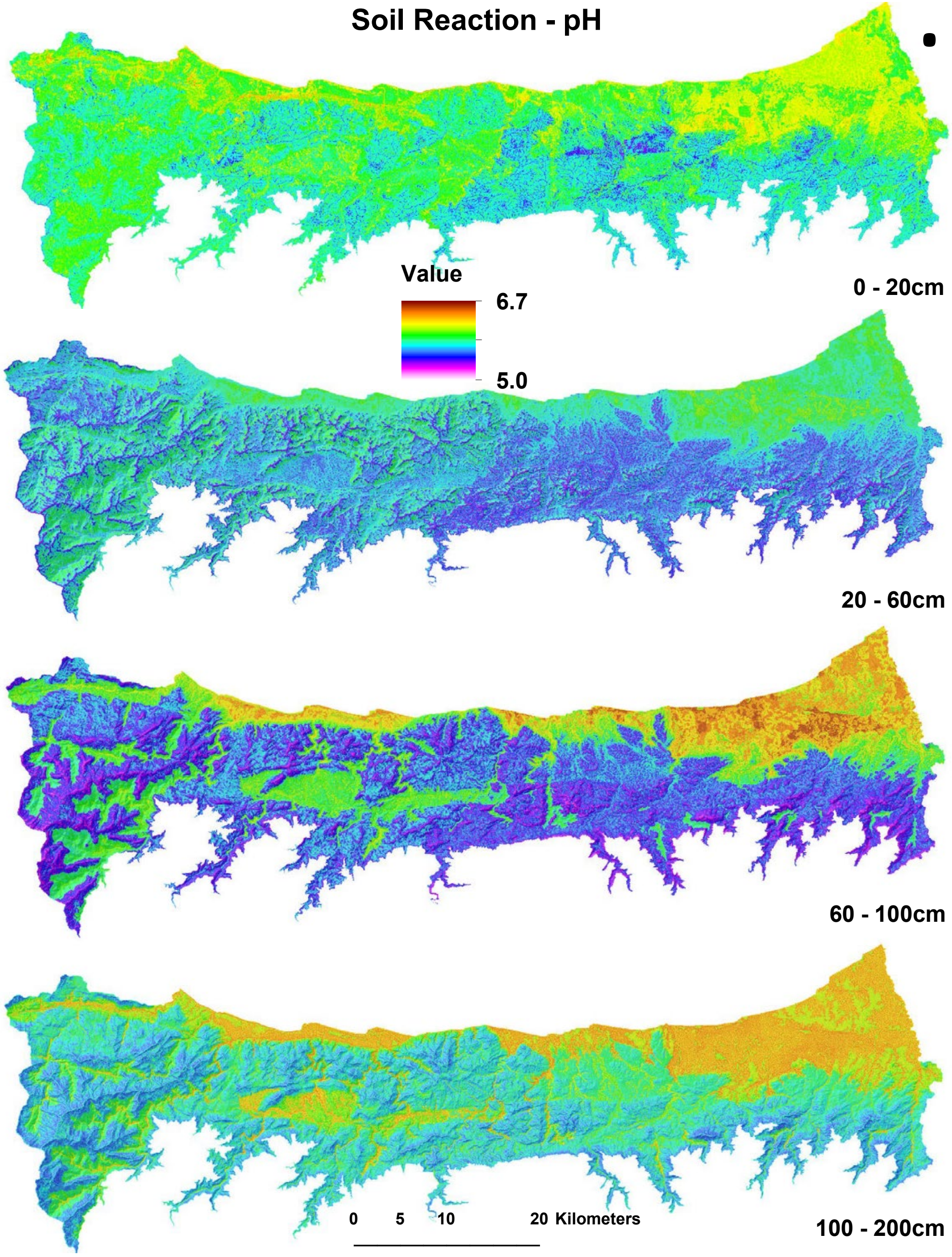

Figure 106.—Soil reaction (pH) distribution for soil layers at depths of 0–20, 20–60, 60–100, and 100–200 cm.

Formation and Classification of the Soils

Factors of Soil Formation

Soil covers the surface of the Earth as a three-dimensional body of varying depth and is made up of different proportions of organic and mineral material, pore space containing gases, and water. Soils differ in their appearance, productivity, and management requirements due to their chemical and physical properties. The characteristics and properties of soils are determined by physical and chemical processes that result from the interaction of five soil-forming factors.

These factors of soil formation are interdependent, and few generalizations can be made regarding any one factor unless the effects of the other factors are known. The term “pedogenesis” is often used to connote the process of soil formation.

The soil-forming factors are parent material, climate, organisms, time, and relief or topography. Parent material is the source material in which soils formed. Soils are influenced by the texture and structure of the parent material and its mineralogical and chemical composition. Climate is predominantly the temperature and the kind and amount of precipitation. Organisms are the plants and other organisms living in and on the soil, including humans. Time refers to how long the soil-forming factors have been operating. Relief or topography is the shape and elevation of the landscape. It affects internal and external soil properties, such as soil drainage, aeration, susceptibility to erosion, and the soil’s exposure to the sun and wind (Jenny, 1941).

The process of soil formation is a sequence of events involving biogeochemical reactions that are energized by climate and spatially related to relief or topography (Buol et al., 2003). The physical and chemical properties of soils are altered by these reactions over time. The influence of any one of these factors varies within the survey area. Soils may differ significantly from place to place in the survey area and within very short distances. In other places, the survey area may have vast stretches of the same type of soil because of uniform soil-forming factors.

Parent Material

The material in which soils form is called parent material. Few soils weather directly from the underlying rocks. More commonly, soils form in materials that have moved from elsewhere.

Soils generally have a dominant kind of parent material but are influenced by other types of parent material. Material that has been moved only a few meters by gravity is known as colluvial parent material. Such material is extensive on the gently sloping to moderately steep foothills and alluvial fans in map units 102, 202, and 203. Material that has been moved long distances by wind is known as eolian parent material. Material that has been moved by water is known as alluvial parent material. Such material is in some areas of the nearly level map unit 304 on alluvial plains.

The Sierra Nevada de Santa Marta is a broad area that has been influenced by tectonic forces and filling by volcanic materials. New source materials for soil formation were created as rivers meandered across the landscape, cutting into and eroding various geologic formations. The rivers then deposited the new unconsolidated sediments. The new sediments vary in chemistry and size, depending on their source. The size of the sediments is also dependent on the amount of energy in the water that carried them. The source of most of the materials deposited by rivers is the uplifting mountain ranges in the south. Several episodes of uplifting and subsequent erosion resulted in various depositions of weathered igneous and metamorphic parent materials throughout the area, in particular in the narrow plains and valleys and to a lesser extent on the wide plains.

Climate

Differences in climate can result in differences in soils. Temperature and moisture influence soil formation. Weathering is most active when soils are moist and warm, which are conditions conducive to rapid chemical reactions. Cooler temperatures result in slower chemical reactions. During periods of rainfall, water carries dissolved or suspended solids through the soil in a process called leaching. Variations in temperature and moisture cause varying patterns of weathering and leaching in the soil. Seasonal and daily changes in temperature affect moisture effectiveness, biological activity, rates of chemical reactions, and kinds of vegetation.

The climate of Santa Marta de Sierra Nevada is predominately udic. The average precipitation is 1,722 mm. The average annual temperature is 23.7 °C. Fluctuations in temperature and moisture affect the rates of decomposition and accumulation of organic matter and the rates of mineral weathering. Cycling of bases, therefore, is pronounced in areas that have warm climate and large amounts of vegetation. In Santa Marta de Sierra Nevada, the combination of rainfall patterns and relatively high temperatures throughout the year, the vigorous plant growth, and the accelerated chemical and biological processes of soil formation lead to accumulation of organic matter and soil development. However, due to a combination of large rainfall events and high erosion rates on exposed surfaces of the surrounding mountains, deposits often interrupt the soil development.

Organisms

Plants, animals, microorganisms, and humans affect the formation and shape of soils. Flora, such as fungi and bacteria, can help to decompose organic matter and add nutrients to the soil. Animals and microorganisms mix soils and form burrows and pores. Plant roots open channels in the soils. Abandoned tunnels fill with loose material from the overlying horizons and transmit water more readily than the surrounding undisturbed soil material.

Different types of roots have different effects on soils. Grass roots are fibrous near the surface and easily decompose, adding organic matter to the soil. Fine grass roots can extend below the surface for many feet. Plant roots also help to develop soil structure and improve aggregate stability. Vegetation increases soil stability by protecting the surface against erosion. Taproots open pathways through dense layers. Microorganisms affect chemical exchanges between roots and soil.

The native vegetation depends on climate, topography, and biological factors plus many soil factors, such as density, depth, chemistry, temperature, and moisture. Leaves from plants fall to the surface and decompose on the soil. Organisms decompose these leaves and mix them with the upper part of the soil, thereby cycling nutrients and energy back to vegetation.

Trees and shrubs have large roots that may grow to considerable depths and aid in the fracturing of underlying rocks.

Root growth and humification of organic matter deep within soils can darken soils to a considerable depth. Humification occurs when leaves, wood, roots, and animals are decomposed by microorganisms and converted to humic substances. Humic substances are broadly defined as products of organic matter decomposition that are relatively resistant to further microbial decomposition. Humic substances that contain high amounts of carbon can persist in the soil for a long time—on the order of hundreds to thousands of years. Some examples of humic substances are humic acids, fulvic acids, and humins. Humification is common on prairies where there is prolific root growth of native grasses.

Time

Soil formation processes are continuous. Over time, soils exhibit features that reflect the other soil-forming factors. Recently deposited material, such as material deposited by a flood, exhibits no features from soil development activities. The previous soil surface and underlying horizons become buried.

The different horizons in a soil profile and the degree of development can be directly related to time. Terraces above the active flood plain, while similar to the flood plain, are older land surfaces and thus the soils on the terraces exhibit more horizon development.

For example, summits are more stable landscapes than side slopes and alluvial plains. Map units on summits, such as map units 102 and 205, have therefore had more time to develop a strongly expressed soil horizon (Bt) than sites on side slopes and alluvium plains, which have only weakly developed horizons (Bw).

Topography and Relief

Topography refers to the shape of the landscape, and relief refers to differences in elevation. Overall, the landscapes in Sierra Nevada de Santa Marta, including ravines, alluvial fans, colluvium, erosional surfaces, and deposits, are the result of erosional and depositional processes. These processes may have occurred in response to changes in climate and tectonic activities. Cyclic periods of landscape stability and instability influence the types of soils that form. Overall slope and aspect of the landscape can affect the moisture and temperature of the soil. Slopes that face the sun are warmer. The surface horizon of steep soils on back slopes, such as map units 203 and 205, is thinner than that of the more nearly level soils, such as map unit 102, which are on summits. Also, more bedrock from the underlying geologic formations is exposed on the steep, dry slopes.

Soil forming factors continue to affect soils even on stable landscapes. Materials can be deposited or removed from the surface by wind and water. Additions, removals, and alterations are slow or rapid, depending on climate, landscape position, and biological activity. In Sierra Nevada de Santa Marta, alterations by climate and biological activity are rapid. Generally, the youngest geomorphic surfaces are alluvial fans, flood plains, and basin floors associated with the major rivers and streams and areas where alluvium has been deposited.

Classification of the Soils

Soils are named and classified on the basis of physical and chemical properties in their horizons (layers). Color, texture, structure, and other properties of the soil to a depth of 2 meters are used to key the soil into a classification system. This system helps people to use soil information and also provides a common language for scientists.

Soils and their horizons differ from one another, depending on how and when they formed. Soil scientists use the five soil-forming factors to help predict where different soils may form. The degree and expression of the soil horizons reflect the extent of interaction of the soil-forming factors with one or more of the soil-forming processes (Simonson, 1959). When mapping soils, a soil scientist looks for areas with similar soil-forming factors to find similar soils. The properties of the soils are described. Soils with the same kind of properties are given taxonomic names. Soils are classified, mapped, and interpreted on the basis of various kinds of soil horizons and their arrangement. The distribution of soil orders corresponds with the general patterns of the soil-forming factors within the survey area.

The system of soil classification used by the National Cooperative Soil Survey has six categories (Soil Survey Staff, 1999 and 2010). Beginning with the broadest, these categories are the order, suborder, great group, subgroup, family, and series. Classification is based on soil properties observed in the field or inferred from those observations or from laboratory measurements. The categories are defined in the following paragraphs.

ORDER. Soil taxonomy at the highest hierarchical level identifies 12 soil orders. The names for the orders and taxonomic soil properties relate to Greek, Latin, or other root words that reveal something about the soil. The differences among orders reflect the dominant soil-forming processes and the degree of soil formation. Each order is identified by a word ending in sol. An example is Inceptisol.

SUBORDER. Each order is divided into suborders primarily on the basis of properties that influence soil genesis and are important to plant growth or properties that reflect the most important variables within the orders. Sixty-four suborders are recognized at the next level of classification. The last syllable in the name of a suborder indicates the order. An example is Ustept (Ust, meaning dry climate, plus ept, from Inceptisol).

GREAT GROUP. Each suborder is divided into great groups on the basis of close similarities in kind, arrangement, and degree of development of pedogenic horizons; soil moisture and temperature regimes; type of saturation; and base status. There are about 300 great groups. Each great group is identified by the name of a suborder and by a prefix that indicates a property of the soil. An example is Haplustept (Hapl, meaning minimal horizonation, plus ustept, the suborder of the Inceptisols that has an ustic moisture regime).

SUBGROUP. There are more than 2,400 subgroups. Each great group has a typic subgroup. The typic subgroup is the central concept of the great group; it is not necessarily the most extensive. Other subgroups are intergrades or extragrades. Intergrades are transitions to other orders, suborders, or great groups. Extragrades have some properties that are not representative of the great group but do not indicate transitions to any other taxonomic class. Each subgroup is identified by one or more adjectives preceding the name of the great group. The adjective Oxic identifies the subgroup that has an almost complete absence of weatherable primary materials. An example is Oxic Haplustepts.

FAMILY. Families are established within a subgroup on the basis of physical and chemical properties and other characteristics that affect management. Generally, the properties for family placement are those of horizons below a traditional agronomic plow depth. Among the properties and characteristics considered are particle-size class, mineralogy class, cation-exchange activity class, soil temperature regime, soil depth, and reaction class. A family name consists of the name of a subgroup preceded by terms that indicate soil properties. An example is fine-loamy, mixed, subactive, isothermic Oxic Haplustepts.

SERIES. The soil series is the lowest category in the soil classification system.

The series consists of soils within a family that have horizons similar in color, texture, structure, reaction, consistence, mineral and chemical composition, and arrangement in the profile. An example is the Santa Marta 6 series. The names of soil series are selected by the soil scientists during the course of mapping. The series names are commonly geographic place names or are coined. They could also be named after a major geographic region and numbered, for example, Santa Marta 3 and Santa Marta 6.

Table 15.—Taxonomic Classification of Soil Profiles for Major Soil Map Units According to the U.S. Soil Taxonomy (Soil Survey Staff, 2010).

SMU symbol	Soil profile	Taxonomic classification
101	Santa Marta 06	Fine-loamy, mixed, subactive, isothermic Oxic Haplustepts
102	Santa Marta 04	Fine-loamy, mixed, subactive, isothermic Oxic Haplustepts
102	Santa Marta 07	Fine-loamy, mixed, subactive, isothermic Oxic Haplustepts
102	Santa Marta 09	Fine-loamy, mixed, subactive, isothermic Oxic Haplustepts
102	Santa Marta 08*	Fine-loamy, isothermic Oxic/Udic Haplustepts
202	Santa Marta 10*	Fine-loamy, isothermic Oxic/Udic Haplustepts
202	Santa Marta 13	Coarse loamy, mixed, superactive, isothermic Oxic Haplustepts
203	Santa Marta 12	Fine-loamy, mixed, subactive, isothermic Oxic Haplustepts
304	Santa Marta 03	Fine, mixed, subactive, isohyperthermic Oxic Haplustepts
304	Santa Marta 05	Loamy-skeletal, mixed, semiactive, isohyperthermic Oxic Haplustepts
103	Santa Marta 01	Coarse-loamy, subactive, isothermic Oxyaquic Haplustepts
205	Santa Marta 02	Fine, mixed, subactive, isohyperthermic Oxic Haplustepts

* Based on auger hole descriptions.

In the survey area, all of the soil profiles that were characterized are classified as Inceptisols (fig. 107). According to soil taxonomic classification, Inceptisols typically have a warm season during which water is available to plants for more than half the year or for more than 3 consecutive months. These soils develop more pedogenic

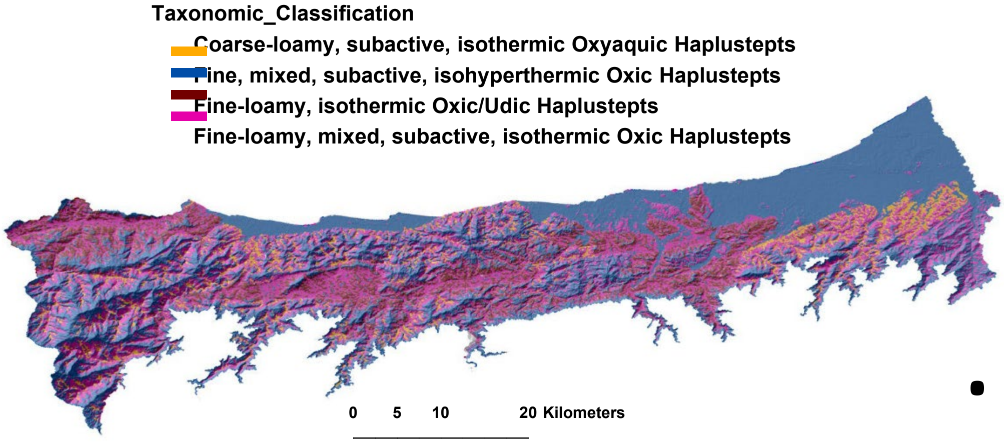

Figure 107.—Taxonomic classification of the soils in Sierra Nevada de Santa Marta.

horizons of alteration or concentration with little accumulation of translocated materials other than carbonates or amorphous silica. The major soil temperature regime is isothermic, which means that the average annual soil temperature is between 15 and 22 °C. The soil moisture regime is ustic, which is typical for tropical and subtropical regions that have a monsoon climate and either one or two dry seasons, usually in the winter and fall.

Cacao Plant Genomic Survey

Figure 108.—*Theobroma* cacao flower. Photo Credit: Mark Guiltinan

Sample Collection

For each tree, a GPS coordinate was recorded and a plastic markers showing a CfP Genetics ID was attached. Samples were permitted by the government of Colombian under the regulations for access to genetic resources and derived products as established by the Ministry of Environment and Sustainable Development of Colombia. Plant phenotype was observed, and photographs were taken of fruit where present. For the phenotypic observations, help was provided by an official cacao crop expert from the National Federation of Cocoa Growers (Federación Nacional de Cacaoteros; FEDECACAO). Mature fruit was imaged where possible, but in some cases only immature fruit was present. Links to photos are provided in the Arc GIS resource as well as in the CfP master database. Leaf samples were placed in plastic bags with desiccant and shipped to the International Center for Tropical Agriculture (Centro Internacional de Agricultura Tropical; CIAT) for DNA extraction and analysis. See the Appendix for detailed protocols. All plant material and DNA extractions are currently stored in the Molecular Genetics and Tissue Culture Laboratory, Crops for Nutrition and Health Research Area, CIAT, Cali, Colombia. The present study included 183 samples from SNSM and DNA from 4 known cacao accessions as controls.

Samples were collected from trees on participant farms. Figure 109 shows the location of each tree as displayed on the GIS resource. The GIS resource can be used to explore all of the information for each of the sampled trees, including GPS coordinates, observations on tree stature, health pod colors, and for most samples, images of pods.

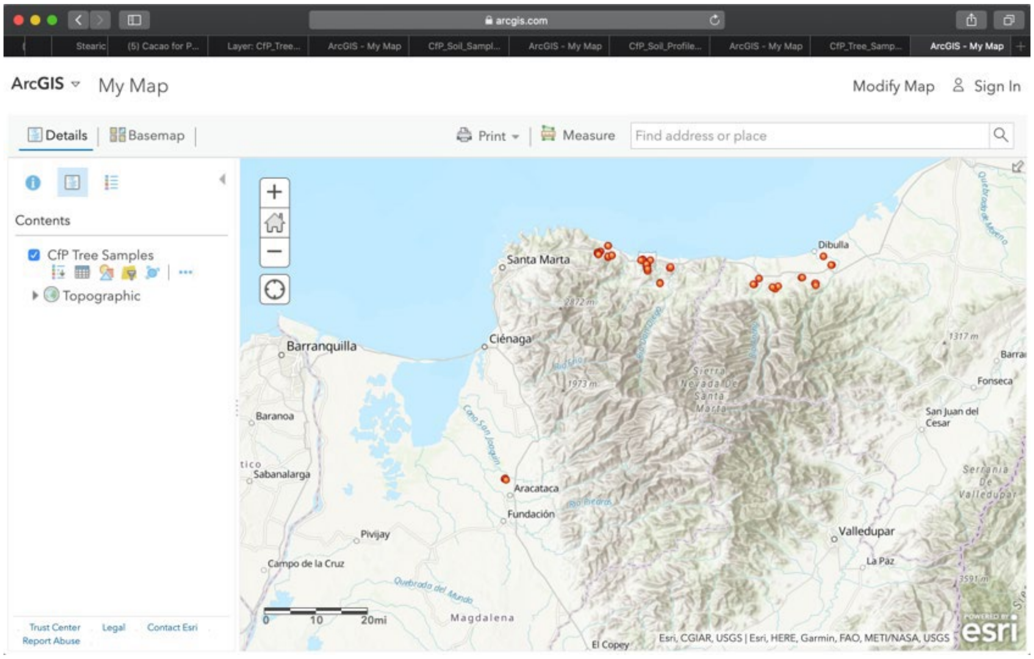

Figure 109.—Location of sampling sites for plant genetic material collection and analysis. For each sample, geographic positions are indicated on the map to single-tree resolution. Each sample position can be selected to access all associated data, including location, SNP genotyping data, photographs, chemical analysis, and general observations.

SNP Genotyping

Single nucleotide polymorphisms (SNP) genotyping was performed with a set of 96 informative DNA markers. Of these, 92 passed the quality control benchmarks. All data are stored in the CfP master data file.

Genetic Diversity Analysis

The population genetic structure of this collection was explored by examining 92 biallelic SNP markers across all samples and 4 reference genotypes. By comparing this data to reference data from USDA–ARS, population genetics methods were used to infer the genetic ancestry of the samples as previously described (Fister et al., 2020).

Total Genetic Diversity

The same data were used to calculate the overall total genetic diversity of the entire collection (fig. 110).

The results indicate that 75% of the genetic diversity originated from just three genetic groups: Amelonado, Iquitos, and Criollo. Two additional groups represent about 8% of the total genetic diversity each (Contamana and Parinari). The remaining 5 genetic groups do not account for more than 5% of the total genetic diversity in the CfP sample set. In summary, although complex hybrids of many types were identified, the genetic background represented in this collection is quite narrow and limited to three main groups. Further sampling is necessary to determine if this trend is found in other cacao growing zones of Colombia.

Hybrids and Complex Hybrids

The STRUCTURE algorithm was used to estimate the genetic makeup of each individual in this population. The result is the structure plot shown in Figure 111. Each

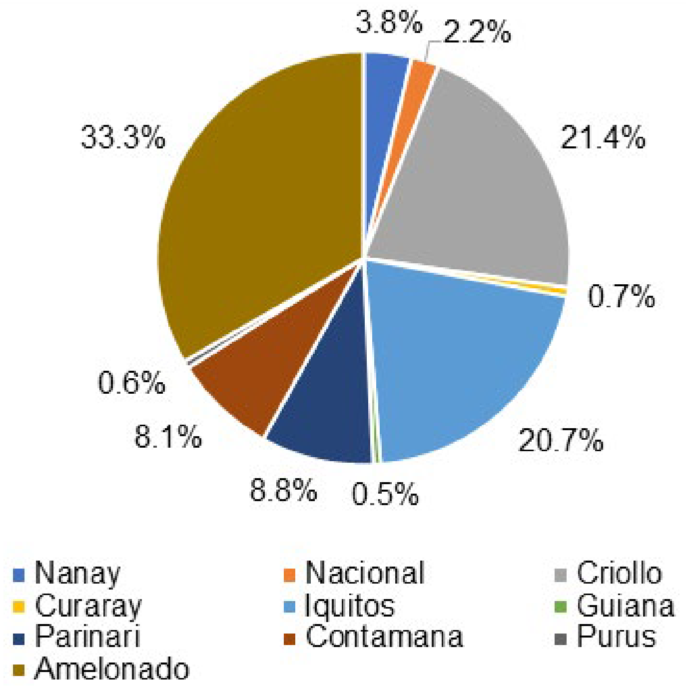

Figure 110.—Total Genetic Diversity Estimates: Color codes start with Nanay at top (3.8%) and continue clockwise in the order: Nacional, Criollo, Curaray, Iquitos, Guiana, Parinari, Contamana, Puris, and Amelonado (33.3%).

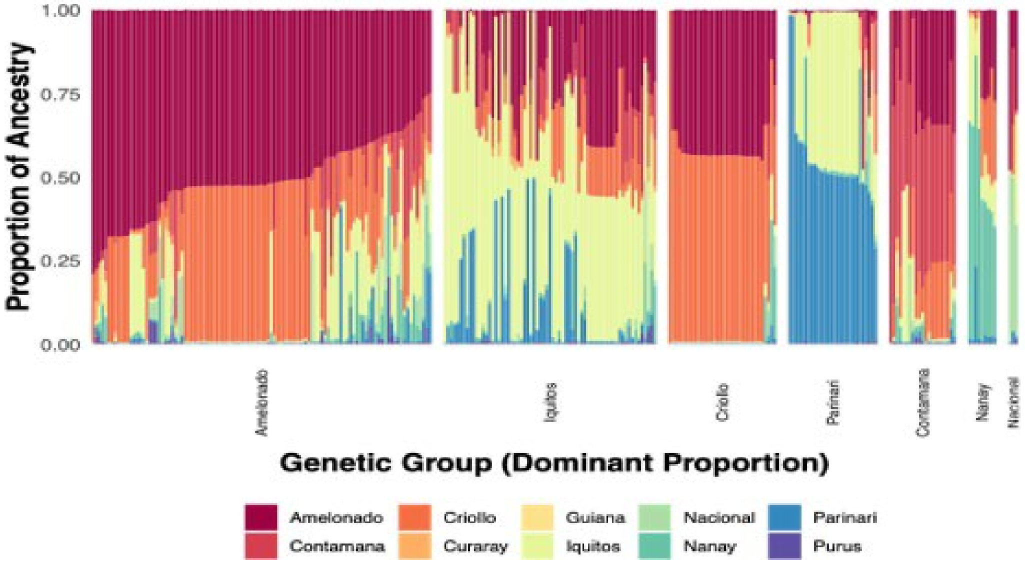

Figure 111.—Genetic diversity analysis STRUCTURE plot.

column in this image represents a single tree. The colors of the stacked bars represent the percent of ancestry in the major cacao genetic groups.

This analysis demonstrates that all the trees in the SNSM collection are hybrids, containing significant genetic information from more than one genetic group. Several general classes of hybrids are observed. Class 1 is Amelonado x Criollo. Class 2 is Amelonado x Iquitos. Class 3 is Paranari x Iquitos. These classes are consistent with information known about the introduction of cacao varieties in Colombia, which has been occurring for at least 100 years. IMC67 from the Iquitos group was a key progenitor because it has resistance to *Ceratocystis* sp., which was a major production constraint in Colombia in 1960s. In PA group, PA46 was a key progenitor for the same breeding objective.

Class 1 hybrids are likely all descendants of Trinitario type clones moved from Trinidad. The cacao variety ICS1 is a member of this class 1 hybrid group. ICS1 is a clone identified in a large screen of hybrid Trinitario cacao growing in Trindad in the 1930s. It has been used, along with other closely related clones, in many cacao planting development projects globally. Class 2 hybrids are likely hybrid descendants of IMC67 and related international clones in the Iquitos group. Similarly, class 3 hybrids likely result from hybrids made with descendants of the PA group, such as PA46.

Correlation Between Leaves, Litter, and Soil Cadmium Concentrations

Data collected as part of the joint soil and plants teams were used to test if the concentration of cadmium in soil, leaves, and leaf litter samples were correlated and to what extent these factors interact. Cadmium concentrations were compared in soil samples and in leaves and litter of nearby, paired CfP sampled trees.

Post_hoc_Cd_types_comparison_NO_LOQ: A mean comparison (ANOVA) and a post hoc (Tukey) test were performed between cadmium in soils-H01 (soil surface layer), leaves, and litter. The analysis was conducted for the sites where cadmium values were above the detection limit in the laboratory. The limit of quantification was 0.065.

> *Conclusion:* There were no significant differences in cadmium concentration between soils-H01 (soil surface layer), leaves, and litter.

PCA_and_Corr_Cds_in_all_farms_NO_LOQ: A Principal Component Analysis (PCA) and a Pearson correlation were used to assess the relationships between cadmium concentration in soils-H01 (soil surface layer), leaves, and litter. Only the sites (points in farms) that had cadmium in both the soils-H01 surface layer and in the litter and leaves were selected. In total, 23 sites of 87 total were available for this analysis.

> *Conclusion:* Cadmium in soils and litter are highly correlated (r = 0.94). Cadmium in leaves is highly correlated with litter (r = 0.96). The highest correlation between cadmium in plants (leaves or litter) and soils is between soils-H1 and leaves (r = 0.89).

In summary, significant differences were not detected in mineral composition of leaves based on different genetic backgrounds, but strong correlations were observed between cacao leaves, litter, and the upper layer of soil or cadmium concentration.

Synthesis: Main Conclusions

- Overall, the sample population had low diversity, containing alleles from mainly three genetic groups with little or no contribution from 5 of 10 groups in the reference set.
- From this information, it can be deduced that farmers are mainly growing trees derived from seedlings, primarily of open-pollinated cacao representing a wide range of hybrid genomes. Some of the progenitors of these hybrids are likely international clone accessions planted in prior cacao-development projects (ICS PA and CCN51).

- Levels of cadmium in soil in the region are generally low but are directly correlated to cadmium concentrations in leaves and litter. Further work is needed to explore the possibility that bioaccumulation of cadmium in upper soil layers is driven by plant uptake from deeper soil layers and accumulation in leaves, followed by leaf fall and decay at the soil surface over many years.
- The low genetic diversity observed in the study area leaves the cocoa crop with a worrying vulnerability to attack by pests and pathogens and stress by changing climate.

This situation presents a current limitation to cacao farm productivity due to the low-moderate yield potential of plants grown from seed. Earlier studies for cacao in a segregating seedling population demonstrated that the best 10% of trees produce the majority of the pods. Cadmium bioaccumulation may play a role in increasing the cadmium content in upper soil layers and in cocoa beans.

Recommendations

Recommendations include leveraging past investments, characterizing the phenotypes of the cacao collection, expanding mapping efforts, and gaining further evidence related to cadmium.

Leverage Past Investments

Samples have been collected, genetic testing performed, and GPS and other phenotypic data on all plants added to a unified database. It is strongly recommended that these resources be extended, maintained, and used in the future by USDA–FAS and stake holders. These resources can increase the impact of cacao sector development projects in the region and throughout Colombia and Latin America. They can not only strengthen efforts related to the genetic diversity of the crop but could also help support a rigorous market study. Such a study could strengthen the value chain through the transformation of cocoa into higher value products, support better sustainability of the crop, and subsequently improve the socioeconomic quality of farmers.

Characterize the Phenotypes of the Cacao Collection

Although the lack of genetic diversity is a threat to the productivity, sustainability, and livelihoods of cacao farming systems, it is also an opportunity to identify new, locally adapted varieties that have high potential for improved yield and quality. Further, the soils in this region are clearly low in cadmium and thus are highly suitable for future expansion of cacao production. The trees characterized in the CfP project, and other areas, potentially represent a mass breeding program waiting to be exploited. Using the methods of farmer participatory breeding, each tree can be followed over time to measure productivity and thereby find high yielding trees. Clones of these trees can be tested in multilocational trials to gain statistical significance and suitability for different environments.

The possibility of introducing new alleles that allow the long-term improvement of both biotic and abiotic agronomic traits can also be considered. One high priority trait that could be used as a selection criterion in the CfP SNSM collection is resistance to drought, which would help to develop cacao trees that are more resilient to climate change and water stress. It would be a strategic advantage to continue leveraging the resources and knowledge of soils and plants of the region. The resources and knowledge can be used in the development of new, locally adapted varieties of cacao and locally adapted and sustainable agronomic practices, which would be validated and disseminated to farmers.

Expand Mapping Efforts

Mapping should be expanded in SNSM and other key cacao production regions of Colombia. The mapping would promote greater impact on the development of Colombia, adoption of cacao as an alternative crop, and development of the cacao value chain. Future effort should expand the geographic reach of the initial pilot study. The CfP mapping team is prepared to work in additional areas in the future. The methods are reproducible, scalable, and applicable to any region in Colombia within security guidelines. Further, farmers could be implemented as scientists (science citizenship approach) to collect samples from remote regions and thereby greatly accelerate future sample collection and reduce the cost of expeditions.

Gain Further Evidence Related to Cadmium

The source of cadmium in cacao growing soils in Colombia should be further investigated to help develop strategies that mitigate or eliminate accumulation to high levels in cocoa beans. Observations have led to a hypothesis that the recycling of vegetative materials on the field (via pruning and leaf drop) could lead to long-term concentration of cadmium in upper soil surfaces and thus increased plant uptake through roots. Further work is needed to test this hypothesis. At this time, removal of leaf litter from plantations is not a practical solution to cadmium mitigation. Without other measures, its removal would have a severe negative impact on soil erosion and biotic factors and would require immense work effort. However, understanding the cycling of cadmium between the soil, tree, and leaf litter layers would provide insight for the design of more productive and sustainable cacao farms.

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Glossary

Many of the terms relating to landforms, geology, and geomorphology are defined in more detail in the “National Soil Survey Handbook” (USDA–NRCS, n.d.; available in local offices of the Natural Resources Conservation Service or at http://soils.usda.gov/technical/handbook/).

Aeration, soil. The exchange of air in soil with air from the atmosphere. The air in a well aerated soil is similar to that in the atmosphere; the air in a poorly aerated soils considerably higher in carbon dioxide and lower in oxygen.

Aggregate, soil. Many fine particles held in a single mass or cluster. Natural soil aggregates, such as granules, blocks, or prisms, are called peds. Clods are aggregates produced by tillage or logging.

Alkali (sodic) soil. A soil having so high a degree of alkalinity (pH 8.5 or higher) or so high a percentage of exchangeable sodium (15 percent or more of the total exchangeable bases), or both, that plant growth is restricted.

Alluvial fan. The fanlike deposit of a stream where it issues from a gorge upon a plain or of a tributary stream near or at its junction with its main stream.

Alluvium. Material, such as sand, silt, or clay, deposited on land by streams.

Alpha,alpha-dipyridyl. A dye that when dissolved in 1N ammonium acetate is used to detect the presence of reduced iron (Fe II) in the soil. A positive reaction indicates a type of redoximorphic feature.

Aquic conditions. Current soil wetness characterized by saturation, reduction, and redoximorphic features.

Aspect. The direction in which a slope faces.

Available water capacity (available moisture capacity). The capacity of soils to hold water available for use by most plants. It is commonly defined as the difference between the amount of soil water at field moisture capacity and the amount at wilting point. It is commonly expressed as inches of water per inch of soil. The capacity, in cm, in a 150-cm profile or to a limiting layer is expressed as:

Very low	0 to 7.6
Low	7.6 to 15
Moderate	15 to 23
High	23 to 30
Very high	more than 30

Base saturation. The degree to which material having cation-exchange properties is saturated with exchangeable bases (sum of Ca, Mg, Na, and K), expressed as a percentage of the total cation-exchange capacity.

Bedrock. The solid rock that underlies the soil and other unconsolidated material or that is exposed at the surface.

Cation. An ion carrying a positive charge of electricity. The common soil cations are calcium, potassium, magnesium, sodium, and hydrogen.

Cation-exchange capacity. The total amount of exchangeable cations that can be held by the soil, expressed in terms of milliequivalents per 100 grams of soil at neutrality (pH 7.0) or at some other stated pH value. The term, as applied to soils, is synonymous with base- exchange capacity but is more precise in meaning.

Clay. As a soil separate, the mineral soil particles less than 0.002 millimeter in diameter. As a soil textural class, soil material that is 40 percent or more clay, less than 45 percent sand, and less than 40 percent silt.

Claypan. A slowly permeable soil horizon that contains much more clay than the horizons above it. A claypan is commonly hard when dry and plastic or stiff when wet.

Coarse textured soil. Sand or loamy sand.

Colluvium. Soil material or rock fragments, or both, moved by creep, slide, or local wash and deposited at the base of steep slopes.

Complex, soil. A map unit of two or more kinds of soil or miscellaneous areas in such an intricate pattern or so small in area that it is not practical to map them separately at the selected scale of mapping. The pattern and proportion of the soils or miscellaneous areas are somewhat similar in all areas.

Control section. The part of the soil on which classification is based. The thickness varies among different kinds of soil, but for many it is that part of the soil profile between depths of 10 inches and 40 or 80 inches.

Corrosion. Soil-induced electrochemical or chemical action that dissolves or weakens concrete or uncoated steel.

Depth, soil. Generally, the thickness of the soil over bedrock. Very deep soils are more than 60 inches deep over bedrock; deep soils, 100 to 150 centimeters; moderately deep, 50 to 100 centimeters; shallow, 25 to 50 centimeters; and very shallow, less than 25 centimeters.

Drainage class (natural). Refers to the frequency and duration of wet periods under conditions similar to those under which the soil formed. Alterations of the water regime by human activities, either through drainage or irrigation, are not a consideration unless they have significantly changed the morphology of the soil. Seven classes of natural soil drainage are recognized—excessively drained, somewhat excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained. These classes are defined in the “Soil Survey Manual.”

Drainage, surface. Runoff, or surface flow of water, from an area.

Ecological site. An area where climate, soil, and relief are sufficiently uniform to produce a distinct natural plant community. An ecological site is the product of all the environmental factors responsible for its development. It is typified by an association of species that differ from those on other ecological sites in kind and/or proportion of species or in total production.

Eolian soil material. Earthy parent material accumulated through wind action; commonly refers to sandy material in dunes or to loess in blankets on the surface.

Erosion. The wearing away of the land surface by water, wind, ice, or other geologic agents and by such processes as gravitational creep.

Erosion (geologic). Erosion caused by geologic processes acting over long geologic periods and resulting in the wearing away of mountains and the building up of such landscape features as flood plains and coastal plains. Synonym: natural erosion.

Erosion (accelerated). Erosion much more rapid than geologic erosion, mainly as a result of human or animal activities or of a catastrophe in nature, such as a fire, that exposes the surface.

Fertility, soil. The quality that enables a soil to provide plant nutrients, in adequate amounts and in proper balance, for the growth of specified plants when light, moisture, temperature, tilth, and other growth factors are favorable.

Fill slope. A sloping surface consisting of excavated soil material from a road cut. It commonly is on the downhill side of the road.

Fine textured soil. Sandy clay, silty clay, or clay.

Flood plain. A nearly level alluvial plain that borders a stream and is subject to flooding unless protected artificially.

Fluvial. Of or pertaining to rivers; produced by river action, as a fluvial plain.

Forb. Any herbaceous plant not a grass or a sedge.

Forest cover. All trees and other woody plants (underbrush) covering the ground in a forest.

Forest type. A stand of trees similar in composition and development because of given physical and biological factors by which it may be differentiated from other stands.

Gravel. Rounded or angular fragments of rock as much as 7.6 centimeters (2 millimeters to 7.6 centimeters) in diameter. An individual piece is a pebble.

Gravelly soil material. Material that has 15 to 35 percent, by volume, rounded or angular rock fragments, not prominently flattened, as much as 7.6 centimeters in diameter.

Ground water. Water filling all the unblocked pores of the material below the water table.

Hard bedrock. Bedrock that cannot be excavated except by blasting or by the use of special equipment that is not commonly used in construction.

Hill. A natural elevation of the land surface, rising as much as 330 meters above surrounding lowlands, commonly of limited summit area and having a well-defined outline; hillsides generally have slopes of more than 15 percent. The distinction between a hill and a mountain is arbitrary and is dependent on local usage.

Horizon, soil. A layer of soil, approximately parallel to the surface, having distinct characteristics produced by soil-forming processes. In the identification of soil horizons, an uppercase letter represents the major horizons. Numbers or lowercase letters that follow represent subdivisions of the major horizons. An explanation of the subdivisions is given in the “Soil Survey Manual.” The major horizons of mineral soil are as follows:

O horizon.—An organic layer of fresh and decaying plant residue.

A horizon.—The mineral horizon at or near the surface in which an accumulation of humified organic matter is mixed with the mineral material. Also, a plowed surface horizon, most of which was originally part of a B horizon.

E horizon.—The mineral horizon in which the main feature is loss of silicate clay, iron, aluminum, or some combination of these.

B horizon.—The mineral horizon below an A horizon. The B horizon is in part a layer of transition from the overlying A to the underlying C horizon. The B horizon also has distinctive characteristics, such as (1) accumulation of clay, sesquioxides, humus, or a combination of these; (2) prismatic or blocky structure; (3) redder or browner colors than those in the A horizon; or (4) a combination of these.

C horizon.—The mineral horizon or layer, excluding indurated bedrock, that is little affected by soil-forming processes and does not have the properties typical of the overlying soil material. The material of a C horizon may be either like or unlike that in which the solum formed. If the material is known to differ from that in the solum, an Arabic numeral, commonly a 2, precedes the letter C.

Cr horizon.—Soft, consolidated bedrock beneath the soil.

R layer.—Consolidated bedrock beneath the soil. The bedrock commonly underlies a C horizon, but it can be directly below an A or a B horizon.

Hydrologic soil groups. Refers to soils grouped according to their runoff potential. The soil properties that influence this potential are those that affect the minimum rate of water infiltration on a bare soil during periods after prolonged wetting when the soil is not frozen. These properties are depth to a seasonal high water table, the infiltration rate and permeability after prolonged wetting, and depth to a very slowly permeable layer. The slope and the kind of plant cover are not considered but are separate factors in predicting runoff.

Infiltration. The downward entry of water into the immediate surface of soil or other material, as contrasted with percolation, which is movement of water through soil layers or material.

Infiltration capacity. The maximum rate at which water can infiltrate into a soil under a given set of conditions.

Infiltration rate. The rate at which water penetrates the surface of the soil at any given instant, usually expressed in inches per hour. The rate can be limited by the infiltration capacity of the soil or the rate at which water is applied at the surface.

Intake rate. The average rate of water entering the soil under irrigation. Most soils have a fast initial rate; the rate decreases with application time. Therefore, intake rate for design purposes is not a constant but is a variable depending on the net irrigation application. The rate of water intake, in cm per hour, is expressed as follows:

Less than 0.6	very low
0.6 to 1.1	low
1.0 to 1.9	moderately low
1.9 to 3.2	moderate
3.2 to 4.4	moderately high
4.4 to 6.4	high
More than 6.4	very high

Ksat. Saturated hydraulic conductivity. (See Permeability.)

Leaching. The removal of soluble material from soil or other material by percolating water.

Liquid limit. The moisture content at which the soil passes from a plastic to a liquid state.

Loam. Soil material that is 7 to 27 percent clay particles, 28 to 50 percent silt particles, and less than 52 percent sand particles.

Loess. Fine grained material, dominantly of silt-sized particles, deposited by wind.

Low strength. The soil is not strong enough to support loads.

Medium textured soil. Very fine sandy loam, loam, silt loam, or silt.

Mineral soil. Soil that is mainly mineral material and low in organic material. Its bulk density is more than that of organic soil.

Miscellaneous area. An area that has little or no natural soil and supports little or no vegetation.

Moderately coarse textured soil. Coarse sandy loam, sandy loam, or fine sandy loam.

Moderately fine textured soil. Clay loam, sandy clay loam, or silty clay loam.

Neutral soil. A soil having a pH value of 6.6 to 7.3. (See Reaction, soil.)

Nutrient, plant. Any element taken in by a plant essential to its growth. Plant nutrients are mainly nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, manganese, copper, boron, and zinc obtained from the soil and carbon, hydrogen, and oxygen obtained from the air and water.

Organic matter. Plant and animal residue in the soil in various stages of decomposition. The content of organic matter in the surface layer is described as follows:

Very low	less than 0.5 percent
Low	0.5 to 1.0 percent
Moderately low	1.0 to 2.0 percent
Moderate	2.0 to 4.0 percent
High	4.0 to 8.0 percent
Very high	more than 8.0 percent

Pan. A compact, dense layer in a soil that impedes the movement of water and the growth of roots. For example, *hardpan, fragipan, claypan, plowpan,* and *traffic pan*.

Parent material. The unconsolidated organic and mineral material in which soil forms.

Ped. An individual natural soil aggregate, such as a granule, a prism, or a block.

Pedon. The smallest volume that can be called "a soil." A pedon is three dimensional and large enough to permit study of all horizons. Its area ranges from about 1 square meter to 10 square meters, depending on the variability of the soil.

Percolation. The movement of water through the soil.

Permeability. The quality of the soil that enables water or air to move downward through the profile. The rate at which a saturated soil transmits water is accepted as a measure of this quality. In soil physics, the rate is referred to as "saturated hydraulic conductivity," which is defined in the "Soil Survey Manual." In line with conventional usage in the engineering profession and with traditional usage in published soil surveys, this rate of flow continues to be expressed as "permeability." Terms describing permeability, measured in inches per hour, are as follows:

Extremely slow	0.0 to 0.025 cm
Very slow	0.025 to 0.15 cm
Slow	0.15 to 0.6 cm
Moderately slow	0.6 to 1.5 cm
Moderate	1.5 to 5.1 cm
Moderately rapid	5.1 to 15.0 cm
Rapid	15.0 to 51.0 cm
Very rapid	more than 51.0 cm

Phase, soil. A subdivision of a soil series based on features that affect its use and management, such as slope, stoniness, and flooding.

pH value. A numerical designation of acidity and alkalinity in soil. (See Reaction, soil.)

Plasticity index. The numerical difference between the liquid limit and the plastic limit; the range of moisture content within which the soil remains plastic.

Plastic limit. The moisture content at which a soil changes from semisolid to plastic.

Plowpan. A compacted layer formed in the soil directly below the plowed layer.

Ponding. Standing water on soils in closed depressions. Unless the soils are artificially drained, the water can be removed only by percolation or evapotranspiration.

Potential rooting depth (effective rooting depth). Depth to which roots could penetrate if the content of moisture in the soil were adequate. The soil has no properties restricting the penetration of roots to this depth.

Productivity, soil. The capability of a soil for producing a specified plant or sequence of plants under specific management.

Profile, soil. A vertical section of the soil extending through all its horizons and into the parent material.

Rangeland. Land on which the potential natural vegetation is predominantly grasses, grasslike plants, forbs, or shrubs suitable for grazing or browsing. It includes natural grasslands, savannas, many wetlands, some deserts, tundras, and areas that support certain forb and shrub communities.

Reaction, soil. A measure of acidity or alkalinity of a soil, expressed in pH values. A soil that tests to pH 7.0 is described as precisely neutral in reaction because it is neither acid nor alkaline. The degrees of acidity or alkalinity, expressed as pH values, are:

Ultra acid	less than 3.5
Extremely acid	3.5 to 4.4
Very strongly acid	4.5 to 5.0
Strongly acid	5.1 to 5.5
Moderately acid	5.6 to 6.0
Slightly acid	6.1 to 6.5
Neutral	6.6 to 7.3
Slightly alkaline	7.4 to 7.8
Moderately alkaline	7.9 to 8.4
Strongly alkaline	8.5 to 9.0
Very strongly alkaline	9.1 and higher

Redoximorphic concentrations. Nodules, concretions, soft masses, pore linings, and other features resulting from the accumulation of iron or manganese oxide. An indication of chemical reduction and oxidation resulting from saturation.

Redoximorphic depletions. Low-chroma zones from which iron and manganese oxide or a combination of iron and manganese oxide and clay has been removed. These zones are indications of the chemical reduction of iron resulting from saturation.

Redoximorphic features. Redoximorphic concentrations, redoximorphic depletions, reduced matrices, a positive reaction to alpha,alpha-dipyridyl, and other features indicating the chemical reduction and oxidation of iron and manganese compounds resulting from saturation.

Relief. The elevations or inequalities of a land surface, considered collectively.

Residuum (residual soil material). Unconsolidated, weathered or partly weathered mineral material that accumulated as consolidated rock disintegrated in place.

Rock fragments. Rock or mineral fragments having a diameter of 2 millimeters or more; for example, pebbles, cobbles, stones, and boulders.

Root zone. The part of the soil that can be penetrated by plant roots.

Runoff. The precipitation discharged into stream channels from an area. The water that flows off the surface of the land without sinking into the soil is called surface runoff. Water that enters the soil before reaching surface streams is called groundwater runoff or seepage flow from ground water.

Saline soil. A soil containing soluble salts in an amount that impairs growth of plants. A saline soil does not contain excess exchangeable sodium.

Sand. As a soil separate, individual rock or mineral fragments from 0.05 millimeter to 2.0 millimeters in diameter. Most sand grains consist of quartz. As a soil textural class, a soil that is 85 percent or more sand and not more than 10 percent clay.

Sandstone. Sedimentary rock containing dominantly sand-sized particles.

Saprolite. Unconsolidated residual material underlying the soil and grading to hard bedrock below.

Saturation. Wetness characterized by zero or positive pressure of the soil water. Under conditions of saturation, the water will flow from the soil matrix into an unlined auger hole.

Sedimentary rock. Rock made up of particles deposited from suspension in water. The chief kinds of sedimentary rock are conglomerate, formed from gravel; sandstone, formed from sand; shale, formed from clay; and limestone, formed from soft masses of calcium carbonate. There are many intermediate types. Some wind-deposited sand is consolidated into sandstone.

Series, soil. A group of soils that have profiles that are almost alike. All the soils of a series have horizons that are similar in composition, thickness, and arrangement.

Shale. Sedimentary rock formed by the hardening of a clay deposit.

Silt. As a soil separate, individual mineral particles that range in diameter from the upper limit of clay (0.002 millimeter) to the lower limit of very fine sand (0.05 millimeter). As a soil textural class, soil that is 80 percent or more silt and less than 12 percent clay.

Siltstone. Sedimentary rock made up of dominantly silt-sized particles.

Similar soils. Soils that share limits of diagnostic criteria, behave and perform in a similar manner, and have similar conservation needs or management requirements for the major land uses in the survey area.

Slope. The inclination of the land surface from the horizontal. Percentage of slope is the vertical distance divided by horizontal distance, then multiplied by 100. Thus, a slope of 20 percent is a drop of 6.6 meters in 33 meters of horizontal distance.

Sodic (alkali) soil. A soil having so high a degree of alkalinity (pH 8.5 or higher) or so high a percentage of exchangeable sodium (15 percent or more of the total exchangeable bases), or both, that plant growth is restricted.

Sodicity. The degree to which a soil is affected by exchangeable sodium. Sodicity is expressed as a sodium adsorption ratio (SAR) of a saturation extract, or the ratio of Na^+ to Ca^{++} + Mg^{++}. The degrees of sodicity and their respective ratios are:

Slight	less than 13:1
Moderate	13-30:1
Strong	more than 30:1

Sodium adsorption ratio (SAR). A measure of the amount of sodium (Na) relative to calcium (Ca) and magnesium (Mg) in the water extract from saturated soil paste. It is the ratio of the Na concentration divided by the square root of one-half of the Ca + Mg concentration.

Soft bedrock. Bedrock that can be excavated with trenching machines, backhoes, small rippers, and other equipment commonly used in construction.

Soil. A natural, three-dimensional body at the earth's surface. It is capable of supporting plants and has properties resulting from the integrated effect of climate and living matter acting on earthy parent material, as conditioned by relief over periods of time.

Soil separates. Mineral particles less than 2 millimeters in equivalent diameter and ranging between specified size limits. The names and sizes, in millimeters, of separates recognized in the United States are as follows:

Very coarse sand	2.0 to 1.0
Coarse sand	1.0 to 0.5
Medium sand	0.5 to 0.25
Fine sand	0.25 to 0.10
Very fine sand	0.10 to 0.05
Silt	0.05 to 0.002
Clay	less than 0.002

Solum. The upper part of a soil profile, above the C horizon, in which the processes of soil formation are active. The solum consists of the A, E, and B horizons. Generally, the characteristics of the material in these horizons are unlike those of the material below the solum. The living roots and plant and animal activities are largely confined to the solum.

Stones. Rock fragments 25 to 60 centimeters in diameter if rounded or 38 to 60 centimeters in length if flat.

Stony. Refers to a soil containing stones in numbers that interfere/prevent tillage.

Structure, soil. The arrangement of primary soil particles into compound particles or aggregates. The principal forms of soil structure are—*platy* (laminated), *prismatic* (vertical axis of aggregates longer than horizontal), *columnar* (prisms with rounded tops), *blocky* (angular or subangular), and *granular*. Structureless soils are either *single grained* (each grain by itself, as in dune sand) or *massive* (the particles adhering without any regular cleavage, as in many hardpans).

Subsoil. Technically, the B horizon; roughly, the part of the solum below plow depth.

Substratum. The part of the soil below the solum.

Subsurface layer. Any surface soil horizon (A, E, AB, or EB) below the surface layer.

Surface layer. The soil ordinarily moved in tillage, or its equivalent in uncultivated soil, ranging in depth from 10 to 25 centimeters. Frequently designated as the "plow layer," or the "Ap horizon."

Surface soil. The A, E, AB, and EB horizons, considered collectively. It includes all subdivisions of these horizons.

Terrace. An embankment, or ridge, constructed across sloping soils on the contour or at a slight angle to the contour. The terrace intercepts surface runoff so that water soaks into the soil or flows slowly to a prepared outlet. A terrace in a field generally is built so that the field can be farmed. A terrace intended mainly for drainage has a deep channel that is maintained in permanent sod.

Terrace (geologic). An old alluvial plain, ordinarily flat or undulating, bordering a river, a lake, or the sea.

Texture, soil. The relative proportions of sand, silt, and clay particles in a mass of soil. The basic textural classes, in order of increasing proportion of fine particles, are *sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay,* and *clay*. The sand, loamy sand, and sandy loam classes may be further divided by specifying “coarse,” “fine,” or “very fine.”

Tilth, soil. The physical condition of the soil as related to tillage, seedbed preparation, seedling emergence, and root penetration.

Topsoil. The upper part of the soil, which is the most favorable material for plant growth. It is ordinarily rich in organic matter and is used to topdress roadbanks, lawns, and land affected by mining.

Upland. Land at a higher elevation, in general, than the alluvial plain or stream terrace; land above the lowlands along streams.

Weathering. All physical and chemical changes produced in rocks or other deposits at or near the earth’s surface by atmospheric agents. These changes result in disintegration and decomposition of the material.

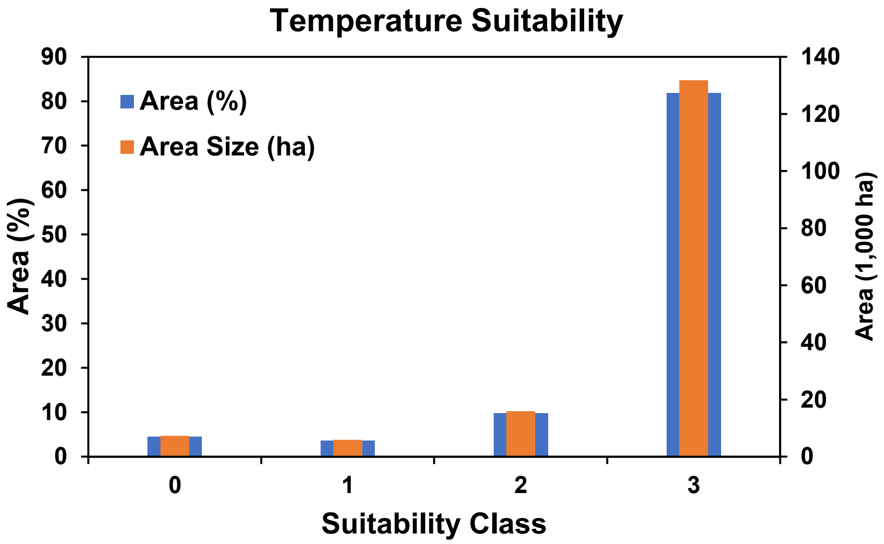
Appendix

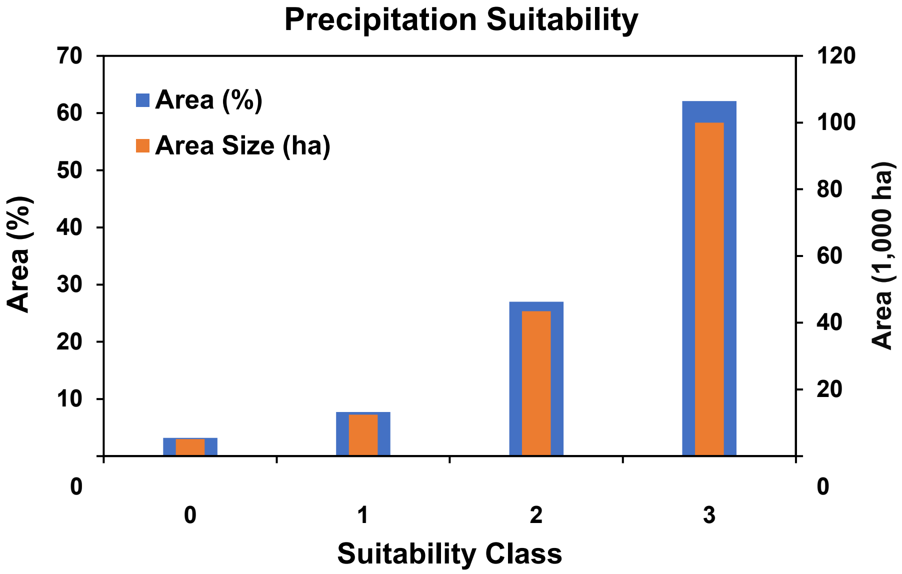
Cacao Suitability Rating Criteria

The factors to used develop the cacao suitability ratings are illustrated in the following figures. For each criterion, the distribution of each suitability class is displayed as an extent in hectares and as a percent of the survey area.

A-1.—Factors Affecting Climate Suitability Rating

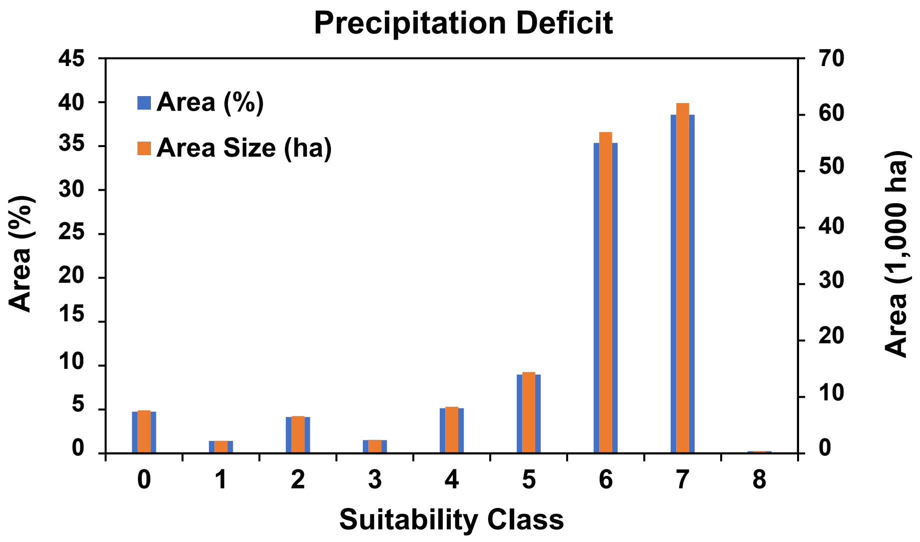
Distribution of suitability classes for temperature, total precipitation, and precipitation deficit.





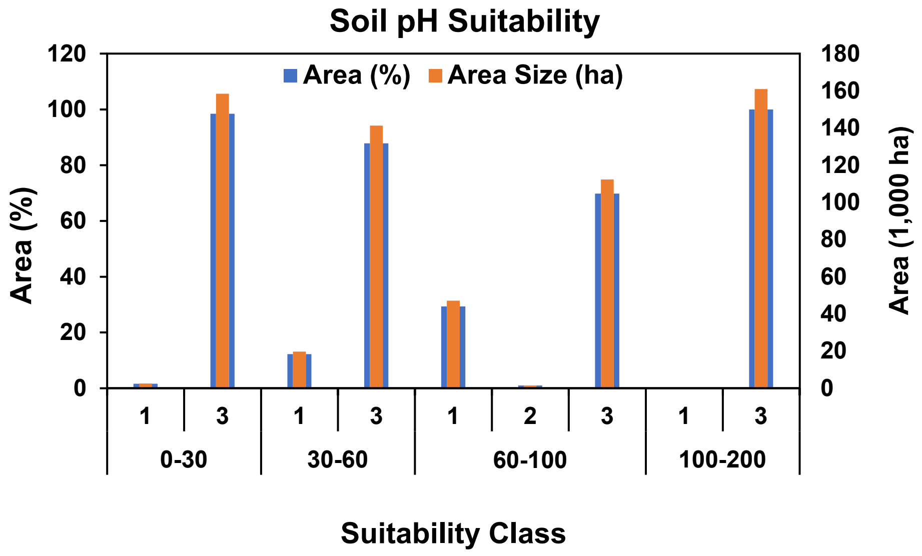
A-1.—Factors Affecting Climate Suitability Rating—cont.

Distribution of suitability classes for temperature, total precipitation, and precipitation deficit.



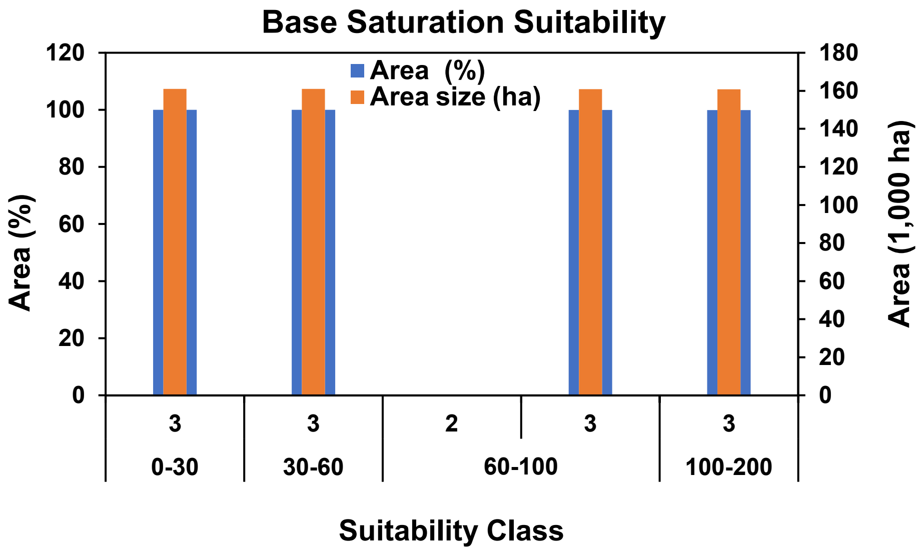
A-2.—Factors Affecting Soil Fertility Suitability Rating

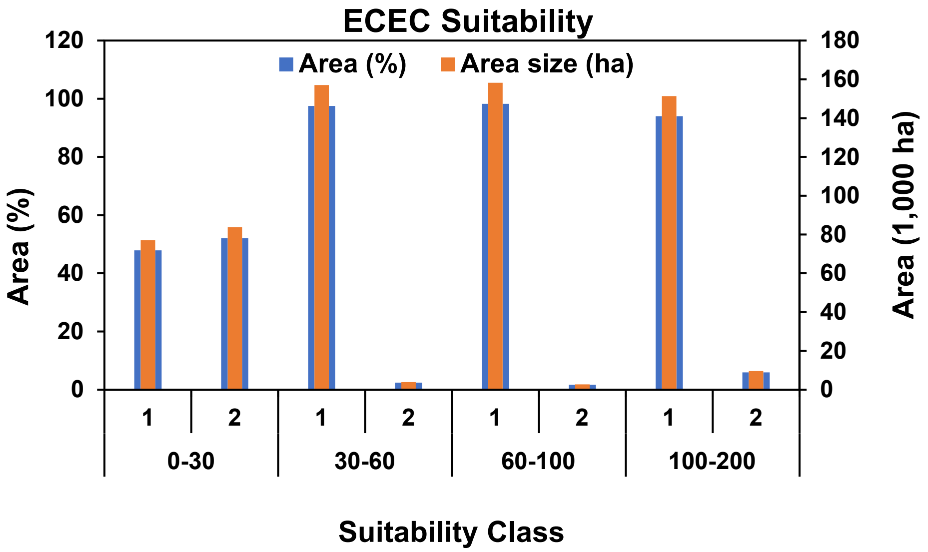
Distribution of suitability classes for soil pH, base saturation (%), cation exchange capacity CEC (cmol(+)/kg soil), and soil organic carbon (%).

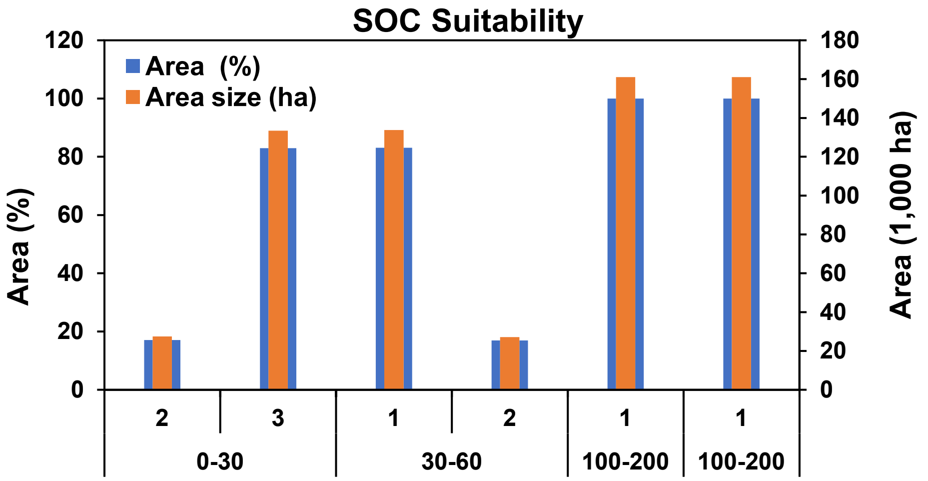


A-2.—Factors Affecting Soil Fertility Suitability Rating—cont.

Distribution of suitability classes for soil pH, base saturation (%), cation exchange capacity CEC (cmol(+)/kg soil), and soil organic carbon (%).





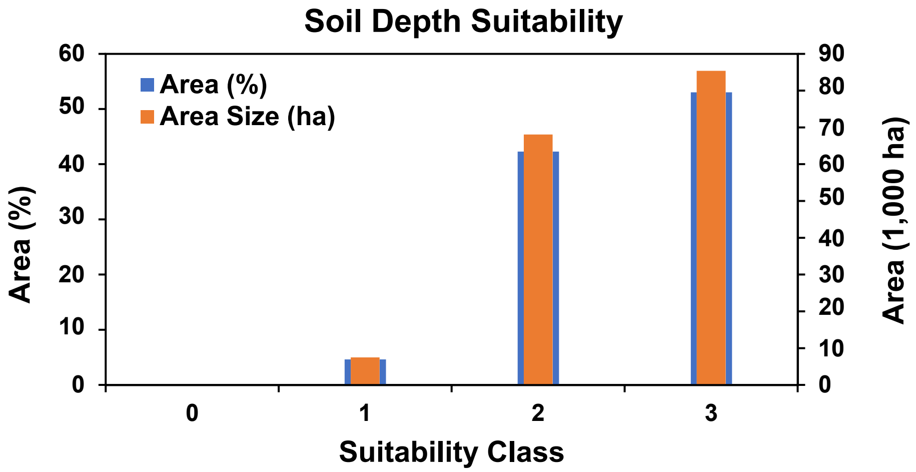


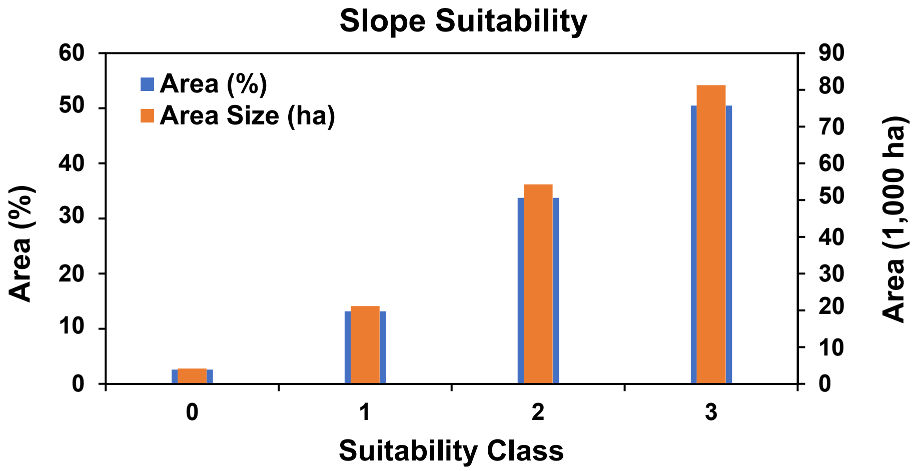
Suitability Class

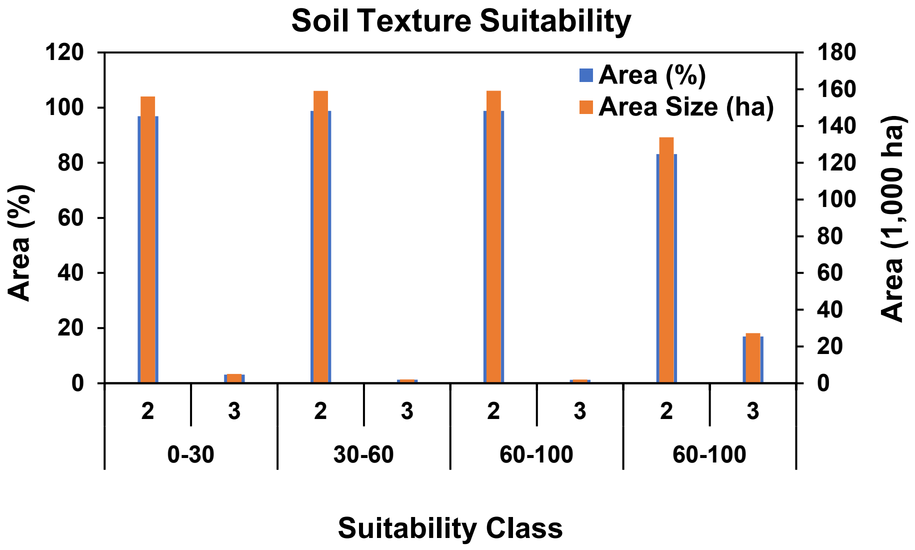
A-2.—Factors Affecting Soil Fertility Suitability Rating—cont.

A-3.—Factors Affecting Soil Conservation Suitability Rating

Distribution of suitability classes for soil depth, slope, and soil texture.

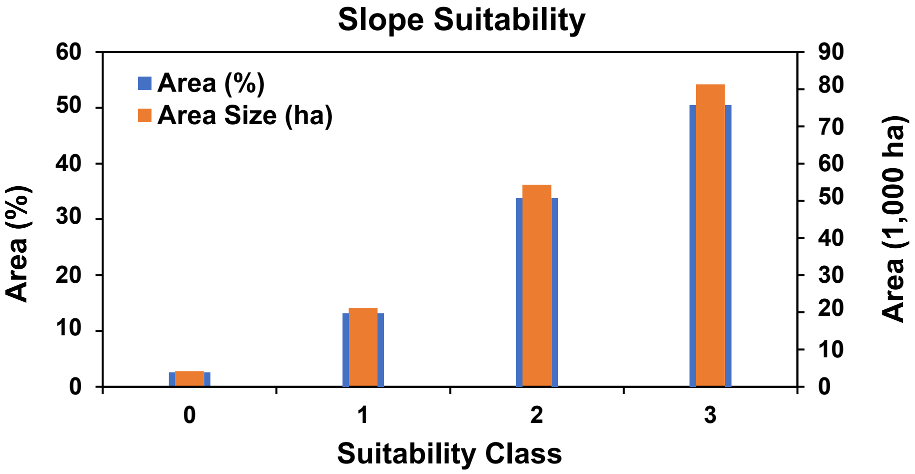

Soil Depth Suitability

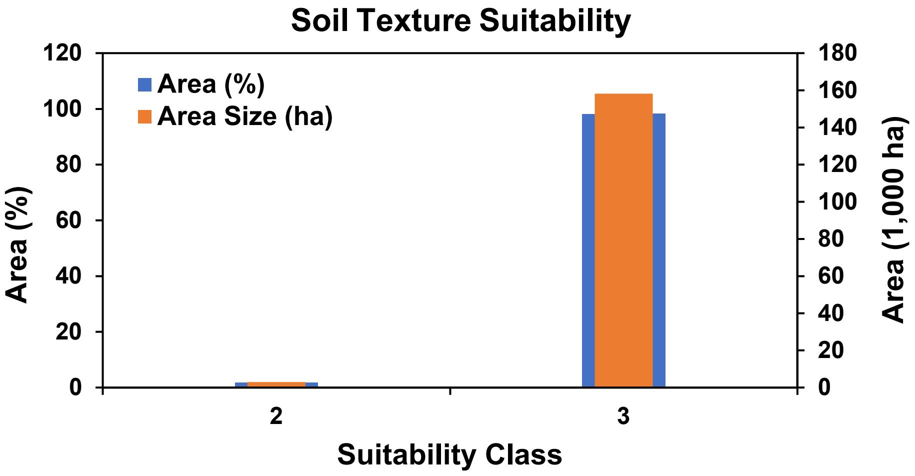

Slope Suitability


Soil Texture Suitability

A-4.—Factors Affecting Tillage Capacity Suitability Rating

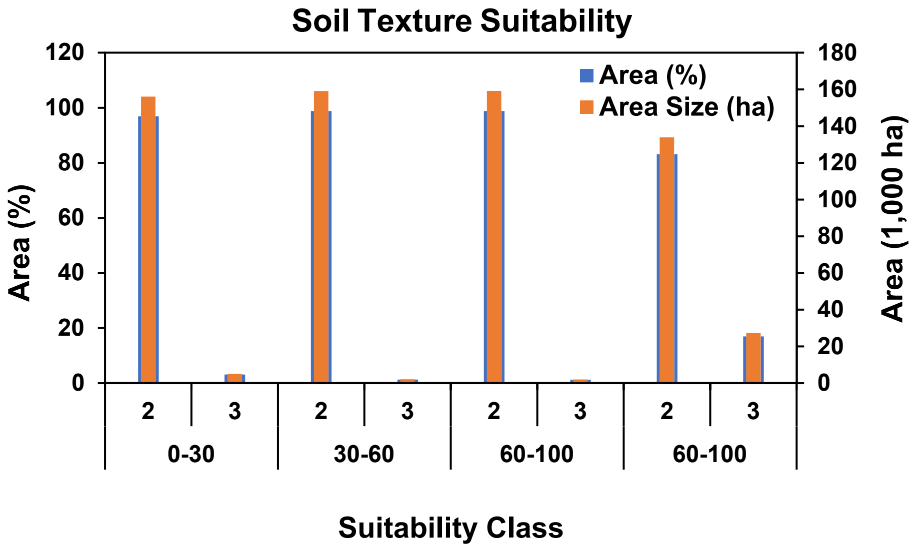
Distribution of suitability classes for slope and soil texture.

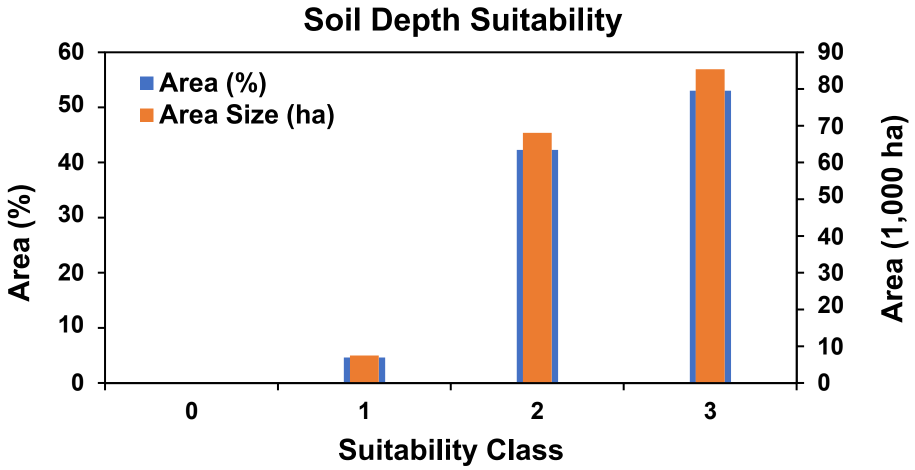




A-5.—Factors Affecting Plant Root Suitability Rating

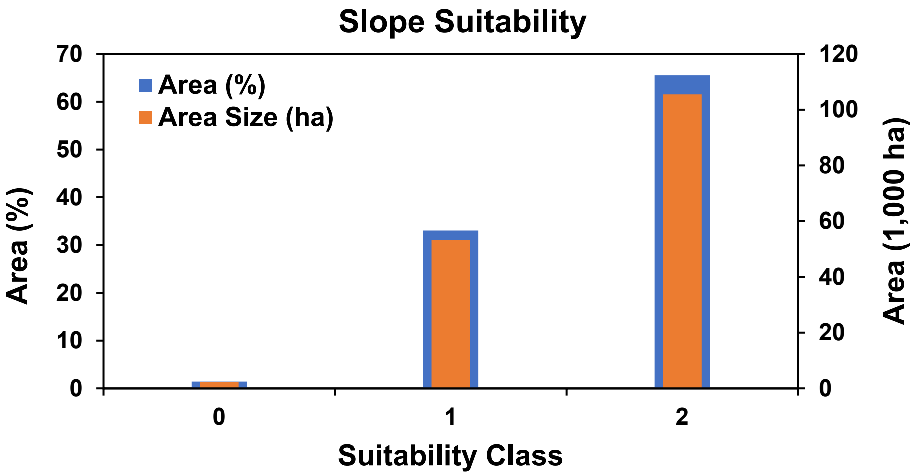
Distribution of suitability classes for soil texture and soil depth.

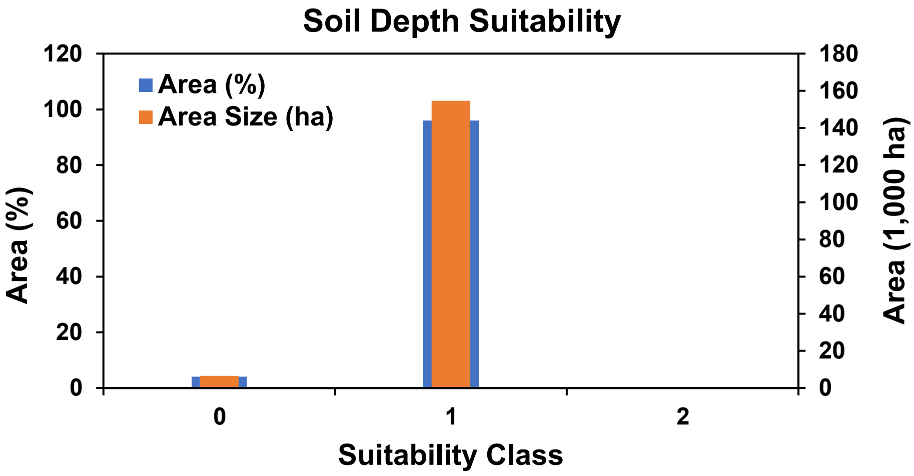




A-6.—Factors Affecting Irrigation Suitability Rating

Distribution of suitability classes for slope and soil depth.





General Irrigation Rating Criteria

Summary

Soil interpretations for “Irrigation-General” evaluate the limitation(s) of a soil for installation and use of irrigation systems. The ratings are for soils in their natural condition and do not consider present land use. This interpretation is for nonspecific irrigation methods and is intended to provide initial planning information. If the type of irrigation system has been determined, additional interpretations provide more specific information. This interpretation does not apply if the crop planned for irrigation is rice or other crops (such as cranberries) that have unique plant physiological characteristics.

The degree of limitation is expressed as a numeric index between 0 (nonlimiting condition) and 1.0 (limiting condition). If a soil property within 150 cm (60 inches) of the soil surface has a degree of limitation greater than zero, then that soil property is limiting and the restrictive feature is identified. The overall interpretive rating assigned is the maximum degree of limitation of each soil interpretive property that comprises the interpretive rule. Lesser restrictive soil features are those that have a degree of limitation less than the maximum and are identified to provide the user with additional information about the soil’s capability to support the interpretation. These lesser restrictive features could be important factors where the major restrictive features are overcome through practice design and application modifications.

Soils are placed into interpretive rating classes per their degree of limitation. These classes are not limited (degree of limitation = 0), somewhat limited (degree of limitation >0 and <1.0), and very limited (degree of limitation = 1.0). The General Irrigation interpretation was developed by the NRCS interpretation and irrigation engineering staff at Temple, Texas. The original interpretation rules and criteria developed by this staff have been modified to meet the need for this application in other regions of the United States.

NOTE: Several soil criteria that result in very limited responses do not apply when rice is irrigated. This report is not applicable to basin-irrigation of rice.

This application is neither designed for nor intended to be used in a regulatory manner.

Scope

Irrigation systems provide supplemental water to crops, orchards, vineyards, and vegetables in areas where natural precipitation does not support desired production of crops being grown.

Description

The soil properties and qualities important in design and management are sodium adsorption ratio, depth to high water table, available water holding capacity, permeability, erosion factor, slope, calcium carbonate content, ponding, and flooding. Soil properties and qualities that influence installation and tillage are stones, depth to bedrock or cemented pan, and depth to a high water table. The properties and qualities that affect performance of the irrigation system are depth to bedrock or to a cemented pan, the sodium adsorption ratio, salinity, and soil reaction. Permanently frozen soils are not suited to irrigation.

Criteria

The interpretive rating is the most limiting of the following restrictive features.

1. Depth to hard bedrock

Shallow depth to hard bedrock limits site preparation, such as shaping and leveling; reduces rooting depth and available water capacity; and restricts installation of underground irrigation practice components. The soil feature considered is the top depth of the first restrictive layer where restrictive type is “bedrock (lithic).” Depth to restrictive feature must be synchronized with the depth to the restrictive feature horizon shown in the horizon table.

Property used: Depth to Bedrock (Modality: Representative value)

Restrictive limits:

Very limiting	<50 cm
Somewhat limiting	≥50 cm and <150 cm
Not limiting	≥150 cm

Null depth is assigned to the not limiting class.

AND

Property used: Kind of Bedrock Restriction (Modality: Representative value)

Restrictive limits:

Very limiting = “bedrock (lithic)”
Not limiting not = “bedrock (lithic)”
Null restrictive feature kind is assigned to the not limiting class.

2. Depth to soft bedrock

Shallow depth to soft bedrock limits site preparation, such as shaping and leveling; reduces rooting depth and available water capacity; and restricts installation of underground irrigation practice components. The soil feature considered is the top depth of the first restrictive layer where restrictive type is “bedrock (paralithic)” or “bedrock (densic).” Depth to restrictive feature must be synchronized with the depth to the restrictive feature horizon shown in the horizon table.

Property used: Depth to Bedrock (Modality: Representative value)

Restrictive limits:

Very limiting	<50 cm
Somewhat limiting	≥50 cm and <150 cm
Not limiting	≥150 cm

Null depth is assigned to the not limiting class.

AND

Property used: Kind of Bedrock Restriction (Modality: Representative value)

Restrictive limits:

Very limiting = “bedrock (paralithic)” or “bedrock (densic)”
Not limiting not = “bedrock (paralithic)” or “bedrock (densic)”
Null restrictive feature kind is assigned to the not limiting class.

3. Depth to cemented pan

Shallow depth to cemented pan limits site preparation, such as shaping and leveling; reduces rooting depth and available water capacity; and restricts installation of underground irrigation practice components. Soil features considered are the top depth of the first restrictive layer where restriction kind = “fragipan,” “duripan,” “petrocalcic,” “ortstein,” or “petrogypsic.” Depth to restrictive feature shown in the component restrictions table must be synchronized with the depth to the restrictive feature horizon shown in the horizon table in the database.

Property used: Depth to First Restrictive Feature (Modality: Representative value)

Restrictive limits:

Very limiting	<50 cm
Somewhat limiting	≥50 and <150 cm
Not limiting	≥150 cm

Null depth is assigned to the not limiting class.

AND

Property used: Kind of Restriction (Modality: Representative value)

Restrictive limits:

Very limiting	= “fragipan” or “duripan” or “petrocalcic” or “ortstein” or “petrogypsic”
Not limiting	not = “fragipan” or “duripan” or “petrocalcic” or “ortstein” or “petrogypsic”

Null restrictive feature kind is assigned to the not limiting class.

AND

Property used: First Restrictive Feature Hardness (Modality: Representative value)

Restrictive limits:

Very limiting	not = “Noncemented”
Not limiting	= “Noncemented”

Null hardness is assigned to the limiting class.

4. Depth to saturated zone

A shallow depth to water table hampers installation of irrigation pipelines, appurtenances, water control structures, and earth forming that might be needed install and maintain an irrigation system. A shallow depth to water table also complicates the irrigation water management requirements for the site and often increases the probability of salinity problems developing. A shallow water table also makes the soil difficult to work, restricts rooting zone, and increases risk of ground water contamination through leaching of nitrates, pesticides, or other contaminants. These areas drain slowly and can become waterlogged and boggy during periods of heavy precipitation. The soil feature considered is the top depth of the first layer where soil moisture layer status is wet or saturated during any month in the growing season. Soil feature used is 60 cm depth as limiting. This limitation can sometimes be overcome with installation of a properly designed drainage system. Greater than or equal to 90 cm is not limiting.

Property used: Depth to High Water Table Minimum in Growing Season (Modality: Representative value)

Restrictive limits:

Very limiting	<60 cm
Somewhat limiting	≥60 cm and <90 cm
Not limiting	≥90 cm

Null depth is assigned to the not limiting class.

5. Low Available Water Capacity

Soils with low available water capacity have limited potential to hold irrigation water. Irrigation system design and management are critical on soil with low AWC to ensure adequate soil water for maximum plant growth and production. The soil feature considered is the (available water capacity x layer thickness) summed through a depth of 150 cm or to a restrictive layer. The value 0.05 cm/cm is considered limiting.

Property used: WMS—Available Water Capacity in Depth 0–150 cm (Modality: High, low, representative value)

Restrictive limits:

Very limiting	≤7.5 cm
Somewhat limiting	>7.5 to <18 cm
Not limiting	≥18 cm

Null AWC is assigned to the not rated class.

6. Sodium content

Soils with high sodium adsorption ratio (SAR) are prone to develop restrictions or reductions to infiltration by irrigation water and rainfall. These constraints are due to soil dispersion caused by sodium in the soil or soil water. Soils with elevated SAR require monitoring of SAR in the soil and in the irrigation water being applied. They also require very careful irrigation-water management and possibly chemical treatment. An elevated SAR can impact expected crop response to irrigation by suppressing plant growth and thereby require a high degree of management. The soil feature considered is the highest sodium adsorption ratio for horizons that have any portion in the depth range 0 to 150 cm.

Property used: Sodium Adsorption Ratio Maximum in Depth 0–150 cm (Modality: Low, high, representative value)

Restriction limits:

Very limiting	>20
Somewhat limiting	>6 and <20
Not limiting	<6

Null SAR is assigned not rated.

7. Flooding

Flooding frequency greater than rare has the potential to damage irrigation infrastructure and to impact the expected crop response to irrigation by causing frequent crop damage. Most irrigation systems involve a relatively high investment in money, labor, or both. Most producers need to be fairly certain the investment will pay off. A frequently flooded area would likely not provide a very stable investment. Frequently flooded areas are more likely to transport nutrients and agricultural chemicals, which are typically applied at a higher rate on irrigated land, off site to receiving surface waters. The soil feature considered is maximum flooding frequency classes over 12 months.

Property used: Flooding Frequency Class, Greatest Any Month (Maximum Duration) (Modality: Representative value)

Restrictive limits:

Very limiting	= “Very frequent”
Somewhat limiting	= “frequent” or “occasional”
Not limiting	= “none” or “very rare” or “rare”

Null frequency is assigned to the not limiting class.

8. Percs slowly

Soils with low hydraulic conductivity (Ksat) have slow percolation, which causes excess runoff and erosion during high precipitation or irrigation events. Agri-chemicals and fertilizers applied to soils that have this limitation can be removed from the site by runoff and thereby impact adjacent surface waters. Timing, application rates, and application methods are management tools for applying these products to soils that are susceptible to slow percolation. The soil feature considered is the horizon that has the lowest Ksat and has any portion in the depth range 0 to 150 cm or to a restrictive layer if less than 150 cm.

Property used: WMS—Ksat Minimum, 0–150 cm or First Restriction (Modality: Low, high, representative value)

Restriction limits:

Very limiting ≤0.14 micrometers/second
Somewhat limiting >0.14 and <.40 micrometers/second
Not limiting ≥1.40 micrometers/second
Null Ksat is assigned not rated.

9. Ponding

Ponding can damage irrigation infrastructure and commonly impacts expected crop response to irrigation by causing frequent crop damage. Most irrigation systems involve a relatively high investment in money, labor, or both. Most producers need to be fairly certain the investment will pay off. A ponding area would likely not provide a very stable investment. The soil feature considered is ponding duration any month during the growing season. This limitation can sometimes be overcome by installation of a properly designed drainage system.

Property used: Ponding Duration During Growing Season (Modality: Representative value)

Restrictive limits:

Very limiting = “long” or “very long”
Somewhat limiting = “brief” or “very brief”Not
limiting = “none”
Null ponding duration is assigned to the not limiting class.

10. Excess salt

Soils with elevated salinity levels require EC monitoring of the soil and the irrigation water being applied. Matching irrigated crop selection to expected salinity levels, proper leaching, and careful irrigation water management are required on soils with elevated salinity. A properly designed drainage system may be required to properly irrigate some soils that have elevated salinity levels. Irrigation runoff and associated subsurface drainage from these soils have the potential to increase salinity levels in groundwater, downstream surface waters, and wetlands. The soil feature considered is the horizon with the highest electrical conductivity 0–150 cm.

Property used: Salinity Maximum (Modality: Low, high, representative value)

Restriction limits:

Somewhat limiting ≥4
Not limiting <4
Null EC is assigned not rated.

11. Slope

Limitation due to slope is highly dependent on type of irrigation system. Moderate slopes can increase runoff and erosion where surface irrigation methods are used with specific types of mobile sprinkler irrigation systems (LEPA, LESA, LPIC, and MESA). LEPA, LESA, LPIC, and MESA sprinklers are equipped with low-pressure spray nozzles that operate on drops. The closer the nozzle spacing and lower the drop, the greater potential for runoff and irrigation-induced erosion on a given soil. Actual limiting slopes for sprinkler irrigation systems using spray nozzles on drops are as follows: LEPA, average slope >1 percent; LESA, average slope >3.0 percent; and LIPC and MESA, either average slope >3 percent and surface texture finer than loam or average slope >5 percent and surface texture loam or coarser. All other sprinkler systems have limitations at ≥15 percent. Surface irrigation systems have a limitation at or above 3 percent slope. The soil feature considered is the component slope.

Property used: Slope (Modality: Low, high, representative value)

Restriction limits:

Very limiting	≥15
Somewhat limiting	>1 and <15
Not limiting	≤1 percent

Null slope is assigned not rated.

12. Soil reaction (too acid or too alkaline)

Low or high soil pH can result in corrosion of irrigation infrastructure, significant increase in the operation and maintenance requirements for the irrigation system, and impact on expected crop response to irrigation by restricting plant growth. The soil feature considered is the (pH) from 0 to 100 cm.

Property used: Soil Reaction 1:1 Water; Minimum, 0–100 cm, and Soil Reaction 1:1 Water; Maximum, 0–100 cm (Modality: High, low, representative value)

Restriction limits, too acid:

Very limiting	≤3.5
Somewhat limiting	>3.5 and <5.0
Not limiting	≥5.0

Null pH values are assigned to the not rated class.

Restriction limits, too alkaline:

Somewhat limiting	>9.0
Not limiting	≤9.0

Null pH values are assigned to the not rated class.

13. Calcium carbonate

Free carbonates below the surface layer can increase the irrigation intake rate. This may lead to reduced irrigation efficiency and effectiveness if water is applied using estimates based on soil texture alone. Calcium carbonate may also restrict intake if the soil is compacted or if equipment blockages form due to precipitation of calcium. Free carbonates can also restrict the available root zone of irrigated crops. The soil feature considered is the maximum $CaCO_3$ equivalent (percent in thickest layer) between 25 and 100 cm or at a restrictive layer.

Property used: $CaCO_3$ Maximum 25–100 cm or First Restriction (Modality: High, low, and representative value)

Restrictive limits:

Somewhat limiting	≥50 percent
Not limiting	<50 percent

Null $CaCO_3$ is assigned to the not limiting class.

14. Seepage

Rapid permeability that allows irrigation water to percolate out of the root zone is undesirable and increases irrigation management expenses. Permeability that maintains irrigation water within the root zone during the consumptive use period is desirable to maintain the growth and vigor of the irrigated crop. The soil feature considered is the horizon with the highest Ksat that has any portion in the depth range 0 to 150 cm or to a restrictive layer if less than 150 cm.

Property used: Ksat Maximum, 0–150 cm or First Restriction (Modality: Low, high, representative value)

Restriction limits:

Very limiting	>44.0 µm/sec
Somewhat limiting	>14.0 to <44.0 µm/sec
Not limiting	≤14.0 µm/sec

Null Ksat is assigned to the not limiting class.

15. Content of large stones (a)

Large stones can impede installation of pipelines and water-control structures; land leveling, shaping, or both; and construction of earthen canals, ditches, or ridges. Large stones can also affect operation and maintenance requirements of the selected irrigation system. Large stones affect expected crop response to irrigation by affecting tillage, planting, and harvesting and because plant growth is reduced along with soil AWC. The soil feature considered is the weighted average percentage of rock fragments of size greater than 75 mm in horizons above a restrictive feature or from 0 to 100 cm in depth.

Property used: Fragments >75 mm Weighted Average in Depth 0–100 cm (Modality: High, low, representative value)

Restrictive limits:

Very limiting	>35 percent
Somewhat limiting	>25 percent to 35 percent
Not limiting	≤25 percent

Null fragment data are assigned not rated.

16. Content of large stones (b)

Excessive stones (rock fragments >25 cm in diameter) on the soil surface layer can impede installation of pipelines and water control structures; land leveling, shaping, or both; and construction of earthen canals, ditches, or ridges. Large stones can also affect operation and management requirements of the selected irrigation system. Large stones affect expected crop response to irrigation by affecting tillage, planting, and harvesting and because plant growth is reduced along with soil AWC. The soil feature considered is percent rock fragments >25 cm in size on the surface soil layer.

Property used: Fragments ≥250 mm on the Surface (Modality: High, low, and representative value)

Restrictive limits:

Very limiting	≥5 percent
Somewhat limiting	>0.1 to <5 percent
Not limiting	≤0.1 percent

Null >25 cm rock fragment data are assigned to the not limiting class

17. Subsidence

The presence of gypsum or soluble salts in the soil, parent material, or bedrock can lead to the formation of subsidence features if the amount of irrigation water applied grossly exceeds evapotranspiration. In humid climates, excessive irrigation of soils over limestone bedrock can also result in sinkhole formation. The soil features considered are the gypsum content of the soil and bedrock and the presence of limestone bedrock.

Property used: Limestone Residuum Test (Modality: Representative value)

Restrictive Limits:

Limiting: If the bedrock is limestone, the site is limited by the bedrock type.
Not limiting: If the bedrock is not limestone, the site is not limited by the bedrock type.

NOTE: As the property is now written, if bedrock is not populated, a NO is returned.
NOTE: This base rule can be expanded to evaluate more types of bedrock.

Property used: Parent Material Origin is Soluble Salt (Modality: Representative value)

Restrictive Limits:

Limiting: If the bedrock is soluble salt, the site is limited by the bedrock type.
Not limiting: If the bedrock is not soluble salt, the site is not limited by the bedrock type.

Property used: Subsidence Due to Gypsum, Rev (Modality: Representative value)

Restrictive limits:

Very limiting	≥30 cm
Somewhat limiting	10–30 cm
Not limiting	≤10 cm

Plant Field Data Collection, Protocols, and Analysis

At each farm and site, both soil and plant material were collected. The sampling design was flexible enough to accommodate diverse situations while also assuring data quality (fig. A-7). Soil samples were described and analyzed using the standard methods described in the soil survey portion of this document. This section contains more details on the collection and analysis of plant materials for genetic characterization.

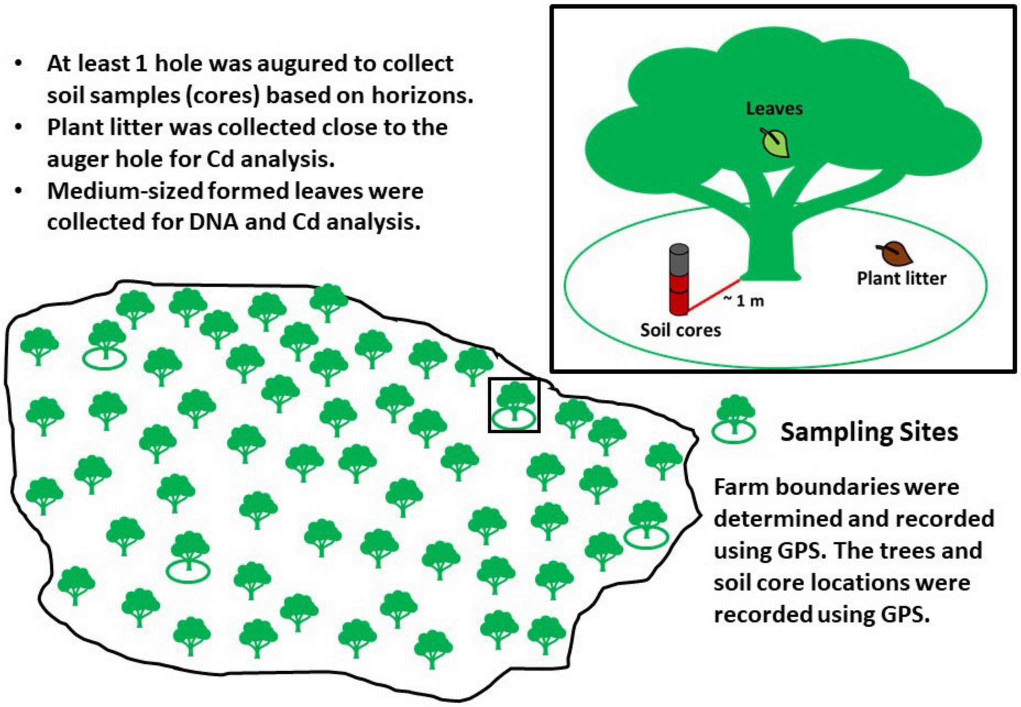


Figure A-7.—Sampling design for collecting soil and plant materials for sites at each farm.

Methods

Key to Sample Notations

Sample IDs for CfP are serial numbers starting with 0001. Plants that were preliminarily identified by a guide or farmer were listed as Clone 0 Type. These identifications are considered educated guesses.

Detailed Protocol for Sample Collection and Processing

1. Adjust the *self-locking tie* lightly on the branch, leaving good additional space around its diameter. This will prevent damage to the branch when it grows.

2. Collect a medium-sized, formed leaf (do not collect shoots) that does not exceed 15 cm in length. Put it inside the paper envelope that is marked with the same code assigned to the tree. If possible, the leaf should not be folded inside the envelope.

3. Place the paper envelope into a plastic Ziploc-type bag, which will have been previously marked and filled with approximately 100 g of silica gel with humidity indicator. Each bag will contain only 5 paper envelopes.

4. To prevent the silica from absorbing excess moisture, the bag should be opened for the shortest possible time. Each time you close it, ensure that it contains as little air inside as possible and that it is well sealed.

5. Distribute the envelopes containing the samples to the width of the plastic bag.
6. Fill in the data *collection form*.

Recommendations: Check every 3 days to determine if the silica gel is still absorbing moisture. If the silica has changed color and the tissue is still wet, replace the silica.

DNA Extraction

DNA isolation was made according to the *Cacao DNA Extraction Protocol, EX11 Version 2* (Zapata, 2016). DNA quality was evaluated following the protocol established at the MGTC laboratory (*Guía Práctica para genotipado de SNPs usando el sistema EP1 y SNPtype Assays de Fluidigm versión F_03*; Quintero et al., 2015).

Briefly, 2 µL of the DNA were electrophoresed in a 0.8% agarose gel (0.5X TBE, stained with SYBRsafe) to confirm its integrity and the concentration was measured by spectrophotometry (Synergy-H1m, Biotek). Prior to SNP genotyping, all samples were normalized at 60 ng/µL.

SNP Genotyping.

SNP genotyping was carried out using the Fluidigm technology (EP1 system) and allele-specific PCR. An array of 96 SNPs was suggested by Dapeng Zhang Ph.D. (USDA) as the most suitable for analyzing the genetic diversity of cocoa germplasm. Fluorescence intensity was analyzed using the *Fluidigm SNP Genotyping Analysis Software version 4.1*.3 and converted to allele calls (Fluidigm, 2018).

Marker Analysis

Informativeness of the markers was assessed by the calculation of descriptive parameters using *PowerMarker V3.25* (Liu and Muse, 2005). Parameters included MAF (Major Allele Frequency), heterozygosity, and polymorphic information content (PIC). A genetic distance matrix was calculated with PowerMaker, and cluster analysis was made with the Unweighted Pair Group Method with Arithmetic Mean (UPGMA).

The probability of identity (PI) and the probability of identity when considering siblings (PIsib) were estimated using *GenAlex V6.502* (Peakall and Smouse, 2012). They were used to determine a minimum number of loci required for reliable genetic tagging. The option *Matching Multilocus Genotypes* was used to identify clones or samples with identical genetic profiles along the whole array of SNPs. Finally, a principal coordinate analysis was used to explore and visualize similarities or dissimilarities of data.

Genetic Assignment Test

Genotypic data were analysed to validate the identity and determine the genetic membership of the sampled trees. Firstly, the clonality (or intra-clone mislabelling) among the multiple individual trees was verified using pairwise multi-locus matching, as implemented in the computer program *GenAlex 6.503* (Peakall and Smouse, 2012; https://biology-assets.anu.edu.au/GenAlEx/Welcome.html).

Samples for which the SNP profiles matched fully at all genotyped SNP loci were declared the same genotype. For a subset of cacao accessions, reference genotype data are available. This reference data set was generated from cacao trees at Marper Farm, Trinidad. These trees have been used by cacao researchers as the original trees for most of the Upper Amazon Forastero germplasm. Genotype data of trees sampled in the SNSM were compared to these reference data for all cases where the data were available. The genetic integrity of the experimental accessions was also assessed by checking their population memberships. An assignment test for the experimental clones was performed using model-based Bayesian cluster analysis software named *STRUCTURE v2.3.4* https://web.stanford.edu/group/pritchardlab/structure.html.

The analysis included SNP sets representing 10 distinctive cacao germplasm groups, which served as references. To ensure that the assignment tests were not affected by the sample size of the tested accessions, the sample size of each of the 10 germplasm groups was brought up to 200. The SIMULATION procedure implemented in the computer program ONCOR was used. The simulated populations were then analyzed together with the selected clones from the Tropical Agricultural Research and Higher Education Center (Centro Agronómico Tropical de Investigación y Enseñanza; CATIE).

An admixed model was selected, and the number of clusters (K value) was set to 10. Five independent runs were assessed for each K vlaue. All runs were carried out using 50,000 iterations after a burn-in period of 50,000. From the five independent runs, the highest Ln Pr (X|K) value was chosen and presented as bar plots for this experiment.

The genetic relationships among the accessions were analysed using principal coordinates analysis (PCoA) in *GenAlEx v 6.503* (Peakall and Smouse, 2006 and 2012). One individual per genotype was used in the PCoA. Typically, the individual used was the one with the least or no missing data. To perform the PCoA, the 90 SNPs were first used to generate a genetic distance matrix using the "codominant-genotypic" setting for distance calculation. The PCoA was subsequently performed using the "Covariance-Standardized" method.

Supplementary Data

Table A-1.—SNPs Array Composition.

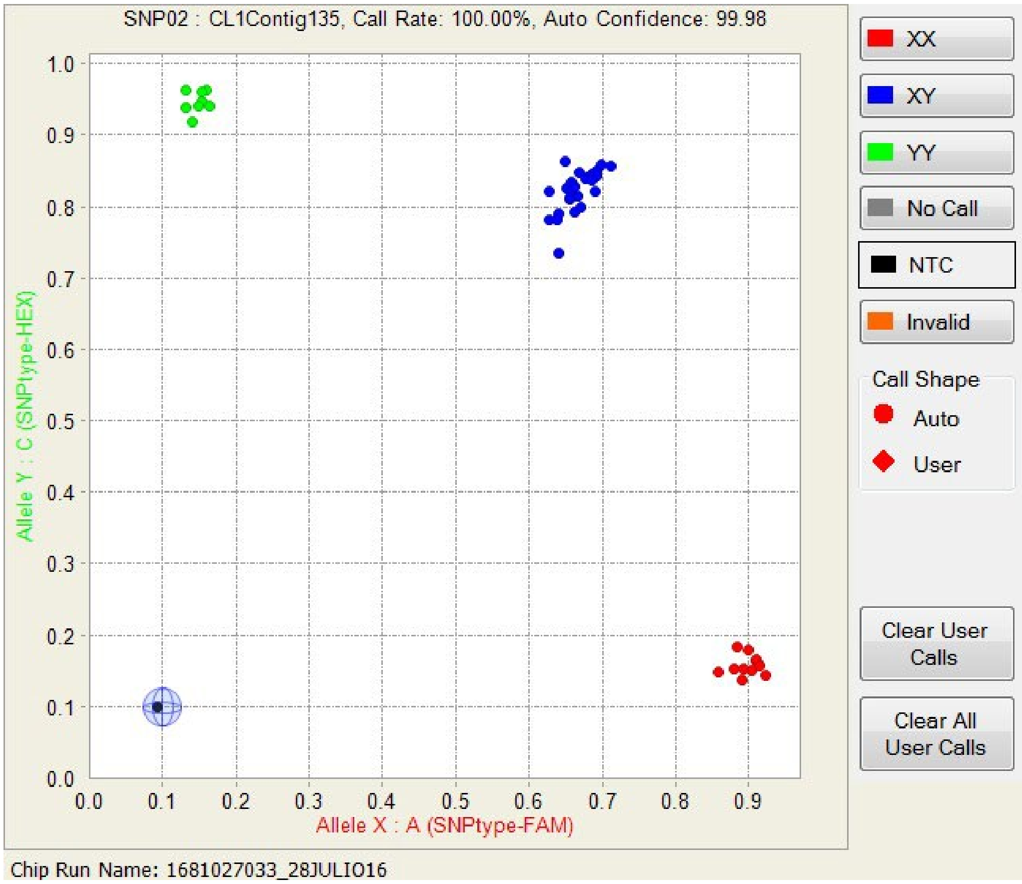
SNP (TropGene_ID)	SNP (CIAT_ID)	Linkage group	Allele1	Allele2
TcSNP205	TcSNP205	1	A	G
TcSNP709	TcSNP709	1	T	C
TcSNP1096	TcSNP1096	1	T	C
TcSNP42	TcSNP42	1	A	G
TcSNP915	TcSNP915	1	A	G
TcSNP418	TcSNP418	1	A	G
TcSNP591	CL77Contig2	1	A	C
TcSNP1350	CL3336Contig1	1	A	C
TcSNP510	TcSNP510	1	C	G
TcSNP1075	CL276Contig1	1	A	T
TcSNP529	CL317Contig1	1	A	C
TcSNP1159	TcSNP1159_2	2	A	C
TcSNP122	TcSNP122	2	T	C
TcSNP1060	CL1002Contig1	2	T	C
TcSNP17	TcSNP17	2	A	G
TcSNP1136	TcSNP1136	2	C	G
TcSNP521	TcSNP521	2	A	C
TcSNP891	CL1Contig69	2	T	C
TcSNP1165	CL1Contig277	2	T	C
TcSNP437	TcSNP437	2	A	T
TcSNP836	CL646Contig2	2	T	C
TcSNP316	TcSNP316	2	A	T
TcSNP996	TcSNP996	3	T	C
TcSNP1149	TcSNP1149	3	T	C
TcSNP19	TcSNP19	3	A	C
TcSNP1062	CL132Contig1	3	A	G
TcSNP689	TcSNP689	3	A	G
TcSNP929	CL209Contig1	3	C	G
TcSNP852	CL4Contig14	3	C	G
TcSNP595	TcSNP595	3	A	G
TcSNP534	CL527Contig1	3	T	C
TcSNP878	CL1312Contig1	3	C	G
TcSNP413	TcSNP413	3	T	C
TcSNP1034	TcSNP1034	4	T	C
TcSNP1175	TcSNP1175	4	T	G
TcSNP277	TcSNP277	4	T	C

SNP (TropGene_ID)	SNP (CIAT_ID)	Linkage group	Allele1	Allele2
TcSNP32	CL3696Contig1	4	A	T
TcSNP1108	TcSNP1108	4	A	T
TcSNP588	TcSNP588	4	A	C
TcSNP60	TcSNP60	4	T	C
TcSNP1194	TcSNP1194	4	T	G
TcSNP395	TcSNP395	4	T	C
TcSNP953	CL2987Contig1	4	A	T
TcSNP872	CL359Contig1	4	C	G
TcSNP372	CL552Contig2	4	A	T
TcSNP886	CL588Contig1	4	T	C
TcSNP751	TcSNP751	5	T	G
TcSNP160	TcSNP160	5	A	T
TcSNP150	CL695Contig1	5	T	G
TcSNP524	TcSNP524	5	T	C
TcSNP577	CL1Contig128	5	C	G
TcSNP28	TcSNP28	5	T	G
TcSNP645	CL318Contig1	5	A	G
TcSNP998	CL1086Contig1	5	A	G
TcSNP561	TcSNP561	6	A	G
TcSNP894	TcSNP894	6	C	G
TcSNP497	TcSNP497	6	T	C
TcSNP632	TcSNP632	6	T	G
TcSNP750	CL745Contig1	6	T	C
TcSNP619	CL456Contig1	6	T	C
TcSNP309	CL581Contig1	6	T	C
TcSNP994	CL171Contig2	6	T	C
TcSNP1126	TcSNP1126	7	A	T
TcSNP944	TcSNP944	7	T	C
TcSNP1383	TcSNP1383	7	A	G
TcSNP791	TcSNP791	7	A	T
TcSNP606	TcSNP606	7	A	G
TcSNP1270	CL2205Contig1	7	T	C
TcSNP547	TcSNP547	8	A	G
TcSNP139	CL858Contig1	8	T	G
TcSNP151	CL235Contig1	8	T	C
TcSNP999	TcSNP999	8	T	C
TcSNP23	TcSNP23	8	T	C
TcSNP269	TcSNP269	8	A	G
TcSNP25	CL8Contig4	9	C	G
TcSNP11	TcSNP11	9	T	G
TcSNP1439	TcSNP1439	9	T	C
TcSNP563	TcSNP563	9	T	C
TcSNP427	TcSNP427	9	T	G
TcSNP172	TcSNP172	9	A	G
TcSNP193	CL1Contig135	9	A	C
TcSNP242	CL918Contig1	9	T	C

SNP (TropGene_ID)	SNP (CIAT_ID)	Linkage group	Allele1	Allele2
TcSNP1253	CL1600Contig1	9	T	G
TcSNP1414	CL139Contig1	9	T	C
TcSNP1442	CL1030Contig1	9	T	C
TcSNP546	TcSNP546	10	A	G
TcSNP1069	TcSNP1069	10	C	G
TcSNP731	TcSNP731_2	10	A	G
TcSNP389	TcSNP389	10	T	C
TcSNP144	CL639Contig1	10	A	C
TcSNP674	TcSNP674	10	T	C
TcSNP917	CL702Contig1	10	T	C
TcSNP1392	TcSNP1392	10	T	C
TcSNP560	CL1Contig113	10	T	G
TcSNP723	CL282Contig2	10	T	G
TcSNP653	TcSNP653	10	A	G

Fidelity of SNP Genotyping System

Figure A-8 shows the allele calling for SNP CL1Contig135. It is a representative SNP genotyping result that shows the high resolution of genotypes homozygous for alternative alleles and the heterozygous individuals clustering in the center. This QC analysis demonstrates the validity and discrimination power of a typical SNP marker used in this study.



SNP02 : CL1Contig135, Call Rate: 100.00%, Auto Confidence: 99.98

Chip Run Name: 1681027033_28JULIO16

Figure A-8.—Allele calling for SNP CL1Contig135.

Table A2.—Descriptive Parameters for 92 SNPs Evaluated in 295 Cacao Trees.

Marker ID	MAF	Heterozygosity	PIC
TcSNP524	0.503	0.503	0.375
CL1Contig113	0.510	0.620	0.375
TcSNP11	0.514	0.427	0.375
CL695Contig1	0.531	0.562	0.374
TcSNP413	0.534	0.645	0.374
TcSNP497	0.538	0.484	0.374
CL132Contig1	0.541	0.403	0.373
CL527Contig1	0.542	0.631	0.373
CL456Contig1	0.544	0.668	0.373
TcSNP606	0.544	0.627	0.373
TcSNP269	0.553	0.624	0.372
CL918Contig1	0.563	0.671	0.371
TcSNP122	0.576	0.447	0.369
CL581Contig1	0.577	0.622	0.369
CL702Contig1	0.578	0.403	0.369
CL588Contig1	0.578	0.641	0.369
CL639Contig1	0.588	0.607	0.367
CL858Contig1	0.594	0.587	0.366
TcSNP563	0.594	0.620	0.366
TcSNP561	0.597	0.346	0.365
TcSNP389	0.603	0.366	0.364
TcSNP205	0.611	0.594	0.362
TcSNP427	0.615	0.510	0.361
CL3696Contig1	0.621	0.594	0.360
CL3336Contig1	0.622	0.437	0.360
CL318Contig1	0.624	0.542	0.359
CL4Contig14	0.628	0.378	0.358
CL235Contig1	0.629	0.566	0.358
TcSNP418	0.629	0.573	0.358
CL1Contig135	0.631	0.527	0.357
CL359Contig1	0.633	0.556	0.357
TcSNP510	0.639	0.544	0.355
CL77Contig2	0.642	0.444	0.354
CL2205Contig1	0.642	0.383	0.354
TcSNP1439	0.647	0.525	0.353
CL1002Contig1	0.647	0.522	0.352
TcSNP1126	0.649	0.525	0.352
TcSNP944	0.650	0.551	0.352
TcSNP653	0.651	0.260	0.351
CL1600Contig1	0.656	0.471	0.350
TcSNP1175	0.658	0.556	0.349
TcSNP1136	0.659	0.363	0.348
TcSNP1159_2	0.660	0.599	0.348
TcSNP521	0.661	0.441	0.348
CL171Contig2	0.661	0.556	0.348
TcSNP632	0.663	0.580	0.347

Marker ID	MAF	Heterozygosity	PIC
CL1Contig128	0.663	0.302	0.347
TcSNP1194	0.666	0.526	0.346
TcSNP731_2	0.674	0.526	0.343
CL1030Contig1	0.681	0.522	0.340
TcSNP19	0.686	0.471	0.338
CL282Contig2	0.688	0.332	0.337
CL1Contig277	0.698	0.481	0.333
TcSNP709	0.699	0.473	0.332
TcSNP751	0.702	0.529	0.331
TcSNP547	0.703	0.369	0.330
TcSNP996	0.708	0.298	0.328
CL317Contig1	0.709	0.398	0.327
TcSNP915	0.710	0.427	0.327
TcSNP1108	0.711	0.515	0.326
TcSNP316	0.729	0.461	0.317
TcSNP17	0.731	0.458	0.316
TcSNP395	0.751	0.451	0.304
TcSNP588	0.751	0.451	0.304
TcSNP595	0.757	0.439	0.300
TcSNP674	0.759	0.427	0.299
TcSNP1034	0.776	0.415	0.288
CL552Contig2	0.781	0.376	0.283
TcSNP42	0.783	0.380	0.282
TcSNP689	0.788	0.383	0.278
TcSNP172	0.799	0.293	0.269
CL139Contig1	0.818	0.282	0.253
CL1Contig69	0.825	0.302	0.247
TcSNP791	0.831	0.244	0.242
CL1086Contig1	0.853	0.254	0.220
CL745Contig1	0.861	0.217	0.211
CL209Contig1	0.861	0.231	0.211
CL646Contig2	0.875	0.197	0.195
CL8Contig4	0.890	0.173	0.177
TcSNP1096	0.892	0.188	0.174
CL2987Contig1	0.898	0.184	0.167
TcSNP1069	0.903	0.159	0.159
TcSNP28	0.907	0.166	0.155
TcSNP1383	0.908	0.163	0.153
TcSNP1392	0.908	0.156	0.152
CL1312Contig1	0.910	0.112	0.151
TcSNP277	0.922	0.143	0.134
TcSNP160	0.926	0.142	0.128
TcSNP437	0.927	0.132	0.126
TcSNP894	0.937	0.113	0.111
TcSNP1149	0.939	0.115	0.108
CL276Contig1	0.941	0.105	0.105
Average	**0.702**	**0.419**	**0.306**

Table A-3 shows the percentage of heterozygosity of the 183 samples from the SNSM and 4 internal controls. Pairwise multi-locus matching was used to cluster samples into groups based on shared genetic information (Identity Group IG).

Table A-3.—Heterozygosity Values and Identity Group Assignment.

USDA ID	Origin	IG	%H
C1Cr40	Control1		0.0
C2ICS1	Control2	IGD	31.5
C3SCA6	Control3		21.7
C4ICS8	Control4		17.4
CfP0174	SNSM		13.0
CfP0043	SNSM		14.1
CfP0137	SNSM		16.3
CfP0152	SNSM		16.3
CfP0140	SNSM		17.4
CfP0175	SNSM		18.5
CfP0120	SNSM		20.7
CfP0151	SNSM		20.7
CfP0157	SNSM		21.7
CfP0145	SNSM		22.8
CfP0150	SNSM		22.8
CfP0141	SNSM		23.9
CfP0148	SNSM		23.9
CfP0138	SNSM		25.0
CfP0132	SNSM		27.2
CfP0172	SNSM		27.2
CfP0034	SNSM		28.3
CfP0095	SNSM		28.3
CfP0096	SNSM		28.3
CfP0139	SNSM		28.3
CfP0161	SNSM		28.3
CfP0101	SNSM		30.4
CfP0149	SNSM		30.4
CfP0179	SNSM		30.4
CfP0014	SNSM	IGD	31.5
CfP0016	SNSM	IGD	31.5
CfP0033	SNSM		31.5
CfP0047	SNSM	IGD	31.5
CfP0076	SNSM	IGD	31.5
CfP0124	SNSM		31.5
CfP0131	SNSM		31.5
CfP0159	SNSM		31.5
CfP0167	SNSM		31.5
CfP0025	SNSM		32.6
CfP0036	SNSM		32.6
CfP0049	SNSM		32.6
CfP0125	SNSM		32.6

USDA ID	Origin	IG	%H
CfP0127	SNSM		32.6
CfP0177	SNSM		32.6
CfP0090	SNSM	IGE	33.7
CfP0091	SNSM	IGE	33.7
CfP0144	SNSM		33.7
CfP0164	SNSM		33.7
CfP0037	SNSM		34.8
CfP0166	SNSM		34.8
CfP0173	SNSM		34.8
CfP0162	SNSM		35.9
CfP0035	SNSM		37.0
CfP0042	SNSM		37.0
CfP0052	SNSM		37.0
CfP0099	SNSM		37.0
CfP0116	SNSM		37.0
CfP0119	SNSM		37.0
CfP0122	SNSM		37.0
CfP0154	SNSM		37.0
CfP0005	SNSM		38.0
CfP0062	SNSM		38.0
CfP0117	SNSM		38.0
CfP0142	SNSM		38.0
CfP0004	SNSM	IGC	39.1
CfP0013	SNSM	IGC	39.1
CfP0039	SNSM		39.1
CfP0068	SNSM	IGC	39.1
CfP0069	SNSM	IGC	39.1
CfP0078	SNSM	IGC	39.1
CfP0136	SNSM		39.1
CfP0168	SNSM		39.1
CfP0171	SNSM	IGC	39.1
CfP0186	SNSM	IGC	39.1
CfP0187	SNSM	IGC	39.1
CfP0003	SNSM		40.2
CfP0017	SNSM		40.2
CfP0146	SNSM		40.2
CfP0163	SNSM		40.2
CfP0169	SNSM		40.2
CfP0009	SNSM		41.3
CfP0134	SNSM		41.3
CfP0006	SNSM		42.4
CfP0015	SNSM		42.4
CfP0029	SNSM	IGP	42.4
CfP0041	SNSM	IGP	42.4
CfP0048	SNSM		42.4
CfP0103	SNSM		42.4
CfP0160	SNSM		42.4

USDA ID	Origin	IG	%H
CfP0038	SNSM		43.5
CfP0050	SNSM		43.5
CfP0051	SNSM		43.5
CfP0147	SNSM		43.5
CfP0153	SNSM		43.5
CfP0165	SNSM		43.5
CfP0129	SNSM		44.6
CfP0133	SNSM		44.6
CfP0032	SNSM		45.7
CfP0054	SNSM		45.7
CfP0106	SNSM		45.7
CfP0135	SNSM		46.7
CfP0028	SNSM		47.8
CfP0102	SNSM		47.8
CfP0118	SNSM		47.8
CfP0126	SNSM		47.8
CfP0130	SNSM		47.8
CfP0020	SNSM		48.9
CfP0081	SNSM	IGO	48.9
CfP0082	SNSM	IGO	48.9
CfP0108	SNSM		48.9
CfP0024	SNSM		50.0
CfP0040	SNSM		50.0
CfP0100	SNSM		50.0
CfP0111	SNSM		50.0
CfP0121	SNSM		50.0
CfP0031	SNSM		51.1
CfP0058	SNSM	IGJ	51.1
CfP0063	SNSM	IGJ	51.1
CfP0089	SNSM		51.1
CfP0027	SNSM		52.2
CfP0053	SNSM	IGM	52.2
CfP0056	SNSM	IGM	52.2
CfP0080	SNSM		52.2
CfP0109	SNSM	IGN	53.3
CfP0110	SNSM	IGN	53.3
CfP0112	SNSM	IGK	53.3
CfP0115	SNSM		53.3
CfP0123	SNSM	IGN	53.3
CfP0158	SNSM		53.3
CfP0180	SNSM	IGK	53.3
CfP0002	SNSM	IGL	54.3
CfP0018	SNSM	IGL	54.3
CfP0044	SNSM	IGL	54.3
CfP0074	SNSM	IGL	54.3
CfP0075	SNSM	IGL	54.3
CfP0079	SNSM	IGL	54.3

USDA ID	Origin	IG	%H
CfP0093	SNSM	IGL	54.3
CfP0097	SNSM	IGL	54.3
CfP0098	SNSM	IGL	54.3
CfP0104	SNSM	IGL	54.3
CfP0105	SNSM	IGL	54.3
CfP0113	SNSM	IGL	54.3
CfP0176	SNSM	IGL	54.3
CfP0083	SNSM	IGB	55.4
CfP0128	SNSM	IGB	55.4
CfP0086	SNSM		58.7
CfP0022	SNSM		59.8
CfP0065	SNSM		59.8
CfP0084	SNSM		59.8
CfP0092	SNSM		59.8
CfP0114	SNSM		59.8
CfP0001	SNSM		60.9
CfP0019	SNSM		60.9
CfP0030	SNSM		60.9
CfP0072	SNSM		60.9
CfP0085	SNSM		60.9
CfP0107	SNSM		60.9
CfP0007	SNSM	IGG	62.0
CfP0023	SNSM	IGG	62.0
CfP0046	SNSM	IGI	62.0
CfP0064	SNSM	IGI	62.0
CfP0066	SNSM	IGI	62.0
CfP0070	SNSM	IGI	62.0
CfP0073	SNSM	IGF	62.0
CfP0077	SNSM	IGF	62.0
CfP0087	SNSM	IGF	62.0
CfP0182	SNSM	IGF	62.0
CfP0008	SNSM	IGH	63.0
CfP0010	SNSM	IGH	63.0
CfP0026	SNSM	IGH	63.0
CfP0045	SNSM		63.0
CfP0055	SNSM	IGH	63.0
CfP0059	SNSM	IGH	63.0
CfP0060	SNSM	IGH	63.0
CfP0061	SNSM	IGH	63.0
CfP0088	SNSM	IGH	63.0
CfP0094	SNSM	IGH	63.0
CfP0156	SNSM	IGH	63.0
CfP0170	SNSM	IGH	63.0
CfP0178	SNSM		63.0
CfP0184	SNSM	IGH	63.0
CfP0021	SNSM		64.1
CfP0057	SNSM	IGA	75.0

USDA ID	Origin	IG	%H
CfP0067	SNSM	IGA	75.0
CfP0071	SNSM	IGA	75.0
CfP0181	SNSM	IGA	75.0
CfP0183	SNSM	IGA	75.0
CfP0185	SNSM	IGA	75.0