3-19-2015

Landscape Legacies of Sugarcane Monoculture at Betty's Hope Plantation, Antigua, West Indies

Suzanna M. Pratt
University of South Florida, spratt2@alumni.nd.edu

Landscape Legacies of Sugarcane Monoculture at

Betty's Hope Plantation, Antigua, West Indies

by

Suzanna M. Pratt

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Arts in Applied Anthropology (Archaeology track)
with a concentration in Heritage Studies
Department of Anthropology
College of Arts and Sciences
University of South Florida

Major Professor: E. Christian Wells, Ph.D.
Thomas J. Pluckhahn, Ph.D.
Robert H. Tykot, Ph.D.
Georgia L. Fox, Ph.D.

Date of Approval:
March 19, 2015

Keywords: historical archaeology, geoarchaeology, landscape change, Antigua, Caribbean colonialism

ACKNOWLEDGMENTS

This thesis would not have been possible without the support of my advisor, Dr. E. Christian Wells, and my committee members, Dr. Thomas J. Pluckhahn, Dr. Robert H. Tykot, and Dr. Georgia L. Fox. Much appreciation is given to Dr. Phil W. Gassman and Dr. Todd D. Campbell of Iowa State University for their invaluable assistance with the EPIC software. Special thanks are extended to Dr. Georgia L. Fox of California State University, Chico, Principal Investigator of the Betty's Hope project, and Dr. Reginald Murphy, Antigua's archaeologist and UNESCO Representative, for providing me with the opportunity to contribute to research at Betty's Hope.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Sugarcane cultivation has played a key role in the development of the Caribbean since the seventeenth century A.D. The Eastern Caribbean island of Antigua in the West Indies was almost exclusively dedicated to sugarcane monoculture from the mid-1600s until its independence from Britain in 1981. This research seeks to better understand the landscape legacies left by long-term sugarcane monoculture at the site of Betty's Hope Plantation in Antigua. This study creates a 400-year simulation of crop yields using the USDA's Erosion Productivity Impact Calculator (EPIC), and evaluates the simulated trajectory of landscape change using historical information about the plantation's agricultural yield and a geoarchaeological analysis of the regional landscape. Findings suggest that some parts of Betty's Hope have experienced degradation due to long-term sugarcane monoculture, but degradation in other parts of the region may be the result of the cessation of commercial agriculture in 1972, when human investment in the highly engineered landscape ended. If these results are representative of other parts of the island, then they suggest that current erosion and degradation experienced today cannot be attributed to intensive plantation agriculture alone, but rather are part of a complex mosaic of human-environmental interactions that includes abandonment of engineered landscapes.

CHAPTER ONE:
INTRODUCTION

1.1 Introduction

In considering human history, there "probably is no greater transformation than the introduction of agriculture" (Redman 1999:81). The intensity of landscape reshaping due to agricultural activities has depended upon a complex set of decisions related to labor input, resource productivity, and the nature of the landscape (Boserup 1965; Redman 1999:46). During the past three centuries, the landscapes of the Caribbean islands have been subject to intensive agriculture and dramatic landscape change. Sugarcane cultivation originated in South Asia centuries prior to the establishment of experimental plantations in the sugar islands off the coast of Africa and in Brazil in the early seventeenth century (Menard 2006:9). From the 1620s, when the first Caribbean sugar plantations began in Barbados, until the abolition of slavery in British territories in 1833, large-scale plantation sugarcane monoculture was present on many of the islands of the Caribbean (Watts 1990:232), shaping the social, political, and economic development of the islands and leaving a tangible legacy in the contemporary anthropogenic landscape.

The English colonized the island of Antigua in 1632, and early settlers survived by growing subsistence crops in a "state of perpetual crisis" (Pares 1950:15). Despite the slow start, the island has a long history of large-scale production and export of sugar products made possible by the labor of large numbers of enslaved Africans. The introduction of sugarcane cultivation dramatically transformed Antigua's landscape, increasing units of cultivation, acreage of sugarcane fields, and capital and labor investments (Sheridan 1960:127). Three centuries of continuous, intensive sugarcane monoculture have been linked to degradation of the Antiguan landscape, including through erosion, changes to the physical and chemical properties of soil, compaction, and decline in soil fertility (Abbott 1964:1; Campbell et al. 1992; Garside et al. 2001:16; Meyer et al. 1996; Ragatz 1928; Sheridan 1960:135; Ward 1978:198). However, the concept of landesque capital—"any investment in land with an anticipated life well beyond that of the present crop, or crop cycle" (Blaikie and Brookfield 1987:9)—challenges the idea that long-term cultivation is the main driver of landscape degradation. A geoarchaeological case study of the landscape legacy (integrating the concepts of niche construction, landesque capital, and path dependence) is needed to determine the combination of human and environmental factors contributing to current landscape degradation.

Betty's Hope Plantation, located on the island of Antigua in the West Indies, has a nearly 300-year history of sugarcane cultivation, and currently faces problems of land degradation, primarily in the form of soil erosion. A geoarchaeological study at Betty's Hope evaluates the "abandoning the garden" hypothesis, which suggests that the abandonment of an "intensive, anthropomorphized landscape dependent on labor for stability" contributes directly to environmental degradation (Fisher 2005:89). There are three main explanations for modern degradation: 1) landscape degradation is predominantly anthropogenic; humans overused the land until it failed; 2) landscape degradation is the product of natural environmental processes, such as climate-induced flooding or drought; or 3) degradation is linked to both human and natural factors, such as degradation caused by the abandonment of an anthropogenic landscape susceptible to natural processes of degradation without human maintenance. This research seeks to determine the combination of natural and human forces that have shaped the course of landscape change in Antigua over time, thereby unraveling the legacy of the sugar industry and the causes of contemporary landscape degradation.

1.2 Background

The United Nations defines land degradation as the "reduction or loss of the biological or economic productivity of rainfed or irrigated land used for crops, or range, pasture, forest or woodlands, which results from land uses or human actions, or combinations thereof" (United Nations 2005:22). Any anthropogenic environmental change that results in a perceived loss of resources can be considered land degradation, including soil erosion, habitat loss, biodiversity loss, soil nutrient depletion, aridification, and salinization (Fisher 2005). The process of land degradation is often cited as a contributing factor in the decline or "collapse" of civilizations (Fisher 2005), wherein the continuous human modification of the landscape reaches a critical point at which the human population can no longer be supported. With environmental resources depleted, the system collapses, ostensibly causing population decline and social, political, and economic reorganization.

Currently, the nation of Antigua and Barbuda faces issues of land degradation. In early May 2004, the United Nations Technical Advisory Committee (TAC) conducted a rapid field appraisal of land degradation in Antigua. The TAC concluded that Antigua is experiencing "serious problems with land degradation in the more vulnerable areas of steep and shallow soils" (United Nations 2005:42). Although the United Nations identified the major cause of this degradation as large numbers of destructive and unmanaged livestock (United Nations 2005:49), sugarcane monocropping has long been thought to have caused widespread environmental degradation in sugar islands of the West Indies (Abbott 1964:1; Campbell et al. 1992; Garside et al. 2001:16; Meyer et al. 1996; Ragatz 1928; Sheridan 1960:135; Ward 1978:198; Watts 1990).

Betty's Hope is one of the largest plantations in the West Indies. Established in 1651 and operating until 1944, it is among the oldest and continuously operating plantations on Antigua (Fox 2013:5). While initially owned by Christopher Keynell, Betty's Hope passed into the ownership of the Codrington family in 1674 and remained owned by this family until 1944 (Fox 2013:5), and agriculture persisted on plantation lands until the sugar industry folded in 1972 (Weaver 1988:321). The Codrington family maintained detailed records (the Codrington Papers) during the plantation's operation. The primary documents are housed in the National Archives of Antigua and Barbuda, and microfilm copies are available from various repositories including the British Museum Library and Simon Fraser University. The Codrington Papers comprise correspondence, lists, and commentary on the daily operations of Betty's Hope and other Codrington enterprises. For Betty's Hope, the Codrington Papers document the plantation's productivity and general operations (Fox 2013:5). Given the recent and dramatic changes in land use in Antigua and the land degradation problems of the present, Betty's Hope Plantation provides a unique case study for assessing the effects of long-term, single-crop cultivation followed by a rapid change in land use. This study provides a contribution to the dialogue on sustainability and demonstrates the advantage of the diachronic perspective uniquely inherent to archaeology. The continuous agricultural activity and labor investment at the site spanning 300 years and the archival evidence provide two lines of evidence for assessing the course of land degradation in Antigua.

1.3 Summary of Theoretical Approach

This research draws upon concepts from the natural and social sciences in order to understand how interlinked natural and human factors affect the landscape over time. By understanding how anthropogenic and natural forces have influenced each other in the past, this study seeks to determine the course of landscape change in Antigua and identify the causes of modern land degradation. Landscapes are the result of interplay between "historically determined structures and contingent processes" (McGlade 2003:461) and must be understood as the product of long-term impacts of the human-environmental system. The concepts of landscape legacy, niche construction, landesque capital, and path dependence provide a foundation from which to understand the complex relationship between humans and the environment.

The concept of landscape legacy—the detectable traces of past anthropogenic environmental alteration visible in contemporary landscapes—provides a way of understanding the impact of three centuries of intensive monoculture on the physical landscape of a historical sugarcane plantation in Antigua (Lewis et al. 2006:73). To bring resolution to the landscape legacy of the sugarcane industry, I draw upon the concepts of cultural soilscapes and soilscape legacies, which address the effects of past human-environmental interactions that are detectable in analyses of archaeological soils (Wells 2006:126; Wells et al. 2013). The understanding of human-environmental interactions can be traced to niche construction theory, which addresses the way organisms shape—and are shaped by—their environments (Kendal et al. 2011; Odling-Smee et al. 1996:641, 2013:5). The same theory can be applied to human settlements: the development of agriculture and rise of large, permanent settlements—a form of cultural niche construction—fundamentally altered the global landscape and contributed to subsequent niche constructions to adapt to changing conditions (Kendal et al. 2011:789; Laland and Brown

2010:100; Laland and O'Brien 2010). In the social sciences, the concept of landesque capital describes anthropogenic alterations to the environment that increase crop yields and landscape health (Blaikie and Brookfield 1987:9; Clark and Tsai 2009; Erickson and Walker 2009; Morrison 2014; Widgren 2007). The investment of landesque capital enables more efficient land use and maximizes resource extraction. When pressures such as resource strain or land degradation arise, humans respond to the new situation by investing in new technologies and agricultural practices to ensure the continued success of their agricultural endeavors. Path dependence then provides an explanation for how landscape change is contingent upon decisions made in the past that then constrain future choices (Chase and Chase 2014). The environment and human settlements are mutually influential; changes to one create a response in the other, and the landscape bears the legacy of this continuous coevolution.

This research tests the hypothesis that investments of landesque capital prevent land degradation and contribute to increased productivity over time. Traditional views of agriculture suggest that over time, production either remains constant or declines and erosion increases. In contrast, landscapes into which investments of landesque capital have been made experience constant or declining rates of degradation and constant or increasing productivity over time. By examining the landscape legacy of Betty's Hope Plantation as a case study, this research sheds light on how particular human actions in the past both affected and continue to affect the landscape today.

1.4 Organization of the Thesis

This research was undertaken in order to serve as a pilot study for the viability of assessing long-term landscape change using a combination of geoarchaeological and historical data. Soil samples were removed from the landscape of Betty's Hope in June 2014 by Dr. E. Christian Wells of the University of South Florida, with the assistance of students participating in the Betty's Hope Archaeological Field School, directed by Dr. Georgia Fox of California State University, Chico. Geochemical analyses were conducted from September to December 2014 in the Laboratory for Anthropogenic Soils Research at the University of South Florida. During this period, I also created a simulation of sugarcane yields over time using the USDA's Erosion Productivity Impact Calculator (EPIC) and reviewed relevant historical documents to determine historical sugarcane yields at Betty's Hope. This research contributes to both plantation and historical archaeology in the Caribbean by providing a perspective of the ways in which past human activity altered the landscape. While much is known about the historical Caribbean sugar industry and intensive plantation agricultural system, few studies have examined the impacts of these developments on the local landscape and addressed the present-day consequences environmental of such anthropogenic changes. This research contributes a historical geoarchaeological case study to Caribbean plantation archaeology and provides a preliminary discussion of the ways in which an Antiguan plantation affected the local landscape over time.

This thesis is organized into eight chapters. Chapter 2 reviews the various theoretical approaches employed to understand human-environmental dynamics and the ways in which humans modify and are modified by their environments. I explore the concepts of niche construction and landesque capital and discuss ways in which these can be combined with concepts of path dependency and landscape and cultural soilscape legacies in archaeological approaches to studying human-environmental interactions and anthropogenic landscape change over time.

Chapter 3 reviews the cultural-historical development of the sugarcane industry in the Caribbean, especially concerning Antigua. I review the early colonial history of the West Indies and discuss the rise of large-scale plantation sugarcane monoculture in the region. I then explore the relevant literature of environmental impacts of sugarcane monoculture and the landesque capital strategies employed by Caribbean planters. The chapter then focuses on the history of the sugarcane industry in Antigua in particular in order to contextualize the site of Betty's Hope Plantation. The chapter concludes with an overview of the current land degradation problems in Antigua.

Chapter 4 summarizes the methods used to collect and analyze data for this research. I first discuss the Erosion Productivity Impact Calculator (EPIC) simulation and discuss how I input relevant climate, soil, and agricultural data to model 400 years of sugarcane monoculture in Antigua. I then discuss the four historical documents from which I extrapolated information about historical sugarcane yields and the various unit conversions involved. I discuss the field methods for collecting soil samples at the site of Betty's Hope and the various laboratory methods employed in the subsequent analyses.

Chapter 5 reports the results of the EPIC simulation and the annual sugar yields extrapolated from historical records. This chapter presents a comparison of these two lines of data and a discussion of major historical events during the last three centuries that may have affected sugarcane yields. The chapter concludes with a decade-by-decade discussion of historical sugarcane yields and relevant political, economic, and climatic events.

Chapter 6 reports the results of the geoarchaeological analyses conducted on soil samples from 20 soil profiles near the site of Betty's Hope. The chapter opens with expectation for a normal soil in Antigua, in order to provide a baseline of what results are expected from a soil profile showing no anthropogenic inputs or degradation. I then describe each of the 20 soil profiles and report unexpected deviations from the normal profile in each.

Chapter 7 synthesizes the results of the EPIC simulation, the examination of historical records, and the geoarchaeological analyses. I first summarize the relevant findings from the comparison of the simulated and historical sugarcane yields and the geoarchaeological analyses. I then discuss the legacy of sugarcane in the landscape of Betty's Hope Plantation, as informed by the results of the aforementioned analyses.

Chapter 8 summarizes the major finding of this work and suggests avenues for future research in determining a more detailed landscape legacy of the sugarcane industry in the West Indies. I discuss how this study fits into the broader realm archaeological studies focused on human-environmental dynamics and ways in which future research of this type will be beneficial in determining the long- and short-term causes of contemporary landscape degradation problems in Antigua and elsewhere in the Caribbean.

CHAPTER TWO:
THEORETICAL APPROACHES TO LANDSCAPE LEGACY

2.1 Introduction

It is well established that humans modify the world around them such that the landscape retains evidence of their activities (Crumley and Marquardt 1990; Gonzales Scollard 2008:54). This research draws upon the concept of landscape legacy—the detectable traces of past anthropogenic environmental alteration visible in contemporary landscapes—to understand the impact of three centuries of intensive monoculture on the physical landscape of a historical sugarcane plantation in Antigua. Numerous other theories and concepts contribute to the understanding of how humans have interacted with the environment over time in an agricultural context. In this chapter, I define landscape legacy and the role of cultural soilscape legacies in bringing past human activity into visibility through archaeological research. I address niche construction theory as a theoretical foundation for understanding the relationship between humans and their environments. I then explore the concept of landesque capital by tracing the development of theories related to the relationship between human populations and environmental resources, and by demonstrating how landesque capital provides a way of thinking about how human investments create heavily engineered landscapes. I also discuss path dependence as an explanatory theory for how certain human decisions about landscapes constrain and enable future environmental modification. The study of human-environmental interactions encourages transdisciplinary research into geographically diverse, long-term trends. Multiple archaeological case studies highlight the value of a landesque capital approach to understanding landscape legacies and represent the broader importance of archaeological perspectives in environmental and landscape research.

The concept of landscape legacy suggests that the traces of past human actions are detectable in the examination of the contemporary landscape. Landscape legacy derives from the related concepts of cultural soilscapes and soilscape legacy. The concept of cultural soilscape legacies elucidates the subtle effects of anthropogenic landscape elements preserved in soils. Further, landscape legacy is informed and extended by concepts of niche construction theory, landesque capital, and path dependence. Niche construction theory serves as the theoretical foundation for understanding how organisms shape and are shaped by their environments, therefore determining their future development and evolutionary pressures. This concept can be extended to understanding how humans and the environment operate in tandem to enable and constrain future changes in both. While the evolutionary implications of potential niche-constructing activities in Antigua are out of the scope of this research, the understanding of how humans interact with the environment is fundamental to understanding landscape legacies. Both Malthus's and Boserup's theories of humans and the environment, especially in regard to agriculture, serve as precursors for the concept of landesque capital, which describes enduring anthropogenic landscape elements that increase the health or productivity of the land. Very generally, investments of landesque capital can be understood as a form of niche constructions as humans alter the environment, and, in doing so, create new situations to which they must adapt in the future. The lasting effects of landesque capital investments contribute to the creation of a highly engineering landscape dependent on human inputs for stability. The concept of path dependence contributes to the understanding of the ways in which human actions limit possible future actions. Past land use decisions and investments of landesque capital fundamentally alter the landscape, thus constraining the options for future actions related to agriculture and land use. This research investigates how continuous investments of landesque capital by a path dependent society changed the landscape of Betty's Hope Plantation in Antigua. Through the examination of cultural soilscapes, the landscape legacy of sugarcane monoculture can be elucidated, unraveling the complexity of past human and environmental interactions.

2.2 Landscape Legacies

Landscape archaeology is a development of regional-scale archaeological research focused on human-environment interactions, an area of research that has long been important in archaeology (Fisher and Thurston 1999; Marquardt and Crumley 1987; Trigger 1989:279-303). A 'landscape' is a broad concept that can be defined as a unit of human occupation. Landscapes are composed of humans, the anthropogenic ecosystem, and the way landscapes are conceptualized, experienced, and symbolized. Landscape archaeology is concerned with how human social, political, and economic systems are caused by and subsequently interact with intentional strategies of landscape manipulation (Fisher and Thurston 1999:630).

In Antigua and other places where land degradation is a growing problem, the understanding of landscape change in the past yields information potentially applicable to creating long-term land management solutions. Landscapes are the result of historical path dependence; both deliberate and unintentional human actions frequently determine subsequent historical pathways (Arthur 1988; McGlade 2003:461). Landscapes can be envisioned as nonlinear systems whose evolution is determined by abrupt transitions, the history of which can be detected archaeologically (McGlade 2003:461). The archaeological record preserves "hundreds of situations in which societies were able to develop long-term sustainable relationships with their environments, and thousands of situations in which the relationships were short-lived and mutually destructive" (Redman 1999:4). The landscape is a palimpsest of natural and human modifications over time; the current state of the landscape is the product of the coevolution of the social and natural dynamics within the environment (Fisher et al. 2009:11; van der Leeuw 2009:43). Archaeological approaches to examining landscapes over time combine the natural and social sciences in analyses that account for multiple factors in landscape change with a long-term perspective.

Acceleration of anthropogenic environmental and climatic change over the last 300 years has been largely attributed to industrialization, but such changes are often associated with a longer history (Kirch 2005). Since the development of agricultural societies and the associated population expansion during the early Holocene, humans have irreversibly affected the natural landscape (Kirch 2005). Early narratives of the human-environmental past suggest that pre-agricultural landscapes were pristine and "primitive" societies were "noble savages" who existed as stewards of the environment (Denevan 1992; Kirch 2005). The noble savage myth is deeply rooted in Western culture, but it is now widely accepted as false (Kirch 2005:410). As Denevan (2005) and others argue, the concept of the pre-Columbian pristine American environment is a continuation of the myth of the noble savage, but in reality, the landscape of the Americas in 1492 was the product of millennia of human impacts (Denevan 1992; Kirch 2005:411). Despite the dismissal of the noble savage myth, researchers (who are aware of the impact of prehistoric cultures on the environment) generally suggest that current environmental changes and crises are phenomena of the last three centuries, launched by the industrial revolution (Kirch 2005). Agricultural landscapes are built environments, representing large- and small-scale accumulations of anthropogenic manipulations over time (Erickson and Walker 2009:233). In all cases, nature has been transformed in the process of production through labor, society, and history, resulting in land improvement or degradation over time (Erickson and Walker 2000:233, Kirch 2005; Redman 1999, 2005). Analysis of the slower-moving processes of change enables understanding of the evolutionary history of landscape change before the industrial revolution. An archaeological perspective in environmental research is widely acknowledged as valuable for understanding long-term human-environmental dynamics (Fisher and Feinman 2005; Hill 2004; Kirch 2005; van der Leeuw and Redman 2002).

In the 1950s to 1960s, archaeology borrowed heavily from the natural sciences and research explored the relationship between human populations and their environments (Steward 1955; Flannery 1968). These studies gave rise to environmental archaeology, a field that often relies on proxy data to represent former human-environmental systems and landscapes (Kirch 2005:414). Archaeological research into landscapes (rather than individual sites) has resulted in the borrowing of theories and concept from other social and natural sciences in order to study landscapes as a whole (Wells 2006:125). The physical remains of past human activity often extend over entire landscapes, hence environmental archaeology approaches are especially relevant for studying agrarian landscapes, where past periods of cultivation have left a record of landscape manipulation in the form of soil modifications, abandoned canals, field systems, terrace complexes, and irrigation networks, etc. (Kirch 2005). The study of ancient agrarian landscapes has enabled recreation of the long-term trajectories of past agricultural systems (Kirch 2005:416). The field of geoarchaeology, which borrows methods from geology, geomorphology, and pedology, has also contributed new ways of studying past human-environmental dynamics. Geoarchaeology is concerned with the sedimentary and depositional contexts of archaeological sites and anthropogenic landscapes as a whole (Kirch 2005:425).

Geoarchaeological studies examine the impact of agricultural systems on soils and explore how soils have sustained agriculture over long periods (Kirch 2005:426). Soil modification is often overlooked as a form of landesque capital, but anthropogenic soil alteration can create enduring "beneficial changes that yield capital for use by future generations" (Brookfield 2001:185).

Recognizing the value of studies that shed light on the past with implication for the present, Fisher and Feinman (2005) advocate a greater incorporation of archaeology in the study of contemporary environmental crises. Consideration of past anthropogenic environmental changes in specific landscapes can help us understand the forces affecting the present environment and current human-environmental relationships. The long-term perspectives of human-environmental interactions are necessary to understand and evaluate contemporary environmental debates, interpretations, and policies.

Many similar and overlapping theoretical approaches have been employed for researching landscape change over time (including historical ecology, agroecology, political ecology, resilience theory, and complexity theory). Fisher and Feinman suggest uniting all these theories under a single paradigm from which to base future studies. Research of landscape change and human-environmental interactions is an increasingly important field, necessitating cohesion and articulation of general theoretical assumptions to unite and guide subsequent research. They outline three fundamental concepts for visualizing human-environmental interactions over time: 1) culture change and the environment are connected and the relationship is constantly renegotiated at many temporal and spatial scales; 2) the landscape is a palimpsest and current human-environment choices are always influenced by previous landscape changes; and 3) landscapes are dynamic entities composed of multiple areas experiencing distinct trajectories of change. Fisher and Feinman argue that these three concepts are the base assumptions serve as the starting point for archaeological research into human-environmental dynamics. With clearly articulated assumptions, further studies can produce data and analyses relevant to understanding and solving current environmental issues, including those involving landscape degradation.

Wells and colleagues introduce the notions of cultural soilscapes and soilscape legacies as analytical and methodological concepts for investigating landscape legacies and the impact of humans on the environment in the past. Wells defines *cultural soilscapes* as areas of the Earth's surface that are "the result of spatially and temporally variable geomorphic, pedogenic and cultural processes" (Wells 2006:125). Archaeological studies of cultural soilscapes emphasize the so-called *soil memory,* meaning the reflection in the soil of physical, biological and chemical effects of different human activities, including modification to soil structure, soil pH, aeration and water drainage, nutrient cycling, soil temperature changes, and the addition of anthropogenic materials (Wells 2006:126). The inclusion of culture, broadly defined as "learned and shared knowledge and beliefs that simultaneously produce, and are produced, by human behavior" (Wells 2006:125), to soil research adds the human element, suggesting that soils are not formed solely by natural processes. Cultural soilscapes reflect the human-environmental relationship, revealing the effects of both human and natural processes over time. As Brookfield (2001) points out, soil modification is often overlooked as a form of landesque capital. Cultural soilscapes provide a record of past natural and human changes, chronicling the construction of a cultural niche. The concept cultural soilscapes helps to understand how humans modify the physical environment at the landscape scale and how the physical environment shapes human behavior (Wells 2006:126).

Wells and colleagues (2013) apply the concept of soilscape legacies—the "long-term socioecological consequences of human interactions" with "soil bodies that have been physically and chemically altered as a direct result of human behavior (Wells et al. 2013:23-24)—in the Palmarejo region of Honduras's Naco Valley. The study incorporates archaeological perspectives and the human factors into the natural sciences, elucidating the combination of slow-moving natural and human processes that have shaped the landscape in the past. Using archaeological, geoarchaeological, and pedological approaches, Wells and colleagues recreate the soilscape legacy in Honduras. Using geomorphic mapping, excavation, and interpretation of stratigraphy, and shallow and deep auger probing, their research reveals the changes to the soilscape over time, revealing the trajectory of landscape change (Wells et al. 2013:34). They conclude the Naco Valley region experienced periods of erosion, deposition, and landform stability in the late Holocene (Wells et al. 2013:48). These findings are relevant for environmental modeling and contemporary conservation planning to link the present environmental issues and agricultural practices to the past human-environmental dynamics (Wells et al. 2013:49).

Research at Betty's Hope draws upon the related concepts of cultural soilscapes and soilscape legacies as a way to characterize the landscape legacy of the sugarcane industry visible today. The analysis of archaeological soils provides a source of data that can reveal past anthropogenic and natural change over time. At Betty's Hope, the rise and fall of intensive sugarcane monoculture can be detected through the analysis of soils at the plantation site, shedding light on the particular landscape legacy of the Caribbean sugarcane industry. Landscape legacy can be further understood through concepts of niche construction theory, landesque capital, and path dependence.

2.3 Niche Construction Theory

A "greater appreciation of the plantation's impact on the landscape" (Fox 2014:36) is emerging from current research at Betty's Hope as understanding of how agricultural production and associated human activities create both intended and unintended changes to the landscape. Three centuries of intensive monoculture at Betty's Hope use created a number of new selective pressures; Fox (2014) suggests niche construction theory provides a theoretical foundation for understanding how human actions affect the stability and connectivity of an ecosystem, sometimes creating cultural selection pressures that are stronger than natural ones (Fox 2014:36). The culturally derived selective pressures are exacerbated when major land use decisions come into play, such as the dedication to growing a single crop (Fox 2014:37). Antigua's transformation into a dominant sugar island dramatically changed the landscape as notions of European agricultural productivity were transplanted into a new, Caribbean island ecosystem (Fox 2014:37; Martin 1785; Meltzer 2003:223-224). The construction of large sugar plantations, with processing facilities, living spaces, water systems, livestock, and vast field of sugarcane altered the natural landscape, creating the potential for negative impacts on the island's fragile ecosystem and a host of new selection pressures (Fox 2014:37).

Niche construction theory (NCT), as the name implies, draws upon the concept of niche construction, introduced to evolutionary biology by Richard Lewontin (1982) in the 1980s, referring to the modification "of both biotic and abiotic components in environments via trophic interactions and the informed physical 'work' of organisms" (Odling-Smee et al. 2013:5). NCT emphasizes the ability of organisms to modify their environment and thereby influence their own and other species' evolution (Kendal et al. 2011:785). The theory is concerned with the change to selection pressures in the environment caused by the organism, not necessarily by the modification of the environment. According to NCT "organisms, through their metabolism, their activities, and their choices, define, partly create, and partly destroy their own niches" (Odling-Smee et al. 1996:641). If each generation of organisms changes the environment in some way because each organism inherits the genes that cause it to do so, then earlier generations of organisms can modify the scope of natural selection for future generations through repetitive niche construction.

Niche construction theory provides theoretical insights to integrate ecosystem ecology and evolutionary theory by enhancing understanding of how ecosystems change over time (Odling-Smee et al. 1996). Niche construction is related to evolution in that environments change species through selection, and species alter their environment through niche construction. In ecology, niche construction theory is supported by a body of conceptual and formal theory exploring the potential of niche construction for evolutionary biology (Odling-Smee 2013:5). Niche construction offers three major contributions to evolution. Niche construction can influence spatial and temporal patterns of selection processes on the organisms that construct the niche; niche construction can increase the number of individuals within a species; and through the process of modifying their own niches, organisms can change the niches of other species in the ecosystem (Odling-Smee et al. 2013:5-6).

NCT accounts for the role of human development and cultural processes in human evolution through the modification and ecological inheritance of selective environments. While this research is not concerned with testing the evolutionary implications of anthropogenic landscape change, NCT provides a multifaceted approach to analyzing the cumulative impact of human activities on a particular landscape over time (Fox 2014:34). Fox (2014:34) and Laland-Brown (2010:315) suggest that NCT is useful in the realm of archaeology because encourages the incorporation of human activities (in addition to general climatic and environmental variables) in driving environmental change and human evolution. NCT considers both environmental and human factors and the interaction between the two in determining landscape change. Humans differ from other organisms in that they can respond to previous environmental alterations not only through genetic evolution, but also through cultural niche construction (Laland and Brown 2010:100).

Niche construction theory provides an understanding of how organisms both change and are changed by the environments in which they live. The theory provides a framework for thinking about landscape change as a synergistic human-environmental process in which humans alter the environment and then must respond to the new situation created by these alterations. As agriculture developed and populations grew, new selection pressures arose as a result of human actions, initiating the need for human populations to adapt through the creation of a new cultural niche to compensate for the new conditions. The concept of landesque capital emerges in discussions of niche construction as a way to characterize the human alterations to the environment in response to population and resource pressures, dramatically transforming the natural landscape.

2.4 Landesque Capital

The term "landesque capital" first emerged in Amartya Sen's (1959) discussion of choice in agricultural techniques in underdeveloped countries. Assuming agriculture maximizes output without sacrificing future growth and that land is an important factor of production, Sen models how land and labor relate to agricultural technologies in developing countries (Sen 1959:280). He distinguishes between two kinds of capital: laboresque capital, which replaces labor (e.g., machinery), and landesque capital, which replaces land (e.g., fertilizer). Despite Sen's work, the concept of landesque capital is most often attributed to Piers Blaikie and Harold Brookfield (1987), who used it to describe the durable consequences of past human action. Blaikie and Brookfield (1987:9) define landesque capital as "any investment in land with an anticipated life well beyond that of the present crop, or crop cycle. In his later discussion of intensification and innovation in agriculture over long periods, Brookfield (1984:16) describes landesque capital as the results of human innovation: "some innovations create landesque capital, which then persists with only a need for maintenance; other innovations require continued application and leave no lasting mark on the land."

Landesque capital can encompass a number of investments into the landscape to increase agricultural yield: fertilization, controlled burning, irrigation systems, canals, dams, reservoirs, terraces, etc. Landesque capital implies beneficial impacts upon the landscape to create more productive and/or sustainable agriculture in the future. While the concept of landesque capital does not imply that all anthropogenic landscape change is beneficial, it provides a name for changes to the landscape that do not affect the environment in a negative way. However, as Eric Clark and Huei-Min Tsai (2009:151) point out, we should avoid hard and fast categorization of landscape alterations as landesque capital or not. Landesque capital includes only investment in the land that creates "enduring beneficial change through improving the capability of land" (Clark and Tsai 2009:151). This excludes enduring investments in the land that do not result in beneficial changes, whether intended to do so or not. For example, the construction of an irrigation network is generally intended to benefit multiple crop cycles by providing a constant water supply, but over-irrigation with saline water could eventually cause salinization of the land to the point where cultivation is impossible. So long as the irrigation system improves the productivity of the land, it can be considered landesque capital, but if the intended beneficial changes do not endure, it cannot be considered landesque capital.

Although the widespread use of the term “landesque capital” took hold in the 1980s, similar concepts emerged in earlier theories about humans and the environment. Studies of the effects of agriculture on the environment trace back to the now-mostly-obsolete Malthusian theory of population growth and environmental carrying capacity and to Ester Boserup’s theory of agricultural intensification.

In an essay addressing population growth, Thomas Malthus (1798) observed that population growth rates increased when food resources were plentiful and decreased when resources were scarce. He suggested two mechanisms that kept population within the limits of the food resources: positive checks that increase the death rate (e.g. famine, disease, and war), and preventive checks that reduce the birth rate (e.g. birth control, abortion, and delayed marriage) (Malthus 1798). Malthus assumed that a particular environment has a fixed carrying capacity: a finite amount of resources limits the number of people who can be supported by that environment. Malthusian theory suggests that demographic change is an adaptive factor constrained by the resources available (Boserup 1976; Malthus 1798). When a population increases and food resources are strained, the population checks itself so that it does not exceed the environmental carrying capacity.

One of Malthus’s many critics is Boserup (1976), who, in her discussion of agricultural intensification, criticized Malthus for being narrow and unrealistic. Malthusian theory focuses only on the technology of food production, overlooking the effect of nonagricultural technological change on the environment (Boserup 1976:21). Boserup also criticizes Malthus for ignoring the effect of demographic change on the environment and technology (Boserup

1976:21). She suggests that population growth has two possible effects on food production. One is the Malthusian effect, in which an increasing population causes a decrease in crop yield per person. The second possibility is Boserup's alternative to Malthus, in which increasing population provides the motivation to develop more intensive agricultural practices (Boserup 1983:384). Technology and agricultural intensification can overcome the population limits predicted by Malthusian theory. Rather than a particular environment having a fixed carrying capacity, technological innovations and increased labor investment can overcome the natural limits of the environment and allow the same resources to support a larger population (Boserup 1983).

Boserup's alternative parallels Laland and Brown's (2010) suggestion that cultural niche construction can overcome natural selection pressures. The selection pressure in this case is the resource depletion caused by agriculture. Rather than waiting for natural selection to accommodate resource depletion, cultural niche construction can create a more timely response. The cultural niche in Boserup's theory is the development of new technologies and agricultural strategies intended to boost resource extraction in the form of crop yield. Boserup not only takes a more positive view of resource strain than Malthus, she also accounts for the human ability to culturally adapt to new situations. She sees population increases and the resulting resource strain as drivers for the development of technology and effective land management strategies.

Though Boserup does not use the term, her ideas about agricultural intensification are very similar to the concept of landesque capital. According to Boserup, different agricultural systems in different cultures are the result of different population pressures in the past (Boserup 1981). Larger populations necessitate increased investment into the available land and more intensive farming strategies in order to maximize the yield of available food resources.

Populations adapt to resource strain not, as Malthus would claim, by automatically checking the growth in accordance to the environment's carrying capacity, but by increasing the labor input into agricultural practices and developing new technologies and strategies to maximize the potential of available land and resources (Boserup 1975, 1976).

Though Boserup's theory expands upon the possible courses of human development, she has also been critiqued for oversimplifying Malthus's theory and for fundamental shortcomings in her alternative theory (Abernethy 2005). Major critiques include Boserup overlooks drivers of change beside population, sidelines other key processes, misuses synchronic comparisons, and obscures ecological problems in the developing world (Stone 2001:164). A positive relationship between population pressure and agricultural intensity is fundamental to Boserup's theory of agricultural growth (Turner et al. 1977:384), but critics of Boserup's theory noted factors that may modify the suspected relationship between population pressure and agricultural intensity, including crop type, livestock and aquatic resources, precipitation characteristics, and soil conditions (Turner et al. 1977:388). Boserup does not dismiss the impact of variables other than population pressure on agricultural intensity but by arguing that farmers attempt to maximize agricultural output per man-hour of work and by viewing technology as a freely moving variable, she avoids discussing the impact of environmental and other factors (Turner et al. 1977:388). Boserup held environmental factors constant to illustrate the positive relationship between population pressure and agricultural intensification, thereby minimizing the influence of environmental factors on agricultural intensity is minimized despite the role of environment in determining both population pressures and agricultural decisions (Turner et al. 1977:392). Boserup argues that the added work required for agricultural intensification is a deterrent for switching to more productive technologies from less productive ones (Abernethy 2005:55).

People will suffer a degree of food shortage until they are forced out of necessity to develop more labor-intense strategies, but people may return to less labor-intensive practices when population pressure is relieved.

Boserup intentionally oversimplifies Malthus's hypothesis in order to demonstrate that population growth drives anthropogenic increases in the food supply (Abernethy 2005:56). In contrast to Boserup's unidirectional causal pathway, Abernethy's research on population pressure takes a Malthusian view, suggesting that the perception of resource availability, rather than the availability of the resource, influences population size (Abernethy 2005). The perceived need for more food may drive changes in demographic variables (such as encouraging smaller family sizes to reduce food resource competition), rather than population pressure simply driving food production (Abernethy 2005). While Boserup's theory acknowledges the capacity of humans to alter the environment to serve their needs, she overlooks the other possible responses to resource strain (Abernethy 2005; Grigg 1979:73).

Boserup's analysis of agricultural development reinforces the value of exploring causal relationships. Necessity drives populations to find new ways to meet their needs; the greater the population, the more investment in the land and the greater the agricultural intensification in order to meet the population's resource needs. This is an example of cultural niche construction: growing populations strain available resources, stimulating the construction of a cultural niche to overcome these pressures. In turn, the resulting agricultural intensification affects the environment that encouraged the intensification in the first place. Agricultural intensification allows land to be used more efficiently but requires more labor input to make it so. Boserup's theory of agricultural intensification is compatible with the concept of landesque capital, which includes any investment into the land to increase resource return (crop yield). The cultural niche is created through investments in strategies designed to increase the productivity of the land. The developments Boserup identifies are often also given as examples of landesque capital: land clearing, terrace construction, field leveling, water systems, etc., suggesting that the investment of landesque capital is a process of human niche construction. (Boserup 1975:258).

The investment of labor in developing and implementing practices to alter the landscape and increase resource yield is a process by which humans construct a cultural niche in response to increasing resource strain due to population growth. Landscape modification, often at monumental and regional scales, can be carried out either over short periods with heavy labor investments or incrementally over a long period (Doolittle 1984; Erickson and Walker 2009:234). Landscape changes can be coordinated in advance or simply occur as the result of multiple changes over time (Doolittle 1984; Erickson and Walker 2009:234).

Intentional improvement of the land can increase its value and productivity, and negligence or improper use can devalue the land (Widgren 2007:63). Landesque capital refers to a wide variety of investments to the land, but emphasizes the enduring nature and positive effects of such investments. Blaikie and Brookfield (1987) distinguish between land management designed solely for the production of a current crop, which is not landesque capital, and the "purposive land management designed to secure future production," which is landesque capital (Blaikie and Brookfield 1987). Landesque capital is a type of innovation that "once created, persists with the need only of maintenance," thus the initial investment is intended to benefit future crop cycles beyond a single season (Brookfield 1984). Additionally, only those investments with positive effects are considered landesque capital. An investment that is intended to enhance resource yield but ultimately fails to do so cannot be considered landesque capital.

Brookfield (2001) uses the concept of landesque capital to widen the context of the debate over the cause of agricultural intensification. Brookfield suggests that in addition to population growth, two other factors affect intensification: the use of all forms of capital investment and the use of sophisticated organizational skills. The capital in a given agricultural region includes the human labor force, buildings, tools, and vehicles; and "the natural potential of the land itself is a form of capital, and farmers can both draw it down, and enhance its qualities" (Brookfield 2001:184). Organized labor is involved in the creation of long-term investments in the land (e.g. terraces, drainage, irrigation, soil modification). The investment of labor and the organization required to arrange such modification can contribute to agricultural intensification. Labor and organization were certainly factors at play in the development of Antigua's landscape, where large amounts of slave labor enabled continuous sugarcane production for centuries. For the purposes of this research, any human action that alters the landscape in an enduring manner is considered landesque capita, whether or not these actions were voluntary or forced. Brookfield's suggestion that all forms of capital and organizational strategies contribute to agricultural intensification is relevant for understanding how the Antiguan landscape was shaped by people in the past laboring to maintain long-term intensive agriculture.

A major shortcoming of the concept of landesque capital is that it is more of a descriptive term (and a rather broad one) than a functional theory. Kathleen Morrison (2014) argues that "landesque" is too limited and "capital" is more metaphorical than a descriptive. "Landesque" literally means "of the land," thus the term "landscape" could be just as functional because landscapes reflect the natural and anthropogenic physical characteristics and the imagined, symbolic, and social dimensions of specific places (Morrison 2014:51). "Capital" could be a metaphor for a vague idea of a resource or stored value, or it could be a more Marxian term meaning a tool in the service of production (Morrison 2014:55). Morrison suggests reworking the landesque capital concept so that it might apply more broadly to processes of agricultural production across time and space. Rather than using "landesque capital," she proposes "enduring landscape elements" as a more specific and appropriate term (Morrison 2014:59). She promotes a generalizing approach to encompass the "productive force of anthropogenic landscapes, organisms, and forms of knowledge operating as contingent historical outcomes" in order to recognize the labor of past peoples in creating landscapes that continue to be productive today (Morrison 2014). She suggests moving past analysis of how enduring landscape features came to be and encourages a greater focus on the legacies of these features from their creation to the present (Morrison 2014:70). Investments in the landscape can be "reused, reworked, and reimagined" in different contexts over time, such that the reconstruction of past landscapes requires a consideration of the constant human intervention over time (Morrison 2014:70). This suggestion emphasizes the continuous process of landscape change rather than simply the identification of individual modifications.

While the concept of landesque capital is somewhat vague, it highlights the way producers create lasting value in specific landscapes, thus improving the long-term potential of those places (Morrison 2014:49). The "analytical promise" of the landesque capital concept is that it takes into account historically contingent and emerging human-environmental dynamics (Morrison 2014:58). Instead of positing that humans are inevitably detrimental to the environment, scholars who use the notion of landesque capital recognize that people have, intentionally or unintentionally, both enriched and degraded their environments. Morrison's approach to incorporating the history of enduring landscape features can help assess the anthropogenic changes to a landscape over time and puts the concept of landesque capital in terms that complement the cultural niche construction theory. Morrison's emphasis on the landscape legacy of landesque capital investments draws attention to the continuous process by which humans modify, and are modified by, their environments.

Like Morrison, Widgren (2007) highlights the need to understand the history of land use in order to understand global differences in agricultural productivity. Environmental studies emphasizing landesque capital broadens the historical portrayal of the human-environmental relationship in which humans contribute to environmental decline (Widgren 2007). Many environmental histories recount past anthropogenic destruction of the environment; a narrow view that does not account for the human ability to induce positive changes. Landesque capital approaches, on the other hand, acknowledge that humans can improve natural conditions and create the conditions necessary for future sustainable land use. However, every human action upon the environment modified it in more ways than the human actors can perceive (van der Leeuw 2014:217).

The concept of landesque capital challenges both the concept of carrying capacity and the notion that humans inevitably destroy the natural environment. Landesque capital offers a way to understand the investments humans make in their environment to ensure increased resource yield, thus increasing the understanding of how anthropogenic changes in the landscape can be beneficial in the long term (Figure 2.1). Synthesizing this concept with niche construction theory, we can understand how landesque capital investments are a form of cultural niche construction in response to changing environmental conditions, over time creating highly anthropogenic landscapes that endure for centuries. The concept of path dependence explains how anthropogenic landscape modification is contingent upon the past and constrains future modifications and investments of landesque capital to create today's anthropogenic landscapes.

2.5 Path Dependence

The mutually enabling and constraining relationship between humans and their environments over time can be explained by the concept of path dependence, the process by which people keep their ways even when the context in which they exist is changed. Path

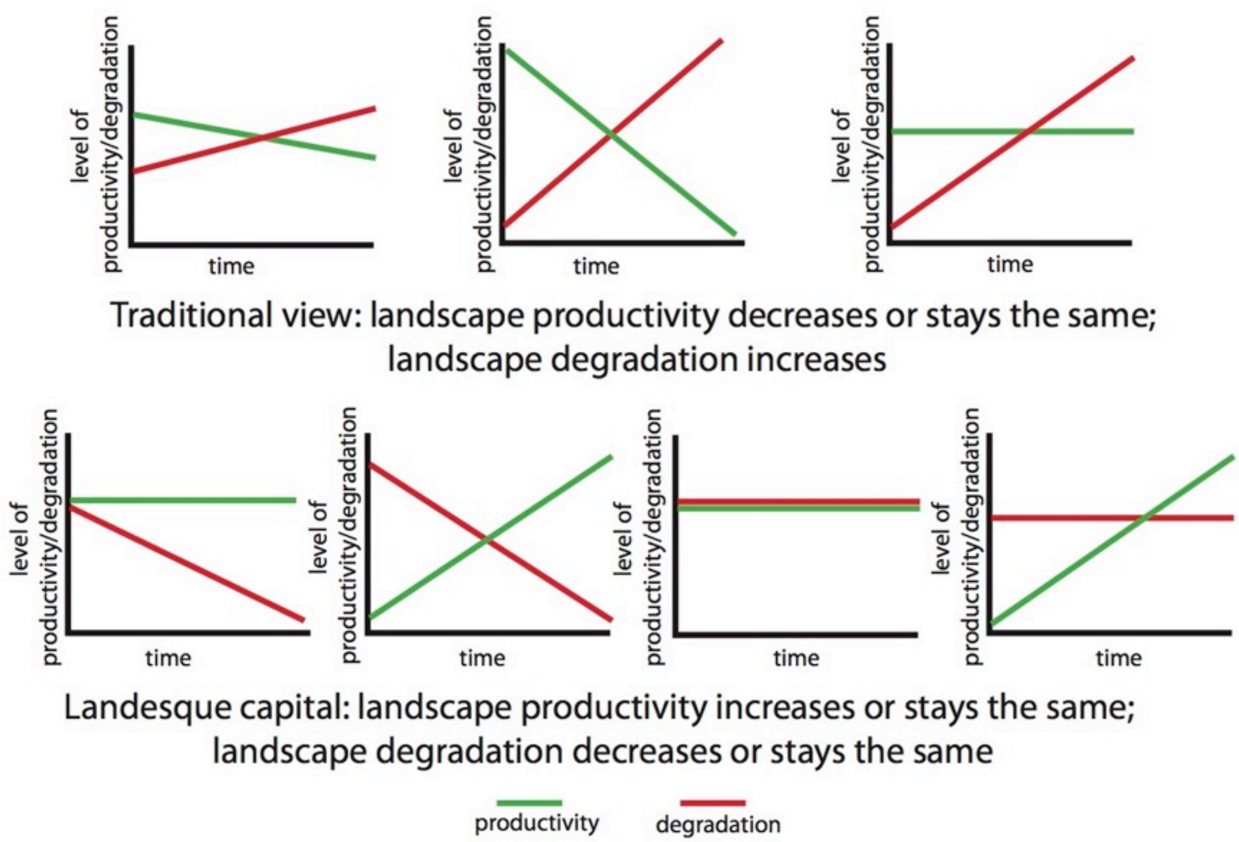


Figure 2.1. *Hypotheses. Trajectories of agricultural productivity (green) and degradation (red) over time according to traditional view of human impact on landscapes and the landesque capital alternative.*

dependence is an economic concept explaining how the set of decisions one must make in any given circumstance is constrained by the decisions one has made in the past, even though past circumstances may no longer be relevant (Liebowitz and Margolis 2000). Path-dependent societies continue following a course of action based on tradition and practice—or short-term "least cost"—even if other alternatives are possible and potentially more desirable in the long-term (Chase and Chase 2014:143). In the social sciences, path dependence refers either to outcomes at a single moment in time or the long run equilibrium of a process, implying that history matters and that amplifications of small differences are a disproportionate cause of later circumstances (Liebowitz and Margolis 2000:982). According to Liebowitz and Margolis (2000), "path dependence can be weak (the efficiency of the chosen path is tied with some alternatives), semi-strong (the chosen path is not the best but not worth fixing), or strong (the chosen path is highly inefficient, but we are unable to correct it)" (Liebowitz and Margolis 2000:985; Roe 1996). Once a society makes a particular commitment, such as to sugarcane monocropping, it is difficult to change the path or trajectory that is followed, regardless of the outcomes (Chase and Chase 2014:143). Similarly, changes to the landscape are constrained by past modifications; for example, the construction of an irrigation system influences the possible uses of an area and the subsequent modifications that may take place there.

As humans modify their environment in response to its challenges, their actions produce short-term and long-term consequences (van der Leeuw 2014:217). Over time, the unintended long-term consequences of human activity can create crises in which resources are depleted, the environment can no longer sustain the human population, or some other disruption to the human-environmental system occurs (van der Leeuw 2014:217). These environmental crises are often the tipping point for civilizations, heralding a collapse or dramatic reorganization as societies struggle to respond to the accumulation of the unintended consequences of their past actions (van der Leeuw 2014). Chase and Chase (2014:143-144) use the "extensive investment in agricultural terracing" at the Maya city of Caracol in Belize as an example of path dependence. Terracing enabled higher agricultural yields and allowed the city to sustain a larger population, but also locked Caracol into a trajectory of path dependence; once landscape modification contributed to increased sustainability, more modification occurred. The city developed a rigid physical layout to maximize available land for terracing and over time, more land and labor were required to maintain soil fertility and agricultural yields. The human-environmental system was stable for a long period, but gradually became more stressed and labor intensive over time; the long-term dependency on terracing meant that Caracol lacked the flexibility to respond to the growing stress on the environment and agricultural system. While the initial investment in landscape modification through the construction of terraces increased agricultural yields and sustained a larger population, the constantly increasing use of agricultural terracing locked Caracol into an inflexible trajectory reliant on terraces. Over time, decreased soil fertility and expansion of the city and its population exacerbated environmental stress meant that the once-successful anthropogenic landscape constrained the city's options to response to environmental stress, leaving the system inflexible, unstable, and vulnerable to collapse (Chase and Chase 2014:151).

The concept of path dependence can help explain both the formation process of the anthropogenic landscape and the persistence of sugarcane monocropping in Antigua for three centuries. Sugar ceased to be profitable to Antiguan plantation owners in the mid-eighteenth century, but Antiguan plantations continued to produce sugarcane until well into the twentieth century (Abbott 1964; Lowes 1994; Midgett 1984). Over time, every society develops traditions, which are path-dependent, meaning the history of the tradition determines its current state at any point in time, constraining the society's options for responding to current challenges and shaping the future (van der Leeuw 2014:216). As with terracing at Caracol, exclusive sugarcane cultivation became ingrained in the Antiguan plantation tradition, reducing the capacity for Antiguan plantation owners to seek more profitable planting methods or crops. Additionally, the landscape modifications themselves are dependent upon modifications made in the past. The rapid deforestation that occurred in Antigua shortly after European colonization then constrained future land use strategies, leading to the planting of sugarcane on ninety percent of Antigua's arable land. While landesque capital describes the changes people make to the landscape; path dependence explains how and why these changes are sustained over time. The persistence of these and subsequent activities visible in today's landscape constitute the landscape legacy of a culture and its decisions.

2.6 Archaeological Case Studies

The concept of landesque capital is applied in academic literature on land degradation, soil and water conservation, natural resource management, landscape archaeology and political ecology (Håkansson and Widgren 2014:7), but few studies have drawn upon landscape legacy and landesque capital as a conceptual foundation for understanding landscape change (Boserup 1975; Håkansson and Widgren 2014:7; Morrison 2014; Widgren 2007:65). The archaeological studies that do incorporate landesque capital reveal the positive and negative effects of long-term investment into the landscape and illustrate the potential of the landesque capital as an analytical concept for understanding human-environmental dynamics. The work of Fisher et al. (2003, 2005), Walker and Erickson (2009), and Clark and Tsai (2009) provide examples of archaeological research involving landesque capital. Fisher and colleagues (2003, 2005) use the concepts of landscape legacy and niche construction to consider the role of humans, using the concept of landesque capital to explain landscape change in Mexico's Lake Patzcuaro basin. Erickson and Walker (2009) examine the impact of roads in the pre-Columbian Bolivian Amazon. Clark and Tsai (2009) discuss the environmental history of Kinmen Island to illustrate the value of a landesque capital approach. These case studies investigate long-term human-environmental dynamics and the promise of landesque capital as an analytical tool.

The work of Chris Fisher and colleagues (2003) on landscape and demographic change in Mexico's Lake Pátzcuaro basin demonstrates the long-term effects of landesque capital investments. Land degradation—anthropogenic environmental change that causes a real or perceived productivity loss—is often considered a factor in the collapse of ancient complex societies. Fisher (2005) conceptualizes land degradation as a human—environmental interaction rather than a purely ecological phenomenon. He explores the implications of this perspective using evidence from a landscape project in the Lake Pátzcuaro Basin exploring diachronic relationships between environmental and social transformations in the development of the pre-Columbian Tarascan Empire. Fisher et al. argue (2003) that initial land degradation was caused by settlement, not by agriculture. Population density inversely correlates with erosion, and land degradation is associated with European conquest but not the introduction of European agricultural strategies (Fisher et al. 2003). In Mexico, the pre-Columbian landscape was relatively stable as the population grew, but after widespread abandonment of large settlements in the early Hispanic period, land practices reliant on labor left the environment vulnerable to degradation (Fisher 2005). The demographic collapse and its immediate effect of land use practices, rather than the land use practices themselves, contributed to the observed landscape degradation. This challenges the prevailing conception about the impact of agriculture, urbanism, and environmental decline—that such human activities cause land degradation gradually over time. This research suggests that the labor-intensive agricultural and environmental engineering projects (the landesque capital investments) necessary to support such large populations caused the rapid degradation of the landscape following demographic collapse, when the labor necessary to the maintenance of the landscape abruptly vanished.

The work of Erickson and Walker (2009) in Bolivia provides another example of research involving the concept of landesque capital as an analytical tool. Erickson and Walker (2009) examine the importance of roads in pre-Columbian agrarian and residential landscapes in the Bolivian Amazon. In contrast to the Western practice of draining wetlands for agriculture, farmers in the Bolivian Amazon may have deliberately constructed earthworks to expand wetlands and increase wetland productivity (Erickson and Walker 2009:233). The construction of causeways and canals facilitated canoe transportation across the landscape and permanently marked the landscape by leaving a gridded structure detectable in the land today. The causeways and canals are a form of landesque capital, representing large-scale, long-term investments of labor and engineering (Erickson and Walker 2009:233). The intentional construction of a grid of canals, causeways, and raised fields created a sophisticated water management system, enabling ease of transportation and agricultural productivity. New generations inherited this landesque capital, allowing the landscape modifications to be reused and reworked over time, as Morrison suggests (Erickson and Walker 2009:250; Morrison 2014:70). The investment of landesque capital created a cultural niche in which pre-Columbian peoples in the Bolivian Amazon could mediate the physical limitations inherent to their environment and create a long-lasting land management strategy.

Landesque capital is also a useful concept in research of more recent land degradation. Clark and Tsai (2009) present an analysis of the environmental history of Kinmen Island, located off the coast of China near Taiwan. Using the guiding concepts of ecologically unequal exchange (the power relations that allow physical transfer of environmental degradation from a powerful location to a weaker one) and the formation of landesque capital, they recreate the course of events shaping Kinmen's landscape in the past. Over seven centuries of salt extraction culminated in the desertification and extreme environmental degradation of the island (Clark and Tsai 2009). More recently, military interests encouraged intensive investment of landesque capital to achieve self-sufficiency and resource security (Clark and Tsai 2009:164). The environmental history of the island reveals periods of unequal resource exchange and periods of landesque capital creation in the form of reforestation, water engineering and management, soil improvement, and protection of coastal wetlands. These strategies resulted in environmental recovery and increased land productivity (Clark and Tsai 2009:160). Clark and Tsai offer their study as a preliminary example of the use of concepts of ecologically unequal exchange and landesque capital to guide analysis of environmental histories. While they admit that more rigorous investigations may reveal trends that can be linked with other historical processes, their study demonstrates the research potential of the landesque capital as a conceptual guide for analysis of human-environmental dynamics.

Landesque capital implies the creation of enduring positive changes to a landscape, a stark contrast to the traditional view that human activity leaves largely negative effects (Brookfield 2001:185; Clark and Tsai 2009:151; Håkansson and Widgren 2007; Widgren 2007:63). Anthropogenic landscape change can contribute to sustainable development and generally positive environmental effects, but some anthropogenic changes can contribute to landscape degradation. These studies demonstrate that the concept of landesque capital can guide analysis of past human-environmental relations, and provide examples of how landesque capital investments can be considered a form of niche construction in response to environmental conditions, contributing to the lasting legacy of past human activity in the landscape. More broadly, these studies illustrate the value of an archaeological perspective in environmental research, demonstrating that the inclusion of human factors sheds like on the synergistic relationship between people and the environment in the past.

2.7 Archaeological Perspectives in Environmental Research

Like Fisher and Feinman, van der Leeuw and Redman (2002) criticize recent studies of environmental dynamics. However, rather than critiquing the lack of a cohesive theoretical foundation, they argue that most recent studies rely on instrumental environmental data. Instrumental data cause research to proceed with a shallow time perspective and produce incomplete models that fail to capture the deeper socio-ecological factors relevant to environmental crises. Archaeology's deep time perspective is suited for examining the long time span and slow processes fundamental to current environmental crises. Methodologically, archaeology is capable of providing relevant environmental data for assessing long-term trends and bridging the gap between natural and cultural perspectives (van der Leeuw and Redman 2002). van der Leeuw and Redman (2002) suggest increased collaboration between archaeologists and scientists in other disciplines to define a common approach to understanding past and present human-environmental systems. Studies incorporating concepts from the natural and social sciences can transcend disciplinary boundaries and produce research relevant for multiple fields.

Answering the call for transdisciplinary research, Lewis et al. (2006) combine ideas from the natural and social sciences with the concept of landscape legacy—the detectable traces of past environmental alteration in today's landscape—to explore anthropogenic modifications to soil. Soil is one of the thinnest and most vulnerable of natural resources, and it is the one upon which, both deliberately and inadvertently, humans have had many major and often irreversible impacts (Redman 1999:82). Lewis et al. (2006) use this concept in their study of the legacy of agriculture near Phoenix, Arizona. Past farming activity left direct and indirect legacies in the soil, which can be discerned through soil chemistry methods. Lewis et al. found that agriculture left a direct legacy in the form of nutrient pools that survived increasing urbanization, and less prevalent indirect legacies, in which modern land use is shaped by past activities (Lewis et al. 2006:703). While the idea that past human activities leave traces on the landscape is not new, the study of soils to discern the legacy of human activity is increasingly valuable.

The combination of archaeology and the natural sciences has contributed to the acknowledgement that soils are important factors in determining agricultural productivity and settlement patterns (Lombardo et al. 2015:67; Kirch et al. 2004; Simpson et al. 2002), increasing the relevance of cultural soilscapes and investigation into their natural and anthropogenic formation processes (Wells 2006:126). The study of soil is relevant for exploring erosion processes by distinguishing between soils formed and altered by natural and human forces, providing an opportunity to address the issues of determining causes of erosion, as pointed out by Hill (2004). Soil is often studied with the assumption that it is the product of multiple natural processes, such as erosion of geological materials, topography, climate changes, living organisms, and time (Wells 2006:125). In contrast, soil research conducted by social scientists emphasizes the human dimensions of soil formation.

Also answering van der Leeuw's and Redman's call for environmental research with an archaeological perspective, Hill (2004) presents research argues that environmental degradation in the form of soil erosion has been a problem for agropastoralists in Jordan for millennia, rather than a more recent phenomenon. The archaeological perspective of long-term land use patterns provides information at a scale and resolution that elucidates past human-environmental dynamics. Erosion is visible and relatively easy to document in the past, but the direct and distant causes of erosion are much more difficult to determine (Hill 2004:397). Attempts to link cultural developments to erosion patterns are hindered by the inherent complexity of erosion processes and the multiplicity of environmental factors at any given point in time (Hill 2004:397). Hill argues that the effect of human societies should be a priority for analyzing environmental change. The soil erosion in Jordan represents one of the most common forms of environmental degradation faced by contemporary farmers around the world (Hill 2004:407). Such erosion is also typical of multi-causal processes that are difficult to interpret, therefore emphasis on the temporal nature of ecological processes and addition of an archaeological perspective can help unravel the multiple variables causing erosion (Hill 2004).

As the case studies presented above demonstrate, archaeology can be combined with environmental sciences to study human-environmental dynamics over long periods and with broad geographic scope. In particular, the concepts of landscape legacy, soilscape legacy, and cultural soilscapes provide a framework for analyzing the way past human activity has left tangible traces on today's landscape. With the understanding that both human and natural forces have contributed to formation processes, the study of archaeological soils can discern these traces of the past. Archaeology contributes the consideration of human influences on the environment in the past, providing a new perspective to understanding and solving environmental problems, including those related to soil resource management (Wells et al. 2013:21).

2.8 Conclusion

It has long been understood that a combination of human and environmental processes in the past has led to modern environments. The concept of landscape legacy incorporates ideas from numerous other theories and concepts used to discuss the mutually influential relationship between humans and their environments. This research investigates the landscape legacy of a path-dependent society engaged in long-term investments of landesque capital as seen through the cultural soilscape legacy still present in the landscape today.

In the natural sciences, niche construction theory addresses the way organisms shape, and are shaped by, their environments. The same theory can be applied to human settlements: the development of agriculture and rise of large, permanent settlements—a form of cultural niche construction—fundamentally altered the global landscape and contributed to subsequent niche constructions to adapt to changing conditions. Malthus's theory suggested that environmental resources were limited such that populations would only grow as large as the environment could support. Boserup offers an alternative theory, suggesting that the human capacity to alter their environment overcomes resource strain. Boserup acknowledges the potential for human action to alter the environment to mediate resource strain and population pressure. Later scholars described these human actions using the concept of landesque capital to refer to anthropogenic alterations to the landscape and environment in order to increase the crop yield and health of the landscape. This investment of labor and building of landesque capital is an example of a niche construction. The investment of landesque capital allows more efficient land use and maximization of resource extraction, fundamentally altering the landscape in which people lived. The landscape bears evidence of the continuous coevolution of the human-environmental dynamic. Archaeology's unique deep-time perspective and landscape-scale level of analysis is suited for combining natural and social sciences to unravel the history of human-environmental dynamics. By determining the combination of continuous environmental and human changes over time, such studies can elucidate the course of landscape change and identify factors contributing to the creation of a landscape at risk for degradation, and/or the direct causes of current degradation.

Antigua's development into a successful sugar island represents the broader transformation of the West Indies as a whole, thus studies of the causes of current land degradation can contribute to understanding of land degradation problems in other Caribbean islands. A multifaceted approach reconstructing precipitation, deforestation, climate change, soil erosion, and sugarcane productivity contributes to a broader understanding of the Antiguan landscape before and after European colonization (Fox 2014:37), though more research outside the scope of this study is needed to incorporate multiple lines of evidence into the understanding of how the landscape has changed over time. This research at Betty's Hope Plantation in Antigua relies upon the concept of landscape legacy to understand the complex relationship between humans and the environment in the past. By understanding how investments of landesque capital changed the landscape and limited future land use decisions, this study seeks to determine the course of landscape change in Antigua and identify the causes of modern land degradation. In doing so, this research of the complex human-environmental relationship in the recent past will contribute to the understanding of the rise and fall of the sugarcane industry in Antigua and the understanding of the enduring landscape legacy of this historical industry.

CHAPTER THREE:
SUGARCANE IN THE CARIBBEAN: THE CASE OF BETTY'S HOPE PLANTATION

3.1 Introduction

The islands of the West Indies "were the first to encounter the initial thrust of European expansion westward across the Atlantic in the guise of Hispanic conquistador enterprise; and they later bore the brunt of the movement by northwest European nations toward tropical plantation development" (Watts 1990:xvii). The most pivotal development in the Caribbean following European colonization was the introduction of sugarcane cultivation and the commercial plantation system. The establishment of the plantations ushered in a period of "overseas capitalism based on conquest, slavery and coercion, and investment and entrepreneurship" (Mintz 2007:9).

From 1665 to 1833, plantation sugarcane agriculture was present on nearly every island of the West Indies. From 1710 to 1750, the northern Leeward Islands (notably Antigua, St. Kitts, Nevis, and Montserrat) collectively became the most productive and profitable sugar colonies of the region (Watts 1990:232). Antigua thus represents a microcosm of the West Indies as a whole, serving as a case study for the patterns and trends of development in the rest of the Caribbean.

3.2 Study Area: Antigua

The islands of the Caribbean lie within the tropics along a broad arc from the western end of Cuba to the southeastern end of Trinidad. Antigua and Barbuda are located in the Lesser Antilles; a chain of small volcanic islands stretching 700 km along the eastern Caribbean Sea

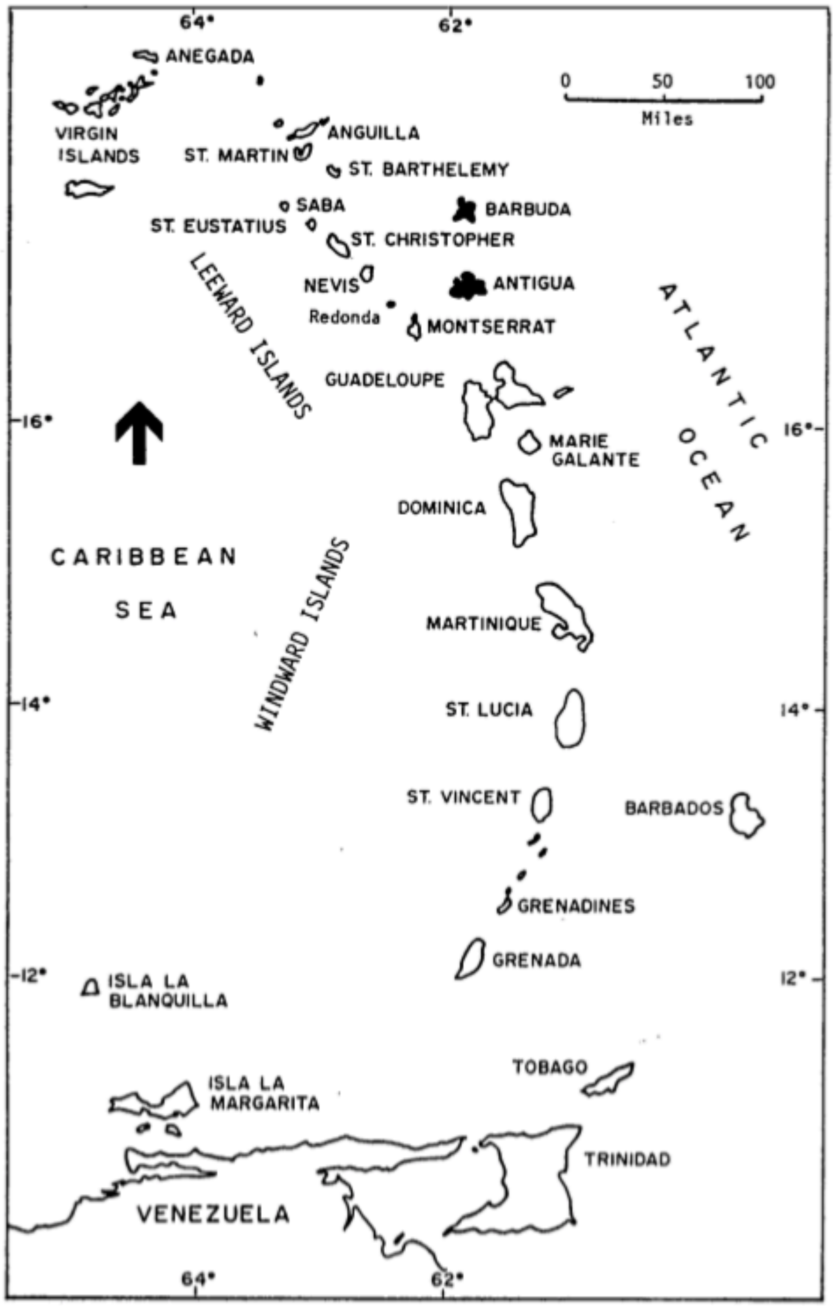


Figure 3.1. *Map. Location of Antigua withing the Leewrd Islands chain (United Nations 2005:3).*

(Figure 3.1; Gonzales- Scollard 2008:6; Watts 1990:3). The term “West Indies” was “used by all European nations to describe their acquired territories in the Americas” (Adderley 2004:1584). Antigua and the neighboring island of Barbuda (together currently a sovereign state) are in the middle of the Leeward Islands, which collectively comprise three percent of the West Indies by area (Fox 2013:2; Watts 1990:4; United Nations 2005:1). Antigua is situated at latitude 17° 10' N by 61° 55' W and is located between the Caribbean Sea and the Atlantic Ocean. The island is roughly round with a circumference of approx. 87 km (54 miles) and a land area of 281 km^2 (108 sq. miles; Sheridan 1960:127; United Nations 2005:1).

The West Indies are located within the tropics, thus the climate is warm and humid; the annual mean temperature variation is low, less than 2.5 ºC in all the Lesser Antilles (Watts 1990:13). While other islands in the Lesser Antilles are geologically unstable due to the subduction of the Atlantic Plate under the Caribbean Plate, Antigua and Barbuda do not experience geologic and volcanic activity, because they are coral limestone islands developed on an older volcanic base (Gonzales-Scollard 2008:7; Watts 1990:12). The bedrock is porous, preventing the resurfacing of freshwater in the form of springs or lakes. The present-day Antiguan landscape is characterized by dry valleys, flat terraces, elevations just above sea level, and little recent surface water (Gonzales-Scollard 2008:7).

3.3 Prehistory and Early Colonial History

The pre-Contact history of the West Indies is complex and not fully understood. It is thought that the first peoples in the Lesser Antilles may have been groups of Paleo-Indians who migrated from South or Central America when sea levels were much lower than at present around 10,000 B.C., though evidence of their presence at this time has not yet been found on Antigua (Wilson 2007:137-188)

Antigua's prehistory encompasses both Pre-Ceramic and Ceramic Periods of Amerindian occupation that can roughly be divided into the Archaic (2000-400 B.C.) and Ceramic Periods

(500 B.C.-A.D. 1493; Murphy 1999:1; Rouse 1992:62-70). As of Reginald Murphy's (1999:1), dissertation on the prehistory of Antigua, over 85 prehistoric sites had been identified on the island. Most Caribbean archaeologists agree that the earliest human settlement in the Antilles was by the Lithic Age or Casimiroid Culture (ca. 4000-2000 B.C.), who likely arrived from Central America (Rouse 1989:121-122; Murphy 1999:1). The second wave of human migration (ca. 2000-400 B.C.) brought Archaic Age peoples from the northeast coastal region of South America to the Lesser Antilles (Murphy 1999:3; Rouse 1992:62-70). The next wave of migration occurred during the middle of the first millennium B.C., as Saladoid groups from the Orinoco River region of Venezuela, migrated to the Lesser Antilles (Murphy 1999:3). By the end of the first millennium A.D., the Saladoid descendants occupied the entire Caribbean archipelago, displacing and/or absorbing the Archaic Age Ortoiroid cultures already living in the Leeward Islands and Greater Antilles (Murphy 1999:3). Archaeological investigations in Antigua produced radiocarbon dates indicating continuous Ceramic Age settlement from the first millennium B.C. until the late fourteenth century A.D. (Murphy 1999:6).

In the centuries before the arrival of Europeans, major changes occurred throughout the archipelago: groups in the smaller islands struggled with resources availability and relations with other groups, while polities on the larger islands in the Greater Antilles began to extend their influence into the Lesser Antilles (Wilson 2007:137-138). Given the relative connectedness of the Caribbean islands and the ease of transportation via watercraft, some areas of the Caribbean underwent a "process of cultural interaction, conflict, and synthesis" (Wilson 2007:138). The heterogeneity of cultures across the Caribbean is visible in the archaeological record, which reveals a diversity of ceramic styles and artifacts (Wilson 2007). By the time of European contact, Antigua was inhabited by sparse populations of post-Saladoid groups scattered throughout the island, but archaeological investigations are ongoing to determine the extent of these populations (Wilson 2007:81; Georgia Fox, personal communication, February 11, 2015).

European contact catalyzed a number of drastic changes for the indigenous people of the Caribbean. Disease, economic disruption, famine, and forced labor in the Greater Antilles contributed to dramatic population decline (Anderson-Córdova 1990; Wilson 1990, 2007:150). Groups in the Lesser Antilles were relatively better off, largely because Europeans did not turn attention to these smaller islands in earnest until the 1620s (Wilson 2207:150). The Lesser Antillean people, known as the Caribs, resisted European attempts to colonize their islands for almost two centuries (Wilson 2007:1). However, there is no archaeological evidence from the early contact period to support the presence of Carib Amerinidans on the island Antigua; the presence of dominant, warlike "cannibalistic" Caribs on Antigua is largely a myth perpetuated by Columbus, who actually never set foot on Antigua (Georgia Fox, personal communication, February 11, 2015). Although European explorers noticed the Leeward Islands, Antigua was not of particular importance to the Spanish and other European powers until much later in the historical period, in the early seventeenth century (Georgia Fox, personal communication, February 11, 2015; Wilson 2007:150).

Antigua was first sighted by Europeans in November of 1493 during Columbus' second voyage to the New World; however, it is unlikely that Columbus ever actually set foot on the island or gave it its current name (Dyde 2000:8). The English established a settlement on Antigua in 1632, when Edward Warner led a group to Antigua from St. Kitts (Dunn 1972:122; Dyde 2000:14). Early settlers managed to survive by growing subsistence crops, but lived in a "state of perpetual crisis" (Dunn 1972:122; Lowes 1994:6; Pares 1950:15). The Antiguan population numbered 750 individuals in 1646 and grew slowly, reaching 1200 by 1655 (Dunn

1972:122). English initiatives in the Caribbean region were precarious until Oliver Cromwell's 1655 Western Design, when Cromwell believed he could attack Spain in the Caribbean and avoid a war in Europe (Georgia Fox, personal communication, February 11, 2015; Taylor 1969). Although Cromwell did not achieve his goal to obtaining control of Caribbean islands from Spain, the Western Design did encourage greater numbers of English settlers in the Caribbean, including on Antigua (Bremer 2012:126).

Despite the slow start, Antigua has a long history of the large-scale production and export of sugar. Information on the early period of Antigua's colonial history is fragmented and contradictory, and it is not clear exactly when the first enslaved laborers were brought to the island: some may have accompanied Warner circa 1632, but generally enslaved Africans "were an insignificant part of society until after the middle of the century" (Dyde 2000:20). Early sugar production may have been carried out by indentured European labor, through by 1672, the earliest year for which there is a reliable count, there were reportedly 570 enslaved Africans and 800 English settlers in Antigua (Dunn 1972:123; Dyde 2000; Lowes 1994:6; Oliver 1894-99:xviii).

The introduction of sugarcane into the plantation system of the Lesser Antilles by northwest European nations took place at a time of rapidly rising demand for sugar in home-county markets that could not be met by the existing areas of production (Watts 1990:177). By the end of the seventeenth century, sugarcane production in Antigua was well established, and launched the island to the top of the Caribbean sugar industry. The British Caribbean developed into a true monoculture by the eighteenth century and by 1708, Antigua became the leading sugar producer in the subregion (Meide 2003:6; Watts 1990:337). With the growth of sugarcane production, Antigua experienced population growth as immigrant and enslaved African populations increased, landscape change as fields were devoted to sugarcane, and economic growth as the island's exports took over the market.

3.4 Sugarcane, Sugar, and Rum

Sugarcane cultivation has been associated with the system of colonial cash crop agriculture since the beginning of European overseas expansion (Meide 2003:3). Despite its historical importance in the establishment of European colonies in the New World, sugarcane is actually indigenous to southeast Asia; it was most likely domesticated in New Guinea several millennia ago and diffused across the globe over time (Menard 2006:9). The Portuguese established the earliest colonial sugar islands in the early fifteenth century in the Azores, Madeira, and Sao Tome (Meide 2003:4; Menard 2006:10; Mintz 1985: 30-35; Watts 1998:80). Taking advantage of the fertile soil, the Portuguese imported African slaves to Madeira, the first so-called "sugar island" of the Atlantic, to clear the land and tend to sugar crops, ultimately developing a plantation system reliant on slave labor that served as a model for later New World sugar industries (Dunn 1972; Meide 2003:4; Mintz 1985:30-35; Sheridan 1960; Watts 1998:80). As Europeans colonized the Caribbean, it became apparent that the tropical climate of the region was suited for growing sugarcane, and it was much cheaper to produce sugar in greater quantities there than in Europe (Meide 2003:3). While the Portuguese established the first sugarcane plantation in Brazil in the late sixteenth century (Menard 2006:10), the first sugar island of the British Caribbean was Barbados (Watts 1990:182).

Sugarcane is a tall, perennial grass that thrives in areas of the tropics with a plentiful supply of water for the initial growth period and a dry, sunny season to encourage the slow process of natural cane sweetening (Watts 1990:176). It can succeed in most soils, so long as they are sufficiently deep and fertile. Planting on a slight slope to improve subsurface drainage and removal of excess surface moisture helps the crop grow (Watts 1990:176). As the plant flourishes in warm, wet, tropical environments, the majority of the world's sugarcane is grown between 22°N and 22°S. Although Antigua is one of the driest islands in the Caribbean, sugarcane cultivation was quite successful; the majority of the sugar grown in Antigua was in the fertile Central Plain region of the island, a region that is generally flat but with several hills rising to an altitude of 200-350 feet (Brown 1913:598, 611). Brown (1913:606) noted the surface soil in the early twentieth century had been disturbed for some depth due to the cane cultivation, “which covers all the available cane-producing land in the island.” He also noted that in the Central Plan region, concentrations of salt in the soil contributed to poor cane growth in an otherwise viable agricultural region (Brown 1913:611). The most commercially relevant product of sugarcane is sucrose, which is extracted from crushing the stalks and processing into cane sugar and other products such as ethanol, rum, and molasses (Sheridan 1960:136; Smith 2005).

Sugarcane cultivation in the Caribbean required a complex planting and harvesting cycle coinciding with the tropical rainy and dry seasons (Dyde 2000:32; Meide 2003:8; Menard 2006:13). In the West Indies, the numerous requirements of cane ripening meant that the cane stalks, or ratoons, were best planted during the rainy period from August to November. The sugarcane cultivation process began as enslaved laborers dug sugar holes or trenches and inserted two-foot-long cuttings of old cane stalks. A field gang of about 30 slaves could plant about two acres of cane per day (Dyde 2000:32). Once covered in soil, the cuttings would sprout new plants, which grew at a rapid rate (Menard 2006:13). Unlike crops cultivated in Europe, sugarcane had a long growth period, taking 16 to 18 months to ripen (Dyde 2000:32). During this time, a continuous and laborious process of weeding, fertilization, and general maintenance was required to maximize the height and health of the cane crops (Dyde 2000:32; Menard 2006:13).

The cane was harvested during the dry season between January and June (Dyde 2000:32; Meide 2003:8; Watts 1990:176), and planters typically staggered their crops in order to spread the harvest period over several months (Menard 2006:13). Mature cane, often over eight feet tall, was cut at the ground level with machetes (Watts 1990:176). Sugar from underripe or overripe cane was inferior, and harvested sugarcane rotted within hours if not immediately processed (Meide 2003:8; Miller 1991:23). Cut cane stalks could be replanted; the new sproutings of cane ratoons reached maturity at a faster rate and required less labor than freshly planted stalks. While the same stalks could be replanted multiple times, the cane's saccharine content gradually declined (Menard 2006:14). Sugarcane required an intense amount of labor to cultivate, harvest, and process, but the crop is unique for the long duration of a plant's yield; crops in the West Indies could be harvested for up to multiple years through the natural rejuvenation of the stalks before it became necessary to replant the cane (Menard 2006:14)).

In the early years of West Indian sugar production in the sixteenth century, knowledge of sugar production techniques was passed on from the Dutch to the English and French planters. Initial production was fraught with poor decisionmaking, lack of familiarity with the crop, labor shortages, drought, and other calamities, which led to haphazard production, and oftentimes, a low-quality sugar product (Georgia Fox, personal communication, February 11, 2015). In general, sugarcane was both grown and processed on the plantation, linking agriculture and manufacturing (Sheridan 1960:127). The process of converting raw cane juice to sugar and rum was complex and varied from location to location, but a general sequence of events can be established (Dunn 1972:192-194; Goodwin 1987:40-46; Menard 2006:13).

Freshly cut cane was transported to the plantation's sugar factory, which consisted of several separate buildings, or one larger structure that housed several distinct workspaces. Cut sugarcane stalks were crushed by a mill (which could be powered by wind, water, animals, or in the nineteenth century, steam), and the raw cane juice was transferred to the boiling house, where it was boiled in a succession of copper kettles (Martin 1784: 285-297; Meide 2003:2; Miller 1991:23; Sheridan 1960:136; Watts 1990:5). The juice was boiled for a time in one kettle before being transferred to the next in sequence, where the process was repeated, and impurities skimmed off (Martin 1784: 285-297; Meide 2003:2; Menard 2006:13; Ragatz 1928:57; Sheridan 1960:136; Watts 1990:113). Cane processing was hot, dangerous, dirty work, and the enslaved Africans who worked the sugar factories were often highly skilled and innovative in their work (Menard 2006:15; Georgia Fox, personal communication, February 11, 2015).

During the boiling process, the cane juice became concentrated into molasses and increased in density after each kettle transfer; after the last boiling, the molasses was scooped into small sugar-loaf molds and left to cool. The sugar cake, called m*uscovado*, could range from golden yellow to dark red in color. The raw sugar was shipped to Europe for direct sale or refined further into white sugar (Meide 2003:2; Watts 1990:113). The final products of sugarcane were sugar in various degrees of refinement, molasses, and perhaps most importantly, rum (Sheridan 1960:136; Smith 2005). The rise of rum production in the seventeenth century paralleled the expansion of sugarcane agriculture and knowledge of alcohol distribution in the Lesser Antilles (Smith 2005:13).

Rum is made by distilling sugarcane juice and the waste products of sugar making (Smith 2005:1). Martin (1784:300) describes the distillation process as fermenting a mixture of "one-third of scum from the cane-juice, one-third of water from the washing of coppers… and one-third lees [yeast]" plus the addition of molasses to the liquid while it distilled. He estimated that "it is no difficulty to produce two hogsheads of rum for three hogsheads of sugar" (Martin 1784:303). Other estimates of rum production in the late seventeenth century suggested that a "large sugar plantation of 750 acres would produce 238,000 pounds of sugar and 60 barrels of rum, about 4,042 gallons, in a 45-week crop cycle" (Smith 2005:22). Plantation accounts reveal that rum yields and the ratio of rum to sugar varied from year to year; accounts from the Codrington estates indicate that plantations increased their rum production from the 1710s to the 1760s, mirroring the growing global demand for rum in the eighteenth century (Smith 2005:88). Rum was a profitable enterprise, and grew in importance to Caribbean sugar planters in the nineteenth century as a means to escape debt as sugar production declined and became less profitable than before (Smith 2005:194).

It is impossible to discuss the significance of sugarcane cultivation and sugar production in the Caribbean without acknowledging the labor requirements and demographic implications. The extension of large-scale sugarcane plantation agriculture throughout most of the West Indies required significant slave labor to fuel it; Caribbean plantations were reliant on enormous numbers of enslaved Africans (Cowton and O'Shaughnessy 1991:33; Dyde 2000:65; Watts 1990:304). The importation of large numbers of slaves bore testament to the substantial amounts of labor required for sugarcane plantations to succeed; fields needed to be prepared, cane needed planting, weeding and harvesting, sugar needed refining, and rum needed distilling (Martin 1784). Slaves were often regarded by plantation owners as "stock" rather than labor; they were seen as multipurpose capital equipment and the most valuable asset on a plantation (Cowton and O'Shaughnessy 1991:34; Hall 1962:308; Martin 1784:251). This is apparent in Samuel Martin's (1784:242) discussion of the duties of planters to their enslaved laborers: plantation owners ought "to treat his negroes with tenderness and generosity, that they may be induced to love an obey him, out of mere gratitude." While Martin (1784:251) acknowledges the vital role of slaves in a plantation's operation, he discusses "the management of negroes and cattle" in relatively equivalent terms.

In the seventeenth century, 100 slaves working 80 acres of cane could produce an estimated 80 tons of sugar a year (Dunn 1972: 191). In 1787, shortly after the 1753 peak of the industry, over 37,000 slaves were reported to live on the island (Lowes 1994:6). The contrast with the relatively small European population (2,590 individuals; Lowes 1994:6) indicates the degree to which Antigua's sugar industry relied on massive amounts of slave labor to produce wealth for the small number of European planters. The relationship between capitalism and slavery was key to the historic rise and fall of the Caribbean sugarcane industry, but detailed discussion of these developments is beyond the scope of this thesis.

The introduction of sugarcane cultivation transformed the islands of the West Indies. By 1750, only a century after the establishment of British colonies in the Caribbean, sugar was transformed from a luxury commodity of the elite to a staple of the middling class (Mintz 1985:45). The global demand for sugar resulted in far-reaching consequences for the Caribbean that can still be felt today. Not only are the legacies of colonialism still tangible in Antigua and other Caribbean islands, the environmental and landscape legacies of long-term intensive monoculture persist.

3.5 Environmental Impacts and Landesque Capital

There is little doubt that the effect of sugarcane on the environment within the Caribbean has been overwhelmingly a negative one (Watts 1990:533). The intensity of this monoculture and the associated unsustainable agricultural practices severely degraded the vegetation and landscape of Caribbean sugar islands, including Antigua (Day 2007:178). The destructive nature of cane agriculture on the landscape was even observed at the beginning of large-scale commercial sugarcane production. Sugar plantations on island of Madeira, the first sugar island of the Atlantic, helped increase sugar use in Europe, but produced unfavorable environmental effects. Following forest clearance and sugarcane cultivation, soil movement and erosion occurred on the slopes of the island (Watts 1990:80). Similarly, it is thought that environmental degradation occurred rapidly in the West Indies following European colonization (Gonzales-Scollard 2008).

The environmental consequences of sugarcane cultivation in the Caribbean were first felt on Barbados, the pioneer sugar island of the West Indies (Watts 1990:221). This situation was repeated on other West Indian islands; following deforestation, exposure to weathering, rainfall and natural disasters caused soil compaction and infilled natural soil pores, thereby increasing surface runoff and the potential for soil erosion (Day 2007; Mulcahy 2004; Watts 1990:221). Heavy rains and hurricanes during the tropical wet season exacerbated the washing of the nutrient-rich litter down sloped portions of the islands; consequently, a portion of the uppermost layer of soil eroded, causing the loss of another portion of nutrient stores (Mulcahy 2004:638; Watts 1990:222). By 1661, the first official comment about decreasing levels of soil fertility in Barbados was made by the President and Council, reporting, "the land is much poorer, and makes much less sugar than heretofore" (Great Britain Public Record Office 1661-1668:45).

Although it has been suggested that agricultural techniques changed very little once they were established in Barbados (Watts 1990), Caribbean planters developed new methods and techniques over time to maximize their declining crop yields (though it is important to note that many early experimentations in agricultural techniques did not work as intended; Georgia Fox, personal communication, February 11, 2015). In response to reduced returns on labor and capital investments into their land, plantation owners undertook landesque capital investments. Among the most successful plantation owners to maintain the productivity in his land was Samuel Martin, the absentee owner of Green Castle Plantation, who returned to Antigua in 1750 (Sheridan 1960:133). In his 1784 *Essay on Plantership*, Martin describes the "art of managing a sugar plantation to the best advantage; so as to make it produce the most, both in quantity and quality" (Martin 1784:236). He describes in detail a variety of practices for sugar planters to stave off the "evils of monoculture" (Ragatz (1928:66), including fallowing, fertilization with manure, tilling, and drainage (Martin 1784). Martin also held that West Indian soils had been depleted of nutrients "by long and injudicious culture" (Martin 1784:253), leading him to develop new methods of tillage and manuring for each Antiguan soil type (Martin 1784:254; Watts 1990:425). He also implemented a system of "round ridging" in which a series of ridges and trenches were constructed on flat land in order to remove excess surface water and allow cane fields to adequately drain (Martin 1784:258-259; Sheridan 1960:133; Watts 1990:426). Martin's round ridges were "12 feet broad, and not above 6 or 8 inches higher in the middle than at the sides" but were not intended for "light soils or steep lands, and even in flat soils, upon loam… because loam melts away by water, as butter does by heat" (Martin 1784:258-259). Martin's essay suggests awareness among sugarcane planters in Antigua that consistent and careful maintenance of the land was required in order to produce large, healthy cane crops and to maintain the size of the yields year after year.

Martin (1784:271-272) also discusses the widely practiced technique of digging cane holes (adopted by the 1720s) as a means to prevent erosion and preserve moisture, both of which had been problems previously with simple trenching for planting cane (Figure 3.2). After the fields were manured, they were gridded into holes measuring approx. 4x4 feet and 9 inches deep, spaced of four-foot distance (Martin 1784:271-272; Ragatz 1928:57; Sheridan 1960:134). The construction of cane holes served to stave off water erosion, maintain soil moisture, protect roots and shoots from wind, and to concentrate fertilizer near the base of the cane (Sheridan 1960:134). According to Martin (1784:271-272), it would take an entire day for 40-60 laborers to construct cane holes on a single acre. The excavated cane holes were covered by cane tops and filled with a layer of mold. As the planted cane sprouted and grew, the hole would be filled with more mold and, occasionally, a compost of manure mixed with cane waste, until the cane field was made level (Martin 1784:271-272; Meide 2003; Rogoziński 1992:131; Sheridan 1960:134).

Figure 3.2. *Cane holes. William Clark's 1823 painting titled "Planting the Sugar Cane, Antigua" depicts a group of enslaved laborers planting sugarcane in the typical square cane holes (The British Library 2015).*

3.6 Antigua's Sugarcane Industry

There is no mention of sugarcane cultivation in Antigua before 1655 (Dyde 2000:20), but once established in the late seventeenth century, it dominated island agriculture, leading the island to be one of the most productive of the West Indies. By 1750, almost all the virgin timber had been cleared and the island was dominated by sugar estates to the exclusion of all other crops, and by its planter elite, which in power and influence rivaled that of Barbados (Watts 1990:340). In 1764, Antigua had over 300 sugar plantations, the mean size of which was approximately 200 acres operated by 100 slaves (Watts 1990:340).

The combination of an increasing labor supply and a limited amount of arable land contributed to the development of intensive cultivation methods on Antigua as plantation owners sought to extract the most profit from their land (Watts 1990). Compounding the inherent difficulty of growing a labor-intensive crop was Antigua's lack of fresh water. Emmanuel Brown, in his 1750 map of Antigua, noted "Antigua is a fine Island, tho' it has not on Single Spring of Water in it: So that in times of drouth when all their Ponds are dry, and their Cisterns almost empty, they are obliged to fetch their fresh water from Montserrat… or… Guardaloup, a Neighboring French Island." (Dyde 2000:3). Sheridan (1960:127) suggests that plantation owners, particularly the aforementioned Samuel Martin in Antigua, actively tried to combat reduced yields caused by land degradation by employing a number of techniques. Sugarcane production skyrocketed, rising from an annual average of 4900 tons in the 1710s to 9,200 tons in the 1760s (Sheridan 1960:127). In 1724, the governor of Antigua reported, "no land on the island remained unplanted" (Sheridan 1960:127). From the period of 1710 to 1750, Antigua and other Leeward Islands (St. Kitts, Nevis, and Montserrat) collectively became the greatest sugar colonies in the region (Watts 1990:232). This economic prosperity is reflected in the demographic changes on the island. The slave population (about 12,500 in 1713) increased steadily, reaching a maximum of almost 37,5000 in the mid-1700s, though the number of slaves imported was never enough to satisfy the demand for labor (Dyde 2000:65). At the height of Antigua's sugarcane industry in the late 18th century, over 90 percent of the island was devoted to agriculture (United Nations 2005:22).

Although Antigua is generally suited for sugarcane cultivation and became very successful in doing so, the varying quality of the island's soils combined with uncertain rainfall created conditions unfavorable for sustained high-yield monoculture (Midgett 1984:34). The island experienced a decline in production toward the end of the eighteenth century due to a combination of factors: soil exhaustion, crop disease, drought, absentee plantation owners, competition from other Caribbean islands, and reduced returns of increasing investment of capital and labor in a limited amount of land (Ragatz 1928; Sheridan 1960:127; Smith 2005:199; Ward 1978:198). From the 1750s until the outbreak of the American War of Independence, the output of sugar from Antigua and the rest of the Leeward Islands declined. The general slump in production coincides with a general pattern of decline of sugar plantations throughout the Eastern Caribbean for this period, which can be seen in the artifacts assemblages and structures (Georgia Fox, personal communication, February 11, 2015; Lowe 1994:8; Watts 1990:315).

In the latter half of the eighteenth century and in the first half of the nineteenth century, Antiguan planters were devoted to large-scale sugar production at a time when prices were falling and increased competition favored the most economical producer. The primary challenge was that although Antiguan soil was suited for growing sugarcane, the island was subject to repeated cycles of drought, some of which lasted for two or three years, and the lack of water was a constant problem (Auchinleck 1956; Lowes 1994:9). Lowes (1994:10) examined island-wide sugar yields from 1820-1870 and found that sugar production “swung wildly from one year to the next”, but that the reported yields display a steady decline. The concerns with drought and unpredictable water supply are evident at Betty’s Hope Plantation in the presence of four deep tanks for water collection at the site, which date to the late seventeenth century (Georgia Fox, personal communication, February 11, 2015).

Difficulties in maintaining a high production yield led to the successive abandonment of sugarcane operations. By 1943, when most Antiguan sugar estates were consolidated into the Antigua Syndicate Estates, Ltd., the island’s sugar acreage had been reduced by half (Midgett 1985:34). Production continued to decline until less than 5000 tons per year by 1970 (Midgett 1985:35), and the Antiguan sugar industry all but ended in 1972, when the last sugar refinery closed and sugar production fell to “negligible levels” (Dyde 2000:278; Weaver 1988:321)

3.7 The Codrington Estates and Betty’s Hope Plantation

Antigua’s prosperity as a European colony was based on its large, intensive sugarcane plantations. Although Christopher Codrington II is “popularly credited with the establishment of sugar in the island” when he arrived in 1674, sugar was already being grown successfully by other planters, but on a very small scale (Dyde 2000:29). Betty’s Hope Plantation is one of the earliest plantations on the island; it was established in the early 1650s by then-governor Christopher Keynell, on a slight rise 110 feet above the central plain, overlooking the surrounding valleys and low hills (Goodwin 1994:101). The plantation was briefly abandoned following Keynell’s death and the French occupation of Antigua in 1666, but was repossessed by the British in 1674 (Dyde 2000:28; Lowe 1951:5). At this time, the land was awarded to Christopher Codrington II, a British resident of Barbados (Lowe 1951:5). Under Keynell, plantations in Antigua grew cash crops such as tobacco and indigo, but under the ownership of the Codrington family, the over 700-acre plantation became Antigua's largest sugarcane plantation (Dyde 2000:29; Lowe 1951:1; Museum of Antigua and Barbuda 2014). Codrington's "aggressive attitude toward plantation management, combined with his introduction of Barbadian production methods" transformed the sugar industry in Antigua (Dyde 2000:29). Codrington built a highly successful sugar empire that ultimately contained five sugar estates (Betty's Hope, Cotton, Cotton New Work, the Garden Estates, and the Cables), over 1000 acres of land, and 800 slaves by the middle of the 18th century (Lowes 1951:1; Watts 1990:404). By the end of the seventeenth century, Betty's Hope had become Antigua's largest and most efficient sugarcane plantation (Goodwin 1994:1010). The estate remained owned by the Codrington family until it was sold in 1944 (Fox 2013:5).

Betty's Hope plantation is located on the island of Antigua on the edge of the island's Limestone region and the Central Plain region, an area with medium-low rainfall and fertile soil (Figure 3.3; Museum of Antigua and Barbuda 2014). The Codrington family was highly successful in transforming the plantation into a profitable business, representing the late seventeenth-century trend of plantation consolidation and dedication to a single crop. Betty's Hope follows a common, but not exact agricultural-industrial Caribbean sugar plantation layout in which the factory complex (mills and boiling/curing houses) is located within viewing distance of the Great House and other support structures, the slave villages, and cane fields (Georgia Fox, personal communication, February 11, 2015; Goodwin 1994:102; Museum of Antigua and Barbuda 2014).

Recent archaeological research suggests that the plantation was constructed in phases paralleling the expansion of the Atlantic sugar trade (Fox 2013). Like most plantations, Betty's

Figure 3.3. *Location of Betty's Hope Plantation (Museum of Antigua and Barbuda 2014).*

Hope had buildings devoted to processing sugarcane and converting raw sugar into exportable products. The iconic twin windmills at the plantation were used to power rollers, which crushed freshly harvested sugarcane to extract sucrose-rich cane juice from the stalks. This windmill technology was partially based on sailing ship technology, where the wind-powered canvas sails on the windmills could rotate at high velocities, making them dangerous, which at times, resulted in tragic accidents, such as limb and head decapitations. During the eighteenth century, the windmills powered three vertical iron rollers in an inefficient system requiring two workers to feed the machine and each cane stalk was crushed twice to extract as much juice as possible (Museum of Antigua and Barbuda 2014). By the early 1800s, the mill system expanded to three horizontally positioned rollers, creating a more efficient procedure that required a single person to feed cane stalks and extracted a greater amount of juice (Museum of Antigua and Barbuda

2014). Each windmill could crush two acres of cane per day; with an average wind, the mill could grind approximately 200 tons of cane to produce 5,500 gallons of syrup (12 tons of crystalline sugar) per week (Museum of Antigua and Barbuda 2014).

Extracted juice was collected at a large iron tank located beneath the rollers and was then pumped to the Boiling House where the remaining fibrous stalks (bagasse) were burned as fuel for the boilers. At Betty's Hope, cane juice boiled in 16 copper hoppers to produce crystalline sugar. The plantation also had a still house for manufacturing rum, the production of which remained a profitable enterprise for the Codrington estates, even when the sale of crystalline sugar was less viable (Georgia Fox, personal communication, February 11, 2015).

Despite intensive monocropping, the plantation's soil continued to yield high quantities and qualities of sugarcane and its byproducts (Museum of Antigua and Barbuda 2014). Like many absentee Caribbean plantation owners, the Codringtons returned to England in 1704, leaving the plantation estate in the hands of attorneys until the early 1900s (Fox 2013). Correspondence from the plantation supervisors to the Codringtons in Dodington, Gloucestershire, England was retained by the family, resulting in a collection of documents recording almost 300 years of plantation operations. These documents—collectively referred to as the "Codrington Papers"—provide insight into the broader Caribbean sugar plantocracy, as well as the Codrington operations in particular.

The Betty's Hope Trust was formed in 1990 to restore the plantation and establish an open-air museum and interpretation Visitors Center (Saunders 2005:30). The plantation is currently a major tourist attraction and the subject of ongoing archaeological research and restoration projects. As a part of the continuous restoration program, the plantation has been surveyed, photographed, and investigated by archaeologists and historians (Saunders 2005:30).

Systematic scientific archaeological investigations at Betty's Hope began in 1999 and continued in 2000 and 2002, conducted by Edith Gonzalez-Scollard through the City University of New York as part of her doctoral research (Gonzales-Scollard 2008). Current archaeological research at Betty's Hope is under the direction of Dr. Reginald Murphy, Antigua's island archaeologist and UNESCO representative, and Principal Investigator, Dr. Georgia Fox of California State University, Chico.

Archaeological investigations began at the plantation in 2007 and as of this writing, have for the last eight years, focused on the Great House Complex, Still House, and one of the slave villages. The project at Betty's Hope "seeks to understand the workings of a sugar plantation from an anthropological perspective," shedding light on colonialism, slavery, environmental devastation, and the changes brought about by early modern cultural contact during the rise of a capitalist economy and growing consumerism (Fox 2103:4; Georgia Fox, personal communication, February 11, 2015).

3.8 Current Land Degradation in Antigua

The combination of cane holing and fertilizing through animal manure in cane agriculture may have staved off soil erosion and nutrient depletion in the early eighteenth century (Watts 1990:435), but many scholars agree that such intensive monoculture causes the soil to lose its original fertility, thereby progressively decreasing crop yields (Abbott 1964:1; Campbell et al. 1992; Garside et al. 2001:16; Meyer et al. 1996; Ragatz 1928:67; Sheridan 1960:135; Ward 1978:198). Early on, L.J. Ragatz (1928) argued that Antigua's sugarcane industry continuously declined because plantations were committed to a single crop that exhausted the soil and relied on outdated agricultural techniques (Ragatz 1928:60, 67; Ward 1978:198). Additionally, Antigua was affected more acutely by period drought than other West Indian sugar islands, a factor that certainly contributed to uncertainty and decline of the Antiguan sugar industry (Ragatz 1928:67). Ragatz (1928:60, 67) argues that planters ignored differences in soil type, planted sugarcane haphazardly wherever it would grow, failed to implement irrigation works, and only applied fertilizer when soil depletion drastically affected yields. While this view that sugarcane cultivation was unrefined and without innovation may be applicable for certain estates in the early years of the Caribbean sugar industry, it is clear that plantations used a variety of landesque capital investments—as Martin's (1784) essay demonstrates—to maximize the crop yield from a limited amount of land (Sheridan 1960). However, the extent to which these innovations and efforts were successful in staving off land degradation remains unknown.

The Antiguan sugarcane industry peaked in the eighteenth century when over 90 percent of Antigua was devoted to agricultural production (United Nations 2005:22). To enable sugarcane production on such a large scale, native forest cover was removed and large acreages of land unsuitable for sustainable agriculture were cleared and planted (United Nations 2005:22). Although sugarcane dominated in Antigua for three centuries, a period of dramatic change to land use occurred from 1961 to 1995 when sugarcane cultivation declined and livestock grazing increased (United Nations 2005:48). Currently, animal grazing wreaks havoc on the landscape, such that indigenous plant species cannot take root because the seedlings are consumed by herds of domestic sheep and goats. Larger livestock, such as cows and an increasing population of free-roaming, feral donkeys, also wreak havoc on the landscape (Day 2007:178; Georgia Fox, personal communication, February 11, 2015). In addition, land clearance for resort tourism has also played a major role in contemporary land degradation (United Nations 2005:22, 49; Georgia Fox, personal communication, February 11, 2015).

In early May 2004, the United Nations Technical Advisory Committee (TAC) conducted a rapid field appraisal of the land degradation in Antigua. Significant topsoil erosion has occurred recently in Antigua, especially in the volcanic region in the southwest of Antigua. In the most acutely affected areas, "it appears that much of the A and B horizons was eroded away" (United Nations 2005:22). Recovery from such degradation of this type and at this scale is very slow, occurring at geological time scales (United Nations 2005:22). The TAC concluded that Antigua is experiencing "serious problems with land degradation in the more vulnerable areas of steep and shallow soils" (United Nations 2005:42). The already severe pressures on Antigua's landscape are expected to be exacerbated by anthropogenic climate change and other human pressures, such as increasing tourism (Day 2007:181).

While the environmental consequences of sugarcane cultivation are well known, the current land degradation in Antigua appears to be a recent phenomenon, not necessarily the accumulation of the effects of three centuries of monocropping. The United Nations' report attributes erosion and land degradation to the rise in livestock grazing following the end of the sugarcane industry. This suggests that the end of sugarcane cultivation may be a factor in tipping off large-scale land degradation, indicating that land degradation is the result of both fast and slow moving processes and is the product of three centuries of monocropping and the abrupt shift in land use in the twentieth and twenty-first centuries.

3.9 Conclusion

Cane agriculture started slowly in the Caribbean region, but once established, left its mark on the landscape. Antigua's role as a major sugar producer makes it representative of the broader, social, political, economic, and environmental trends that characterized the Caribbean from the introduction of European colonization to the end of Antiguan sugarcane production in the 1970s. The trajectory of the Barbados sugar production model and the island environments into which it was introduced were linked: as alterations took place in one, changes occurred in the other (Watts 1990:443). Human manipulation of the environment was pivotal in shaping Antigua's history, from enabling massive sugarcane production to fueling the Atlantic slave trade, and to the collapse of Antigua as a sugarcane powerhouse. This study focuses on a particular plantation in Antigua as a representation of the island itself in order to understand the long-term and recent causes of land degradation by unraveling the trajectory of landscape change from the introduction of sugarcane to the present. Betty's Hope was a large and complex industrial and residential site representative of historical-period Caribbean sugar plantations, thus the site is an excellent case study for investigating landscape change during the past three centuries (Fox 2013:5; Saunders 2005:30).

From a geoarchaeological approach, the plantation and its long history of monocropping represents the entire island of Antigua and the Caribbean region as a whole. The plantation serves as a microcosm for the trends and changes that occurred at similar sugar plantations on the island and elsewhere in the Caribbean. Given the recent and dramatic changes in land use in Antigua and the land degradation problems of the present, Betty's Hope provides an excellent case study for assessing the effects of long-term, single-crop cultivation followed by rapid change in land use. The perseverance of numerous records and personal documents kept by Codrington family provide a wealth of historical data to use in the evaluation of landscape change. These records provide evidence for the amount of sugar produced at Betty's Hope, allowing for inferences between the simulation of the landscape and actual land productivity in the past, which will be investigated in the next chapter.

CHAPTER FOUR:
METHODS

4.1 Introduction

Effective historical archaeology combines multiple research methods to ensure that archaeological and historical data are synthesized in a constructive manner (Deetz 1988:362; Orser 1996). Research into the human and natural causes of contemporary landscape degradation in former sugar islands like Antigua can be accomplished using three main analytical components: a simulation of historic sugarcane yields, historical data documenting historical crop yields, and geoarchaeological data about land degradation. Analysis of the computer simulation, historical records, and geoarchaeological data can unravel the causes, both natural and anthropogenic, of landscape change and current soil erosion at Betty's Hope. As stated in Chapter 1, there are three possible explanations for modern degradation: 1) landscape degradation is predominantly anthropogenic; 2) landscape degradation is the product of natural environmental processes; or 3) degradation is linked to both human and natural factors.

If landscape degradation is predominantly anthropogenic, it can be concluded that humans overused the land until it failed. This view is concordant with arguments that intensive monoculture, especially over long periods, contributes to steady soil exhaustion, erosion, and environmental degradation. If current degradation is attributable largely to agriculture, I expect the historical records to corroborate simulated yields and display a steady decline in crop yields (though year-to-year variation is expected) as the soil is gradually exhausted by monoculture. I expect the geoarchaeological data to provide evidence of gradual erosion and degradation in the past, such as nutrient-depleted soils, where lines of evidence can be found in the presence or absence of phosphate (PO_4); iron (Fe); manganese (Mn); and soil organic matter in buried A horizons. If three centuries of agriculture contributed to degradation, careful examination of the landscape should reveal a recent (post-1972) reversal of these conditions through enrichment and stability of upper soil horizons, indicating landscape recovery from the historical processes that have contributed to current degradation.

If landscape degradation is the product of natural environmental processes, it can be concluded that natural events such as climate-induced flooding or drought have contributed to current land degradation. If degradation is the result of natural processes, I expect the historical records to report a decline in sugarcane crop yields during years of known climatic events, a factor for which the EPIC (Erosion Potential Impact Calculator) model cannot compensate. Rather than a steady decline in crop yields over time, the historical records should display decreases and increases in crop yields following periods of known droughts, floods, and other major climate events. I expect the geoarchaeological data to substantiate the punctuated effects of climatic events, possibly by buried alluvial soil layers or evidence or erosional events in the past. If natural factors are responsible for current land degradation, then the effects of such processes should be visible in the stratigraphy.

An abrupt abandonment of the landscape occurred when the last sugar refinery in Antigua closed in 1972 (Museum of Antigua and Barbuda 2014; Weaver 1988:321), removing the human maintenance of the landscape and thus making it susceptible to rapid degradation. If the abandoning the garden hypothesis is correct, I expect the historical records to provide evidence of relatively stable sugarcane yields (with year to year variation) or gradually declining yields, as human investment of landesque capital should have ameliorated the acuity of natural degradation caused by monoculture (though it is unlikely to have staved it off entirely). The Erosion Productivity Impact Calculator (EPIC) model cannot account for the investment of landesque capital, thus the differences between historically recorded and EPIC simulated yields may corroborate this hypothesis. I expect the geoarchaeological data to provide evidence of recent erosion and degradation, such as buried A horizons under a thick layer of recently eroded sediment. The geoarchaeological data should provide evidence of relative landscape stability in the past (though the effects of climatic events may be present), such that little erosion or nutrient depletion (PO_4, Fe, Mn, organic carbon percentage) is present in A horizons that were cultivated in the past.

4.2 EPIC Model Methods

The Erosion Productivity Impact Calculator (EPIC) model was created in 1981 by the U.S. Department of Agriculture-Agricultural Research, Soil Conservation and Economic Research Services (USDA-ARS, SCS and ERS) at the Grassland Soil Water Research Laboratory in Temple, Texas to determine the relationships between soil erosion and productivity in the United States (Easterling et al. 1992:18; Gassman et al. 2005:2; Williams et al. 1984). The model was developed following the 1977 Soil and Water Resources Conservation Act (RCA), which required the Secretary of Agriculture to assess soil and water resources and make long-range policy decisions about the use and protection of these resources (Williams 1990:421). The EPIC is a mathematical model for simulating erosion, crop production, and related physical processes for different agricultural regions, allowing the input of data pertaining to specific factors for a given location and scale, and the output of reliable erosion and productivity predictions over time (Easterling et al.1992:18; Wingard and Hayes 2013:xvi). The model is used to: 1) assess the effect of soil erosion on productivity; and 2) predict the effects of management decisions on soil, water, nutrient and pesticide movements and their combined impacts on soil loss, water quality and crop yields for areas with homogeneous soils and management (Blacklands Research and Extension Center 2014). The model simulates a hydrologic land use unit (HLU), a field, farm, or small watershed that is homogenous in climate, soil, land use, and topography (Gerik et al. 2013:1).

Such a model can simulate the relationship between soil erosion and productivity for Betty's Hope Plantation, creating a baseline that can be evaluated by archaeological and historical data. The major advantage of the EPIC model is that it predicts crop yields based on specific geographic, climate, and crop data, allowing for the simulation of agriculture over long periods. The major drawback of the model is that it is designed for modern mechanized agriculture and contains parameters for physical processes (including management decisions on soil, water, nutrient and pesticide movements, and their combined impact on soil loss, water quality; Texas AandM AgriLife Research 2014) that cannot be measured for cultivation in the past. Additionally, the exact climate and soil conditions and the area of acreage under cultivation at any one point in time are largely unknown for the Codrington estates, thus the model cannot account for the changes in acreage or agricultural techniques in the past. The model also cannot account for human activity and new investments of landesque capital over time. However, for the purposes of this research, the EPIC model serves to create a hypothetical simulation of crop yields if all soil, climate, acreage, planting strategies are kept constant over time. Obviously, these parameters were not constant during Betty's Hope Plantation's nearly 300-year production span, thus deviations of historical yields in comparison to the EPIC model are expected.

The model incorporates nine discrete categories of variables: hydrology, weather, erosion, nutrients, soil temperature, plant growth, tillage, plant environment control, and economics (Easterling et al. 1992:18; Gassman et al. 2005:4; Gerik et al. 2013:1; Williams 1990:421). The hydrology variables in an EPIC model include predictions of surface runoff from daily rainfall, water percolation through the soil in the crop root zone, lateral subsurface water flow, evapotranspiration, and snow melt runoff. The weather variables include precipitation patterns, air temperature and solar radiation, wind, and relative humidity. Erosion variables include simulations of water and wind erosion patterns. Nutrient variables include the amount of nitrogen and phosphorous in surface runoff. Soil temperature variables rely on the daily average temperature of each soil layer. The plant growth variable uses a single model to simulate the growth of all crops considered in the model. The tillage variable combines nutrients and crop residue with the plow depth to predict the effect of plowing. Plant environmental control variables include drainage, irrigation, fertilization, and lime use. As previously mentioned, these operations changed over three centuries of monoculture at Betty's Hope, thus several of these parameters were deliberately left blank to create a simulation that did not incorporate the effects of tillage, fertilization, and drainage systems (see section 4.3 of this chapter). EPIC operates on a continuous basis using a daily time step (a time step is the interval of time for which the model equations are carried out) and is capable of performing long-term simulations for up to 4,000 years (Gassman et al. 2005:5; Gerik et al. 2013:1). By calibrating the model's variables to reflect the variables of a given agricultural production region, EPIC can estimate the long-term relationship between soil erosion and productivity (Williams 1990).

While the original purpose of EPIC was to estimate soil erosion by water under different crop and land management practices, the model has evolved since its creation in 1981. The EPIC model is currently utilized for a variety of field, regional, and national studies in the U.S. and in other countries. Major applications of the model include studies of: crop growth and yield, irrigation, climate change impacts, nutrient cycling and loss, wind and water erosion, soil carbon sequestration, and economics and environment. To acknowledge the broadened range of applications of the simulation, the EPIC acronym now stands for "Erosion Policy Impact Climate" (Gassman et al. 2005:2).

While EPIC is primarily used in agricultural contexts to simulate soil erosion and the effects of crop management decisions, a small number of archaeological studies have drawn upon the EPIC model to simulate human activities in the past. Huang and colleagues (2006) demonstrate the value of constructing EPIC simulations in their assessment of soil water content, seasonal evapotranspiration, and crop yield predictions in Loess Plateau, China. Using data collected over the course of 20 years, Huang and colleagues determined that EPIC correctly estimated the long-term values of these three variables for crops of winter wheat and maize. Since the simulation is accurate, the EPIC model is reliable for projecting other changes in the Loess Plateau (Huang et al. 2006:1). Because EPIC simulations rely on data about physical processes of the landscape and can operate based on daily measurements, the model can recreate trends in landscape and soil variables in the past and forecast future changes. However, since EPIC produces hypothetical models, they must be tested with real-world data to assess the accuracy of the predictions. Huang and colleagues (2006) prove that the EPIC model for the Loess Plateau was, in fact, accurate in its predictions of values for soil water content, seasonal evapotranspiration, and crop yield. The EPIC model is then reliable enough for use in development of land and crop management strategies.

4.3 EPIC Model Data

In this study, an EPIC model simulates the trajectory of landscape change at Betty's Hope Plantation. The model was created using publicly available data for each of the nine categories of variables. To run the model, as much information as possible was entered into the EPIC program. It is important to note, however, that the data for some categories of variables were extensive and thorough, while the data for other categories were sparse, incomplete, or nonexistent. The EPIC model is a hypothetical recreation of the Betty's Hope landscape, and it is assumed that all variables have been either static or changing at a regular rate, based on the available data put into the model. With as much information as possible entered into the software, the program was executed to model conditions at Betty's Hope in the past. The model provides a hypothetical baseline for changes in soil and crop yield at Betty's Hope. Using data extrapolated from historical records and soil samples, the EPIC simulation can be tested for deviations to the linear projection of change over time.

The EPIC model is maintained by the Texas AandM Blacklands Research and Extension Center (BREC), which provides an interactive software package to help manage and execute large EPIC simulation sets (Texas AandM AgriLife Research 2014). The software version used in this analysis is iEPIC0509, available at http://www.public.iastate.edu/~tdc/i_epic_main.html. I downloaded a 20-record sample dataset provided with the software and modified an existing record to replace sample values with Antiguan soil, weather, and geographic, and to input sugarcane cultivation scheduling and actions (Figure 4.1).

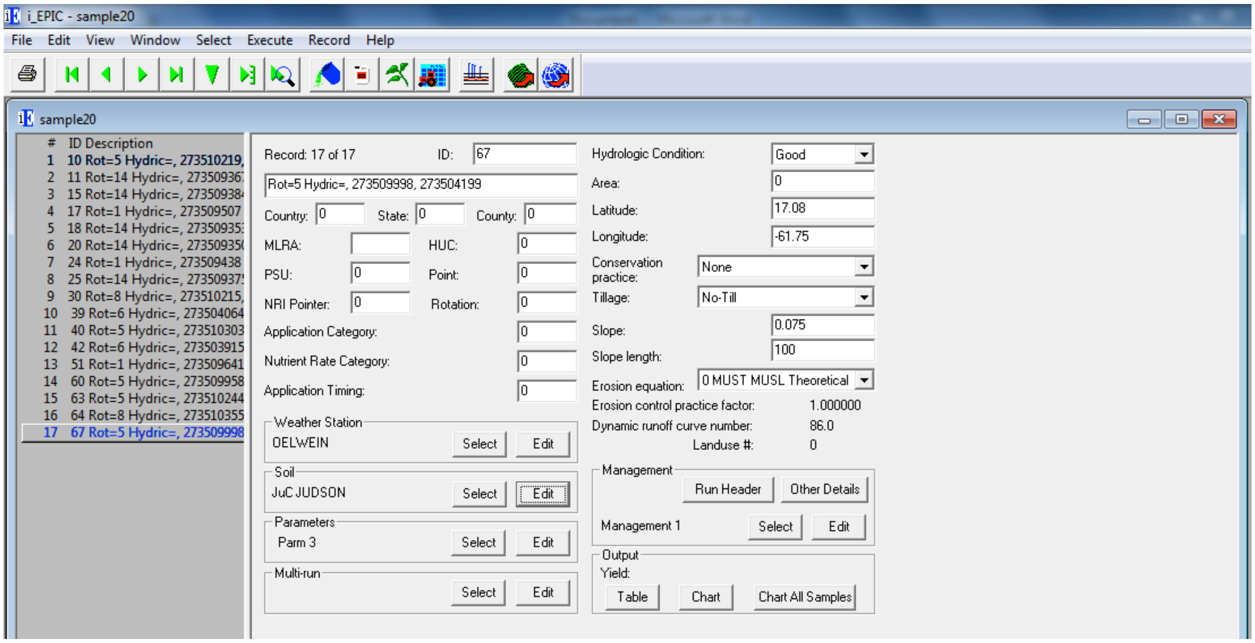


Figure 4.1. *EPIC record. Screenshot of the iEPIC0509 window displaying a record with parameters modified to create a hypothetical agricultural field in Antigua.*

A report of weather data was obtained from WeatherSpark, a website compiling climate data obtained from the National Oceanic and Atmospheric Administration, the Norwegian Meteorological Institute and World Weather Online to generate interactive weather graphs allowing the examination of weather history at weather stations across the globe (WeatherSpark 2014). The Antiguan weather report documents the typical weather in Antigua based on observations recorded between 1974 and 2012. All weather measurements were collected daily at the VC Bird International Airport (Saint John's, Antigua) weather station. For the purposes of generating weather patterns in the EPIC software, I used the average monthly values for precipitation, temperature, humidity, and wind speed provided in the WeatherSpark report. I used Microsoft Excel to calculate the standard deviations for monthly minimum and maximum temperatures and standard deviations and skew coefficients for monthly precipitation as these parameters were required by the EPIC model. Table 4.1 reports the weather data entered into the EPIC model software. Parameters for which I could not obtain data (average monthly solar radiation, probability of a dry day followed by a wet day, and probability of a wet day followed by a dry day) were left blank, as these fields are not imperative for the model to function.

Soil data for the EPIC model were based on values obtained during laboratory analyses of the soil samples removed from Betty's Hope. Auger probe 16 was used to recreate a hypothetical soil profile because this soil profile is located in a fallow field with simple stratigraphy: a thick and fertile A horizon followed by B and C horizons with gradually decreasing mineral concentrations (see Chapter 6 and Appendix VI.xvi for a detailed description of this soil profile). The changes in mineral and particle concentration down this soil profile follow the expected patterns in a normal soil profile. In order to simulate a simple agricultural field using EPIC, I entered the values for pH, organic carbon percentage, calcium carbonate percentage, and soil texture from auger probe 16 to build three soil horizons (Figure 4.2). Sugarcane growth is optimal in well drained, deep, loamy soil with a bulk density of 1.1 to 1.2 g/cm^3 (Bakker 1999:16) thus the bulk density for each layer in the EPIC model was assigned a value of 1.2 g/cm^3. Parameters for which data were unavailable were left blank.

The entry of agricultural operations into the EPIC model proved challenging. The EPIC model is designed to simulate modern farming activities; however, large-scale, mechanized, high-tech agricultural techniques did not exist in Antigua in the seventeenth, eighteenth, or nineteenth centuries. As a result, I created a simple agricultural operation with three steps: planting of crops in a row, harvesting without killing the crop, and termination of the crops (Figure 4.3). No operations for tillage or fertilization were included in order to simulate annual crop yields if human activity was kept constant. This disregards the potential effects of investments of landesque capital—such as liming, manuring, fertilization, construction of cane holes, and tilling—in order to produce a simulation free of human impacts in order for a better

Table 4.1. Antiguan Weather Data (Weatherspark)

	Temperature				Precipitation			Precipitation Occurrence				Other		Wind
Month	Avg. Max.	Avg. Min.	STD Max.	STD Min.	Avg.	STD Daily	Skew Coeff. Daily	Avg. Days of Rain	Prob. dry/wet	Prob. wet/wet	Max. 1/2-hr Rainfall	Avg. Solar Radiation	Avg. Relative Humidity	Avg. Wind Speed
Jan.	27.71	23.25	0.56	0.59	46.00	0.62	0.04	18.00	0.00	0.00	0.00	0.00	0.81	6.30
Feb.	27.82	22.94	0.60	0.45	41.43	0.67	1.20	16.00	0.00	0.00	0.00	0.00	0.79	6.26
Mar.	28.17	23.37	0.68	0.56	33.78	0.47	0.80	14.00	0.00	0.00	0.00	0.00	0.79	6.12
Apr.	28.79	24.01	0.56	0.64	35.46	0.54	0.69	12.00	0.00	0.00	0.00	0.00	0.80	5.92
May	29.53	25.02	0.72	0.47	45.44	0.88	0.64	13.00	0.00	0.00	0.00	0.00	0.82	5.93
Jun.	30.18	25.99	0.45	0.38	38.39	0.54	0.70	14.00	0.00	0.00	0.00	0.00	0.81	6.75
Jul.	30.43	26.11	0.54	0.36	53.10	0.64	1.12	18.00	0.00	0.00	0.00	0.00	0.81	6.98
Aug.	30.70	26.18	0.48	0.38	53.02	0.65	0.52	18.00	0.00	0.00	0.00	0.00	0.81	6.22
Sept.	30.49	25.68	0.64	0.47	52.23	0.73	0.41	16.00	0.00	0.00	0.00	0.00	0.83	5.11
Oct.	30.02	25.20	0.59	0.49	60.89	0.88	0.55	16.00	0.00	0.00	0.00	0.00	0.83	4.70
Nov.	28.97	24.63	1.10	0.59	51.77	0.87	0.21	17.00	0.00	0.00	0.00	0.00	0.84	5.09
Dec.	28.26	23.76	0.61	0.53	51.43	0.96	0.37	17.00	0.00	0.00	0.00	0.00	0.82	5.77

comparison with historical crop yields which do reflect the effects of unexpected human and natural forces. The EPIC model contained data for a variety of crops, including sugarcane, allowing me to specify that agricultural operations to be carried out with sugarcane as the crop.

Sugarcane takes approximately 18 months to mature before it is harvested. In Antigua and the rest of the West Indies, sugarcane was typically planted between August and November, allowed to grow for a year and a half, and harvested between January and June (Watts 1990:176). To account for the multi-year growth period, I set the duration of the agricultural operations to span three years. Consequently, these settings produced crop yield estimates for every third year. These estimates represent the hypothetical amount of sugarcane produced per acre of land per planting/harvesting cycle.

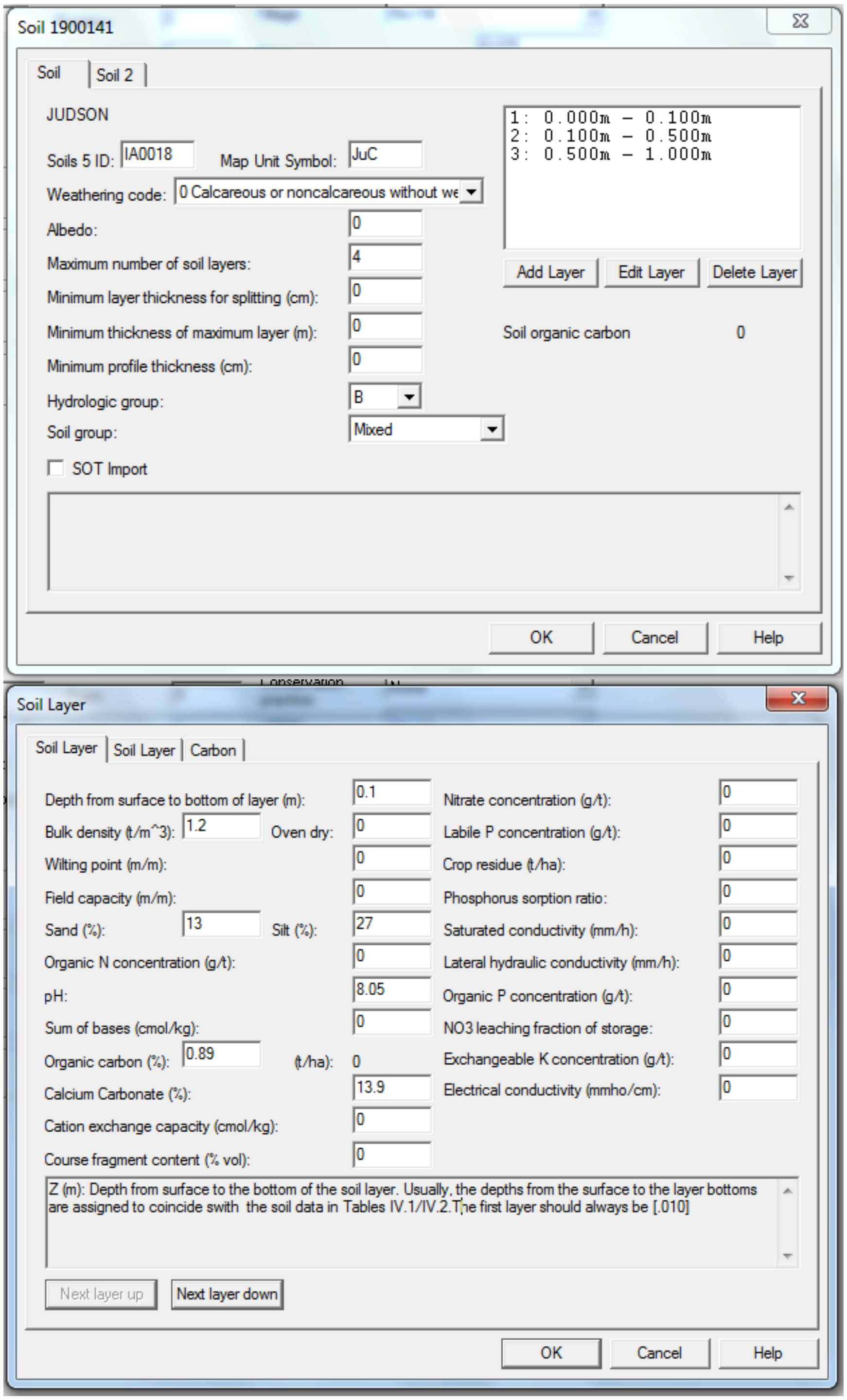
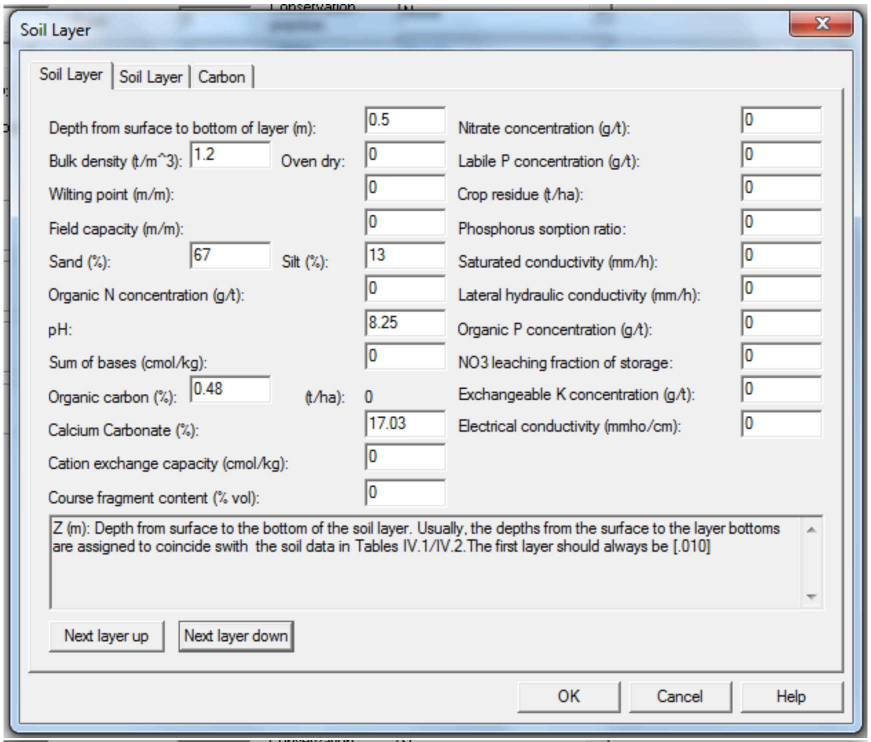


Figure 4.2. *EPIC soil parameters. Screenshots of the EPIC soil parameters using pH, organic carbon percentage, calcium carbonate percentage, and soil texture data from auger probe 16. Top: creation of three soil layers. Bottom: soil layer 1 (A horizon).*



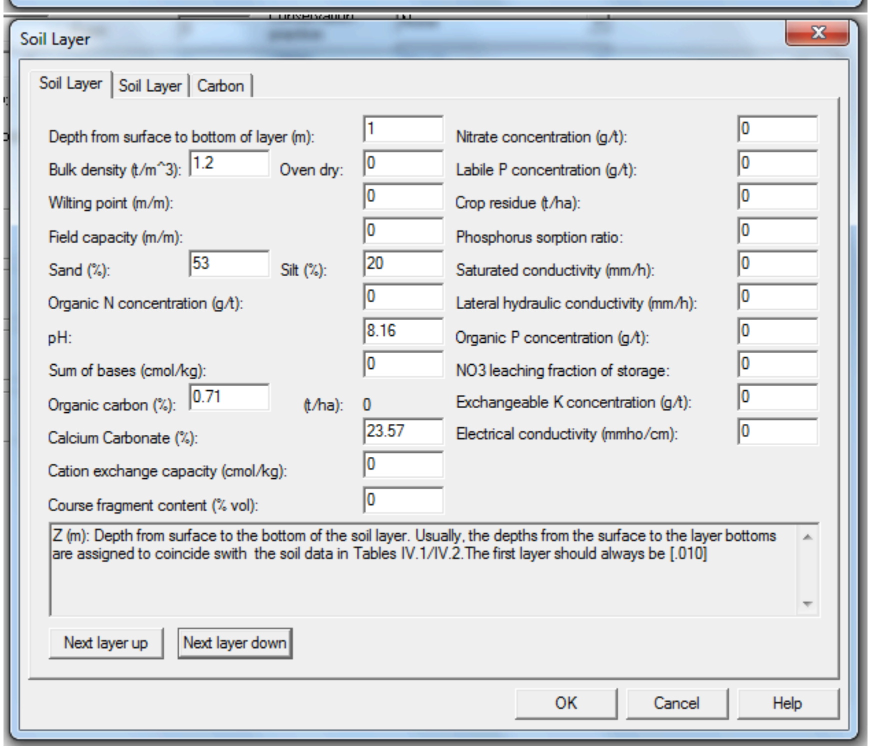


Figure 4.2 (continued). *EPIC soil parameters. Screenshots of the EPIC soil parameters using pH, organic carbon percentage, calcium carbonate percentage, and soil texture data from auger probe 16. Top: soil layer 2 (B horizon). Bottom: soil layer 3 (C horizon).*

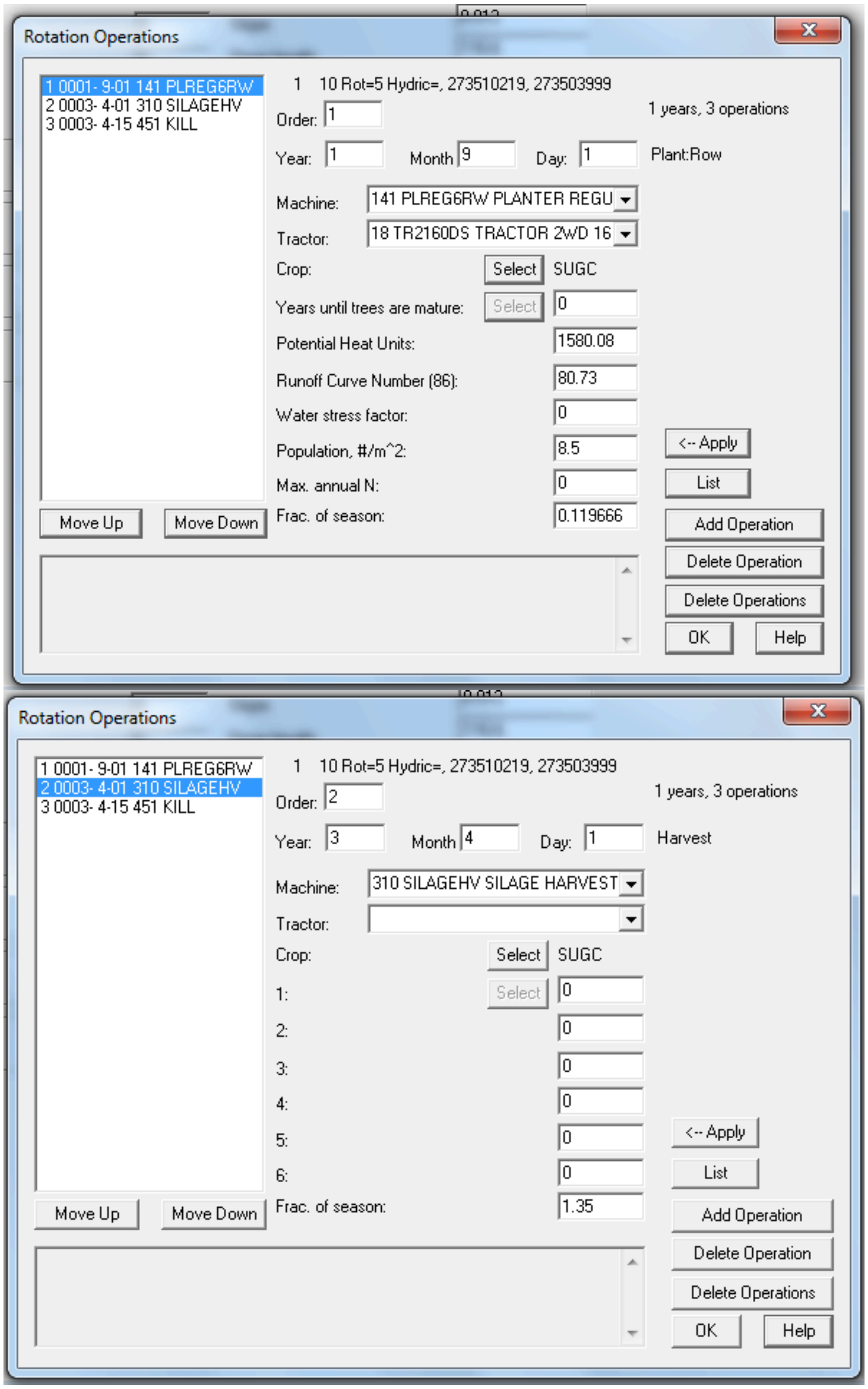


Figure 4.3*. Rotation operations for the EPIC simulation. The first operation (top) instructs the software to simulate the planting of sugarcane in a row, beginning in September of year 1. The second operation (bottom) instructs the software to simulate harvesting without killing the crop at the beginning of April of year 3, allowing the crop to grow for 20 months.*

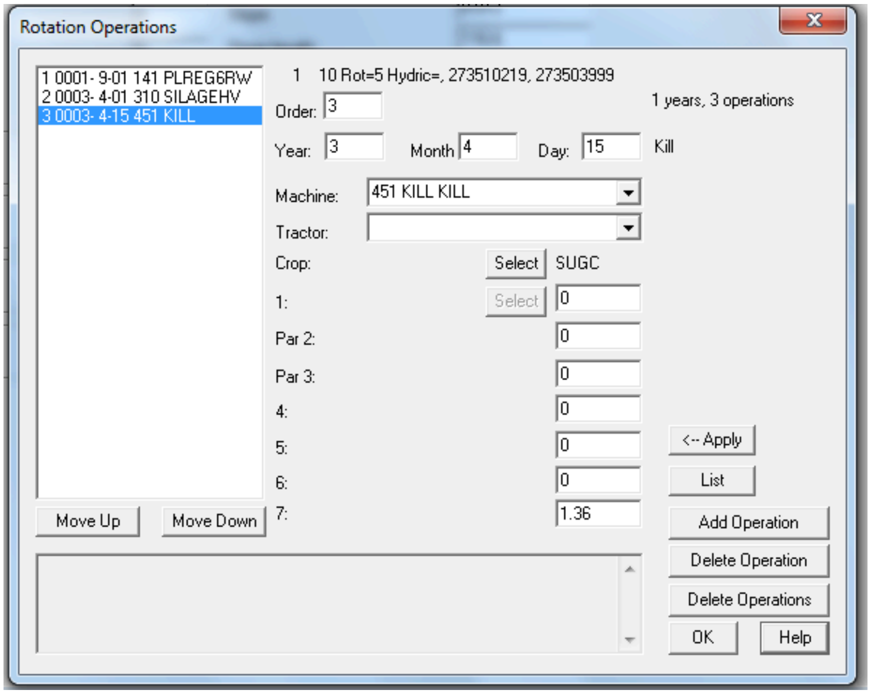


Figure 4.3 (continued). *Rotation operations for the EPIC simulation. The third operation instructs the software to terminate the sugarcane crop in the middle of April of year 3.*

4.4 Historical Records Methods

The second component of this research involves analysis of primary historical records. Historical archaeology is unique in that it deals with the documentary evidence for past human activity. Historical documents and records are a "form of artifact produced under certain material conditions embedded within social and ideological systems" (Hodder 2000:112). Lincoln and Guba (1985) distinguish documents and records based on intended function: documents are personal (diaries, letters, memos, etc.) while records are prepared for some formal transaction (contacts, government documents, bank statements, etc.; Hodder 2000:111). Documents necessitate more contextualized interpretations than the less personal records, though all interpretations of historical documents and records require careful assessment (Hodder 2000:111). In this study, four records provide information about sugar sales and crop yields, providing a proxy measurement for crop yields at Betty's Hope.

The Codrington family owned and operated Betty's Hope from 1674 until 1944, a long tenure for a single family in Caribbean plantation history (Fox 2013:5). As the majority of Antiguan plantation owners, including the Codringtons, were often absentee, lands were left under the management of attorneys and supervisors who sent detailed accounts of plantation affairs, notices of shipments of sugar and rum, and yearly account statements to plantation owners (Sheridan 1957:4). These correspondences frequently included general observations of crop prospects, prices, and political, military, and social affairs on the island (Sheridan 1957:4). Correspondence between the plantation managers and the Codringtons was retained by the family at their estate in Dodington in Gloucester, England, resulting in a collection of documents spanning over 250 years of plantation operations. These documents, collectively referred to as the "Codrington Papers," provide insight into the period of sugar domination in the Caribbean. The Codrington Papers consist of correspondences and other records kept by the Codrington family pertaining to the West Indies and the family's numerous estate holdings in the Caribbean. Collectively, these records date from 1700 to 1939. The original documents are housed at the National Museum of Antigua and Barbuda, but scanned microfilms are accessible online, maintained by the Simon Fraser University Library.

Among the collection of the Codrington Papers are four documents recording sugar sales: "Annual Statements of Total Sugar Crop 1801-1838, with Calculations of Profits from Antigua and Barbuda 1707-1830, etc.," "Sugar Accounts of C. B. Codrington, with M. Trattle, merchant 1802-1807," "Sugar Accounts of C. B. Codrington, with M. Trattle, merchant 1807-1813," and "Account Sales Book of C. B. Codrington for Sugar and Wool 1824-1828" (Codrington Papers, West Indies Correspondence 1807, 1813, 1828, 1838).

The first document provides a record of the annual sugar produced by all Codrington estates in Antigua, including Betty's Hope and three other plantations: Cotton, Garden, and New Work. The other three documents detail the total amount of sugar or rum sold in single transaction, as well as the date of the sale, the transfer of goods, the taxes and costs associated with shipping and customs, and the net profit of the sale in pounds (Figure 4.4). These records provide exact amounts of sugar and rum sales in quantities of hogsheads (wooden barrels containing 63 U.S. gallons), tierces (smaller wooden barrels containing 42 U.S. gallons), and puncheons (large barrels containing 84 U.S. gallons). While the documents record the total amount of sugar produced and sold from all Codrington estates on Antigua, the records contribute a proxy measurement for the crop yield at Betty's Hope Plantation.

I reviewed each of the documents and totaled the quantities of sugar and rum in each sale or annual report. For the first document, "Annual Statements of Total Sugar Crop 1801-1838, with Calculations of Profits from Antigua and Barbuda 1707-1830," annual crop yield (in hogsheads) was provided in a list. A hogshead is an English unit of capacity equivalent to a quarter of an English tun. After conversion to imperial measure in 1824 through the Weights and Measures Act, the hogshead became 52.5 imperial gallons, or 238.7 liters (Great Britain 1824:339). For the sales records with Marmaduke Trattle, I totaled the amounts of hogsheads, tierces, and puncheons of sugar and rum sold per year. I then converted all amounts to hogsheads (one hogshead is equal to 1.5 tierces and 1.33 puncheons). This allowed me to total the number of hogsheads per year produced by all Codrington estates in Antigua from 1707-1751, 1760-1779, 1782-1790, 1802-1814, 1817-1826, and 1828. The gaps in the record during this period are due to the lack of records for these years or the poor quality of the microfilm scan that rendered

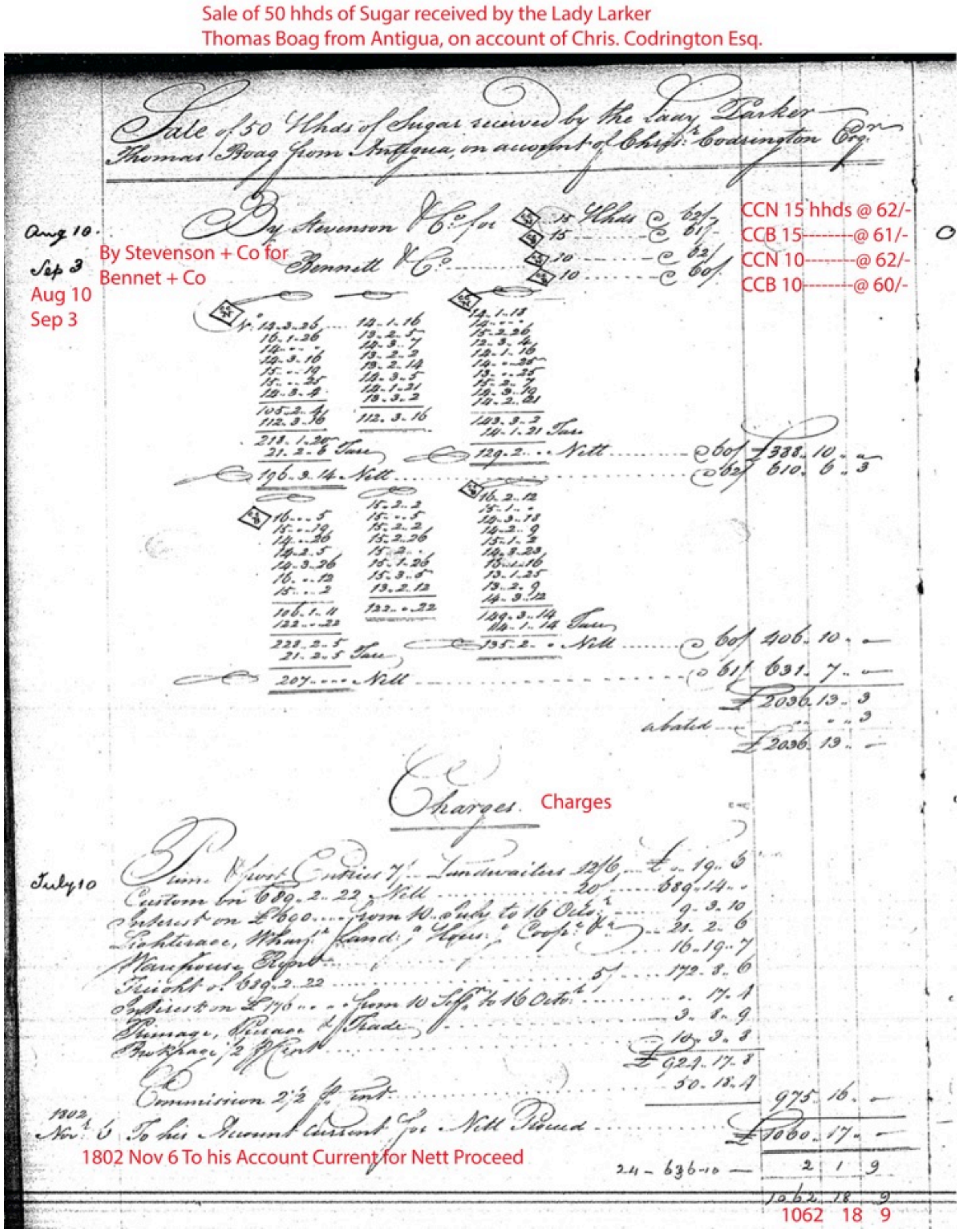


Figure 4.4. Sugar record. *A sugar sales record detailing the sale of 50 hogsheads of sugar in 1802 from the document titled "Sugar Accounts of C. B. Codrington, with M. Trattle, merchant 1802-1807." The red text is a transcription of relevant sales information (SFUL D1610 A60/1; Pratt 2014).*

the documents illegible. Sugar quantities were entered into Microsoft Excel and totaled by year.

I then converted the amount in hogsheads to tons. According to Waterston (1859), in the mid-nineteenth century, sugar hogsheads from the West Indies contained 1456-1792 pounds of dry goods, or the equivalent of 63 gallons of liquid. To convert hogsheads to tons, I multiplied the number of hogsheads by 1456 and divided by 2000. These figures represent the amounts of sugar products produced by the Codrington estates, serving as a proxy for raw sugarcane reaped from the fields. The tons cane/tons sugar ratio, also known as the recovery rate, indicates the quantity of cane required to produce a ton of crystalline sugar (Abbott 1964:12). In 1940, Antigua's ratio of tons of sugarcane to tons of sugar was 8.58 to 1. However, this measure of productivity was calculated for the end of Antigua's tenure as a successful sugar island, and Abbott notes that Antigua was "the most inefficient producer of all the West Indian islands" at this time (Abbott 1964:16). I multiplied the amounts of sugar products sold (in tons) by 8.58 to determine approximate annual crop yields in tons. Although the recovery rate of tons cane to tons sugar was not constant over time, the multiplication by the recovery rate from 1940 does not affect the changes in calculated crop yields from year to year. Using the reported quantities of sugar products sold from 1707 to 1828, I can extrapolate historical crop yields (in tons) and assess the changes in annual yields over time. This also allows for the comparison of historical yields to the simulated yield in tons per acre produced by the EPIC model.

Some of these historical documents also recorded notes and observations about the general status of the Codrington estates. Reports on the status of the sugarcane crop were flagged in the documents for further analysis following the comparison of historic sugar yield and EPIC simulated yields. Historical observations about factors, both human and natural, that may have influenced the sugarcane yield in a given year may be useful in explaining deviations of the historical yields from the simulated yields.

4.5 Geoarchaeological Methods

Geoarchaeology is the application of geological techniques to answer archaeological questions, studying sites within their local and regional geomorphic contexts (Scudder et al. 1996:5; Wilson 2011:1). Geoarchaeology draws on methods and techniques from the fields of geomorphology (study of landforms and the processes shaping them), sedimentology (study of sediment and its formation), structural geology (study of distribution of rock units and their deformational histories), hydrology (study of the movement, distribution, and quality of water), and pedology (study of soils in their natural environment) (Farrand 1975; Holliday 1985; Scudder et al. 1996:5). Geoarchaeology brings together methods and questions from both the natural and the social sciences to examine the natural landscape elements that surrounded or were incorporated into past human settlements. An interdisciplinary approach makes it possible to interpret the ways humans affect the geosphere through subsistence and resource exploitation activities, settlement location, and local and regional land use patterns (Wilson 2011:1).

The physical and chemical effects of humans on natural soils and landscapes can be detected using the most basic tools of pedology: soil morphology, particle-size distribution analysis, clay mineralogy, and patterns of chemical element accumulation (Scudder et al. 1996:8). The application of earth science techniques for the analysis of archaeological soils has generated new levels of understanding of past human activities and use of the landscape (Walkington 2010:123). Long-established methods for analyzing soils can help to understand the changes of soils at archaeological sites over time (Walkington 2010:125).

To elucidate the human relationship with the land, it is necessary to reconstruct the dynamic and static elements of a landscape (Butzer 1982; Waters 1992:91). The dynamic portion of a landscape alternates between periods of stability, deposition, and erosion, the markers of which are preserved in sediments, soils, and erosional events in the stratigraphy (Waters 1992:91). Stratigraphic and geochronological investigations interpret the stratigraphic patterning of sediments, soils, and erosional events in order to determine the spatial and temporal record of landscape aggradation, stability, and degradation (Waters 1992:91).

Soils and sediments have similar components and form a continuum across a landscape. The distinction between sediments and soils is related to the vertical patterning of properties created by in situ transformations (Walkington 2010:123). Sediments are layered and unconsolidated materials of lithic or organic origin; they are generally paler in color and have a lower organic content than soils (Walkington 2010:123). Sediments generally accumulate rapidly during periods of landscape instability and consequently lack the characteristic weathering horizons present in soils (Goldberg and Macphail 2006; Rapp and Hill 1998; Walkington 2010:123; Waters 1992). In contrast, soils develop in situ where sediments are already deposited. Sediments provide information on the depositional processes and the specific environments that were present, while soils preserve evidence of landscape stability, and erosional unconformities provide evidence of landscape degradation (Waters 1992:91).

Geoarchaeological methods and archaeological soils have been used primarily as a means to predict site location, age, and preservation, but analysis of soils can be used to reconstruct landscapes in archaeological contexts (Holliday 2004:240). Human activity in the past disrupted natural processes of landscape evolution, and this landscape legacy can be detected by analyzing archaeological stratigraphic sequences and comparing them to modern regional geomorphology

(Scudder et al. 1996:5; Waters 1992:88). Once a stratigraphic matrix has been created for a site and the soils and sediments have been described, geoarchaeological studies can reconstruct the landscape and evaluate the formation processes (Waters 1992:88). The relationship between sloping ground and colluvium (the material accumulated at the foot of a hill slope) may provide examples of buried land surfaces and stratigraphic records of human activity, where erosion has been active (Goldberg and Macphail 2006:76).

Geoarchaeological investigations contribute to recognizing landscape and environmental change within a region (Wilson 2011:1). Using a suite of common geoarchaeological methods, this research seeks to recreate the trajectory of landscape change in the area near Betty's Hope plantation in order to determine the course of land degradation. Ninety-six soil samples were collected in June 2014 at twenty different locations along two catenas near the plantation, including near a modern farm and village, fallow agricultural fields, and near historical occupation areas (Figure 4.5). A catena is a sequence of soil types on a downhill slope; each soil type differs slightly from the neighboring soils, but all are formed in the same climate and on the same underlying parent material. A mature catena reaches equilibrium when depositional and erosional processes occur at equal rates (Bushnell 1943). The sampling strategy allowed for the collection of soils from the top and bottom of the hill slopes in order to assess disruption to the depositional and erosional patterns. All samples were extracted using a stainless steel bucket auger probe, and smaller samples were removed with a clean trowel and placed directly into sterilized Whirlpak bags for storage, and later transported to the University of South Florida for analysis.

All soils were characterized using Munsell color descriptions and soil texture descriptions. Multiple common laboratory methods were used to examine the soils, including

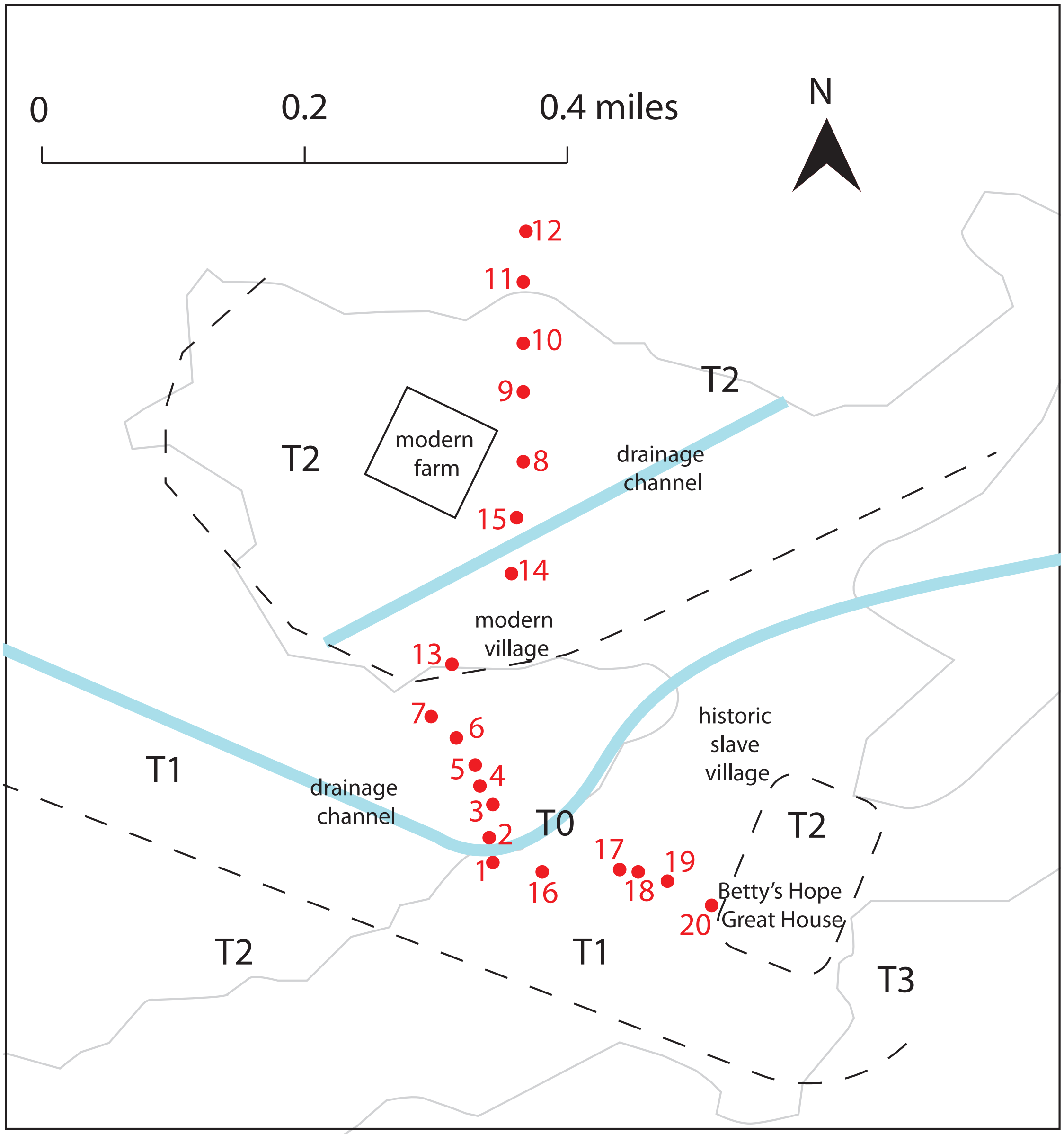


***Figure 4.5**. Locations of the 20 auger probes.*

measurement of pH, acid-extractable phosphates (P), loss-on-ignition (LOI) organic matter and carbonate content, and trace element quantification (Beach et al. 2006:169; Holliday and Gartner 2007:301; Metcalfe et al. 2009; Stein 1986).

4.5.1 Munsell Color

Soil color is a basic classification of soil types as color is an indicator of organic matter, free iron content, and sediment type (Holliday 2004:34). It was observed that determining Munsell color in natural light produced the same description as a characterization produced indoors under fluorescent light, thus all samples were characterized using a Munsell Soil Color Chart in a laboratory setting under constant, static light. Two color values were recorded for each sample: one dry and one slightly moistened. Both values were recorded.

4.5.2 Soil Texture

Particle size analysis is a routine analysis in geoarchaeology and other earth sciences. Soil texture analysis quantifies the amount of sand, silt, and clay in the sample to determine the soil type (Wells 2014). Timpson and Foss (1993) assert that soil particle-size analyses can be one of the most useful laboratory analyses for characterizing soils and parent materials in alluvial systems. Particle size and texture can indicate the sediment type and origin, and these analyses can be particularly useful in determining depositional history and discontinuities in soil profiles, indicating erosion or hiatus in deposition (Goldberg and Macphail 2006:336; Holliday 2004:34; Scudder et al. 1996:18).

To determine the soil textures of the samples from Betty's Hope, I used a simple gravitation method, using three soil separation tubes (A, B, and C), following the procedure outlined by Wells (2014). A small amount of a sample was added to tube A, filling it to line 15, and tapped lightly to allow the sample to settle and to eliminate air spaces. Following this, tap water was added to the tube until filled to line 45. The tube was then capped and shaken for two minutes then allowed to sit undisturbed for exactly thirty seconds. Following this period of settling, the solution in tube A was poured immediately into tube B. Tube B was allowed to stand undisturbed for 30 minutes and the solution was poured into tube C, which did not require a period of settling. The percentage of sand in the sample was determined by reading the soil level of the separated particles in Tube A, dividing by 15, and multiplying by 100. The percentage of silt in the sample was calculated by reading the soil level of the separated particles in Tube B, dividing by 15, and multiplying by 100. The percentage of clay in the sample was calculated by adding the volumes of sand and silt, subtracting this sum from 15, dividing by 15, and multiplying by 100. This process was repeated for each soil sample. Using the resulting percentages of sand, silt, and clay, the soil type for each sample was determined using the USDA soil texture triangle.

4.5.3 pH

The hydrogen potential (pH) of soil reflects the various human and non-human activities that input or deplete hydrogen ions (H^+) and hydroxyl functional groups (OH^-) in soil solutions (Wells 2014). This test considers the relative amount of available H^+ in the soil; the more protons, the more acidic the soil. The more OH^- present, the more alkaline (basic) the soil is. Simple pH tests extract soils from a regular horizontal grid across a surface or in vertical columns, determine the pH of each sample, and then examine the results of interruptions in the pH sequence. Disturbances to a sequence of gradual pH change can then be targeted for further analysis.

A portable digital pH meter was used to determine the pH of soil samples from Betty's Hope. For each sample, 5 g of soil was mixed with 5 mL of distilled water in a small beaker. The sample was agitated until a slurry was formed. The electrode of the meter was inserted into the solution and the pH value was recorded.

4.5.6 Phosphates

The measurement of soil phosphates and elemental phosphorous (P) are common geoarchaeological methods as indicators of human activity (Goldberg and Macphail 2006:346; Holliday and Gartner 2007:301). While humans add a number of elements to soils, phosphorous is unique in its long lifespan, thus elevated levels of total soil P can indicate a number of human activities in the past. Human activity may affect soil P levels through a variety of ways: human and animal waste, food refuse, burials, manure fertilizer, etc. (Holliday 2004:304). Phosphates (PO_4^{2-}) are produced by the decomposition of organic matter, including human bone and tissue, plant remains, and so on. (Wells 2014). Both phosphate and total P can be measured using a variety of methods, but the amounts of reported phosphate will always exceed the amount of reported P (Goldberg and Macphail 2006:346). There are two basic components to P analyses: the extraction of P from the soil and the measurement of P in the extractant.

The basic method for extracting P from the sample is by breaking the bonds between P molecules and their hosts with one or more reagents (Holliday and Gartner 2007:309). This study used colorimetry to determine P content in the samples. The aim of colorimetry is to reduce molybdophosphoric compounds in an acidic environment to create a blue-colored sample solution, the shade of which is proportional to the P content of the particular fraction that was extracted (Holliday and Gartner 2007).

Following the procedure outlined by Wells (2014), the concentrations of phosphates in the Betty's Hope samples were determined by measuring out 2 g of each sample into a test tube.

20 mL of dilute Mehlich II acid (10 mL of concentrated Mehlich II acid put into 100 mL of Type II deionized water) was added to each tube and the tubes were sealed and immediately agitated for five minutes. The soil grains were filtered into clean glass vials using Whatman ashless circle filter paper and glass funnels. Following filtration, the contents of a PhosVer 3 powder pillow were added to each solution and shaken to dissolve. The powder pillows contain ammonium molybdate, which produces a yellow phosphor-molybdate in the presence of phosphates. Through a reduction reaction with the acid, it changes to blue molybden compounds. A portable colorimeter was used to quantify the concentration of phosphates (P, P_2O_5, and PO_4) in the solutions.

4.5.5 Loss-on-Ignition Organic Carbon

Loss-on-ignition is a common and inexpensive method to estimate sediment properties including water content, organic matter, inorganic carbon, and mineral residue (Veres 2002:172). Soil organic matter analysis is used to determine the percentage of organic matter in a sample. If the amount is high (relative to the control or off-site samples), then there is a good chance that high phosphates are a result, at least in part, of the decay of plant material (Wells 2014).

The organic matter content of the samples from Betty's Hope was determined using a loss-on-ignition method. For each sample, 5 g of the sample was placed into a ceramic crucible and weighed on an electronic balance to the hundredths place. The crucible was placed in a drying oven for 2 hours at 105 ºC to run off moisture in the sample. Following this, the crucible was reweighed and placed into a Skutt automatic kiln for 2 hours at 360 ºC to incinerate the organic matter (a process referred to as "ashing"). The crucibles were then allowed to cool for several hours and were reweighed. The proportion of soil organic matter was determined by subtracting the final weight from the dry weight, then dividing the result by the dry soil weight (Wells 2014).

4.5.6 Loss-on-Ignition Calcium Carbonate

Calcium carbonate is the primary component of limestone. Ground limestone is often used as an agricultural additive to neutralize soil acidity The Lesser Antilles are composed of coral limestone bedrock of Plio-Pleistocene age (Watts 1990:12), thus is it expected that lower horizons will have higher percentages of calcium carbonate since the primary parent material of the soils near Betty's Hope is limestone. The presence of calcium carbonate in soil can affect soil productivity by influencing soil pH, structure, and water flow (McCauley et al. 2005:6).

To determine the percentage of calcium carbonate in each sample, further analyses were undertaken on the samples used to quantify soil organic matter. Following the procedure for determining soil organic matter, the crucibles containing the ashed soil samples were returned to the kiln and heated to a 1300 ºC for two hours. The samples were allowed to cool for several hours and reweighed. The proportion of calcium carbonate was determined by subtracting the final weight from the ashed weight, then dividing the result by the ashed soil weight (Wells 2014).

4.5.7 Trace Element Quantification

X-ray fluorescence (XRF) has been a part of archaeological research since the 1960s and is an analytical tool for elemental concentrations, but has not been widely used for soil activity analysis (Shackley 2011). A portable X-ray fluorescence spectrometer was used to determine the major and minor elemental composition of individual soils (Neff et al. 2012; Metcalfe et al.

2009; Shugar and Mass 2012; Stein 1986). This research used a Bruker Tracer III-SD instrument to quantify trace metals present in the soils and sediments removed from Betty's Hope.

The Bruker Tracer III instrument has a beam size of approximately 5 by 7 mm. This beam size can adequately measure elemental composition in homogenous materials, but heterogeneous material including crystalline rocks and ceramics may need to be analyzed numerous times in multiple areas to generate a representative average composition analysis (Aruna et al. 2014:225). A common preparation method for materials such as soil is pelletizing, in which the sample is ground into a homogeneous powder with a hard agate mortar and pestle. A binding agent, such as a powder containing cellulose, starch, or polyvinyl alcohol are mixed into the pulverized sample, and the mixture is pressed into a pellet with a smooth, homogeneous sample surface. As this study is concerned with transition metals, which are not absorbed in the air, gaps between soil particles do not affect the results, thus compression of pulverized samples into pellets was unnecessary. Sample preparation for this analysis consisted of powdering a small amount (3-5 g) of each sample with an agate pestle, or, if samples were compacted and clayey, a small chunk of sample was used for analysis. Each pulverized sample and each solid sample was placed into a clean plastic Whirlpak bag. For bags containing powdered samples, the bags were tapped gently to allow the samples to settle at the bottom and reduce air pockets. The samples were analyzed with a Bruker Tracer III-SD instrument by placing the bag with powered or solid samples against the analytical window of the instrument. The analysis of sample through the plastic barrier of the Whirlpak bag has no effect on sample readings since heavier elements fluoresce higher energy X-rays and thus experience little alteration while traversing through a thin plastic barrier (EDAX Smart Insight 2014). This was tested by analyzing one soil sample four times: twice through the plastic bag and twice without the plastic bag. The results for all four analyses were similar, indicating that the presence of the plastic bag had no effect on pXRF measurements.

Elements were analyzed without a vacuum and run on the 40 kV/11μA setting for 120 seconds. Each sample was analyzed twice, with the instrument's beam directed at a different part of the sample. The quantities of calcium, manganese, iron, zinc, strontium, copper, and lead in each sample were averaged to produce a single value to represent the sample.

4.6 Conclusion

Archaeology is positioned to provide long-term modeling of agricultural systems, urban systems, tropical adaptation, deforestation, and responses to climate change (Chase and Scarborough 2014:2; Lentz and Hockaday 2009). Analyses of landscape change carried out in the natural sciences have not been matched by those in the social sciences with equivalent attention to the human factors contributing to such change (Simpson et al. 2001:175). An integrated approach combining the simulation of agricultural yield, assessment of historical records, and geoarchaeological analyses can illuminate human-environmental dynamic in the recent past.

Archaeology often relies on proxy data to represent former human-environmental systems and landscapes (Kirch 2005:414). The physical remains of past human agricultural activity often extend over entire landscapes; periods of cultivation have left a record of agronomic modification (soil modifications, abandoned canals, field systems, terrace complexes, entire irrigation networks, etc.) (Kirch 2005:416). The archaeological study of agrarian landscapes has made it possible to recreate the long-term trajectory of development, expansion, intensification, and, in some cases, collapse of past agricultural systems (Kirch 2005:416). The combination of multiple methods in this study will contribute to the understanding of the ways in which intensive sugarcane cultivation and its cessation affected the landscape of Betty's Hope Plantation.

CHAPTER FIVE:
EPIC MODEL AND HISTORICAL RECORDS RESULTS

5.1 Introduction

Historical archaeology research since the 1970s has sought "to understand and/or explain the processes by which cultural forms mediate social and ecological relationships among human populations in the post-1500 world" (Deagan 1988:8). The discipline's "strength among the social sciences" is its ability consider to multiple lines of evidence related to past human behavior (Deagan 1988:7), but "for historical archaeology to be effective, research methods must be employed that ensure that both archaeological and historical data be synthesized in a constructive manner" (Deetz 1988:362). Landscape change is one of the many topics that "can be accurately described and understood only by a historical archaeological approach" "through the use of written testimony in conjunction with material byproducts" (Deagan 1988:9).

Historical archeology is suited for assessing landscape change in the recent past. An approach combining geoarchaeological and historical data can reveal the mutually influential relationship between humans and their landscape, providing necessary case studies for comparisons that might ultimately lead to the development of middle-range theory to reasonably explain the past events forming the archaeological record (Deagan 1988:10). A historical archeological approach can contribute to a better understanding of the underlying causes of current land degradation problems. A historical geoarchaeological study of land degradation at a historic Antiguan sugar plantation illustrates how historical archaeology using geoarchaeological methods can provide new insights into contemporary problems.

The EPIC-simulated sugarcane yield produces a null hypothesis of crop yields over time, suggesting what amount of sugar is expected to be if all variables (soil, weather, human activity, etc.) remain constant over time. If the historically recorded yields match the hypothetical EPIC yields, it can be concluded that Antiguan planters were growing sugarcane in a sustainable manner. If the yields do not match the EPIC simulation, it can be concluded that Antiguan farmers were overusing or underusing the land.

5.2 Sugarcane Yields Simulated by the EPIC Model

The EPIC model produced annual values for sugarcane yield (tons/acre), humus mineralization (pounds/acre), nitrification (pounds/acre), evapotranspiration (inches), P mineralized (pounds/acre), and water erosion. As discussed in Chapter 4, the EPIC model was given parameters for Antiguan weather and soil and set to simulate a 1.5-year sugarcane crop cycle from 1650 to 2049. Due to the fact that sugarcane takes 18 months to mature, EPIC produced hypothesized crop yields per acre for every third year. While Betty's Hope would have had multiple crops producing sugarcane each year, the EPIC model provides a proxy for the overall simulated crop yield.

Since all weather parameters, soil parameters, and crop operations were held constant for the entirety of the simulation, it was expected that the EPIC simulation would produce hypothesized crop yields that gradually decline over time. This expectation is informed by the suggestions of previous scholars that continuous monocropping causes a deterioration of the physical and chemical properties of soil and thus smaller yields (Abbott 1964:1; Garside et al. 2001:16; Meyer et al. 1996; Ragatz 1928; Ward 1978:198). It has also been argued that the Antiguan sugarcane industry declined over time due to soil exhaustion and a lack of agricultural technological innovation (Abbott 1964:1; Ragatz 1928; Ward 1978:198). Lowes' analysis of sugar production trends in the latter half of the nineteenth century suggested a steady decline of crop yields, though with yearly variation (Figure 5.1; Lowes 1994:10). This trend, based on historical records, corroborates the claims that sugar production declined over time, therefore it was expected that the EPIC model would simulate gradually decreasing sugarcane yields.

A table with all EPIC results, including crop yields and other physical processes, can be found in Appendix I. A bar chart of the simulated sugarcane crop yields displays the hypothetical crop yield (in tons/acre; Figure 5.2). A line graph of the simulated sugarcane yield (Figure 5.3) displays the changes in the simulated crop yields over time. It is immediately apparent that crop yields decline dramatically from 1652 to 1658 (the first and third crops).

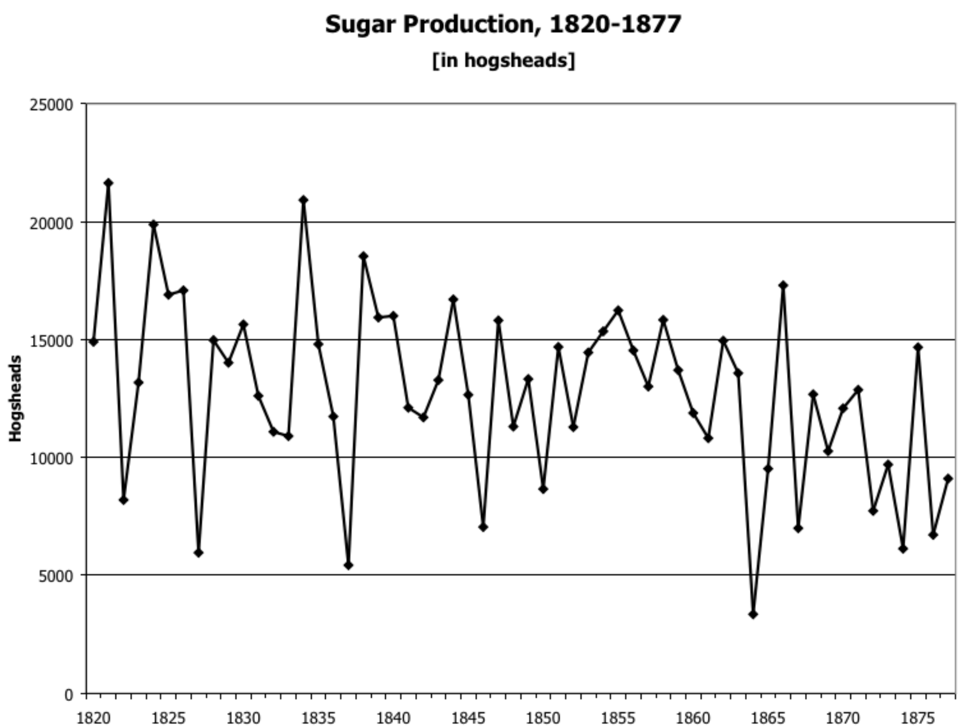


Figure 5.1. *Sugar production 1820-1877. Lowes (1994) reported annual sugar production in hogsheads from 1820 to 1877. While annual yields vary, sugarcane production declines steadily over the 50-year period (Lowes 1994:10).*

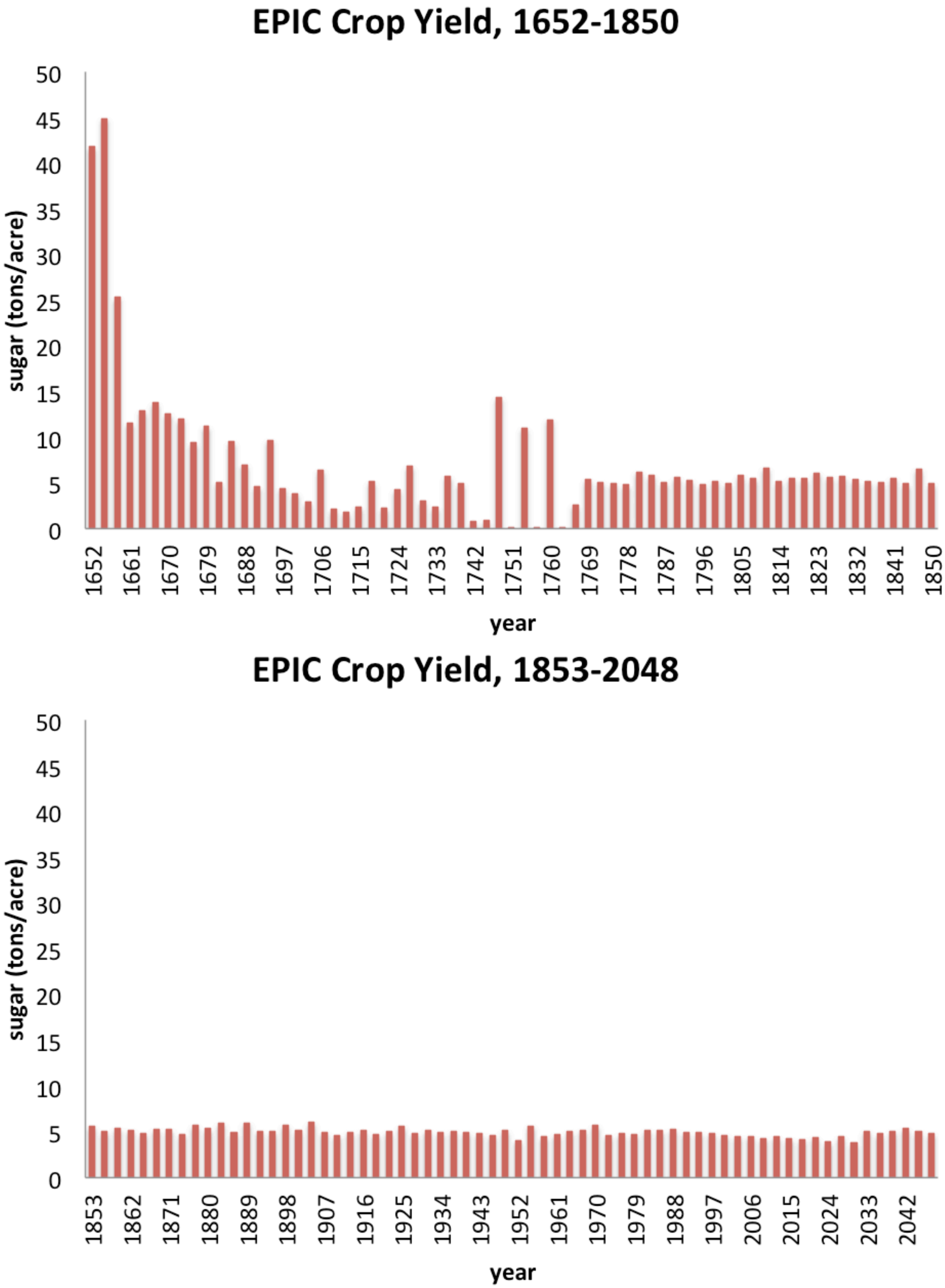
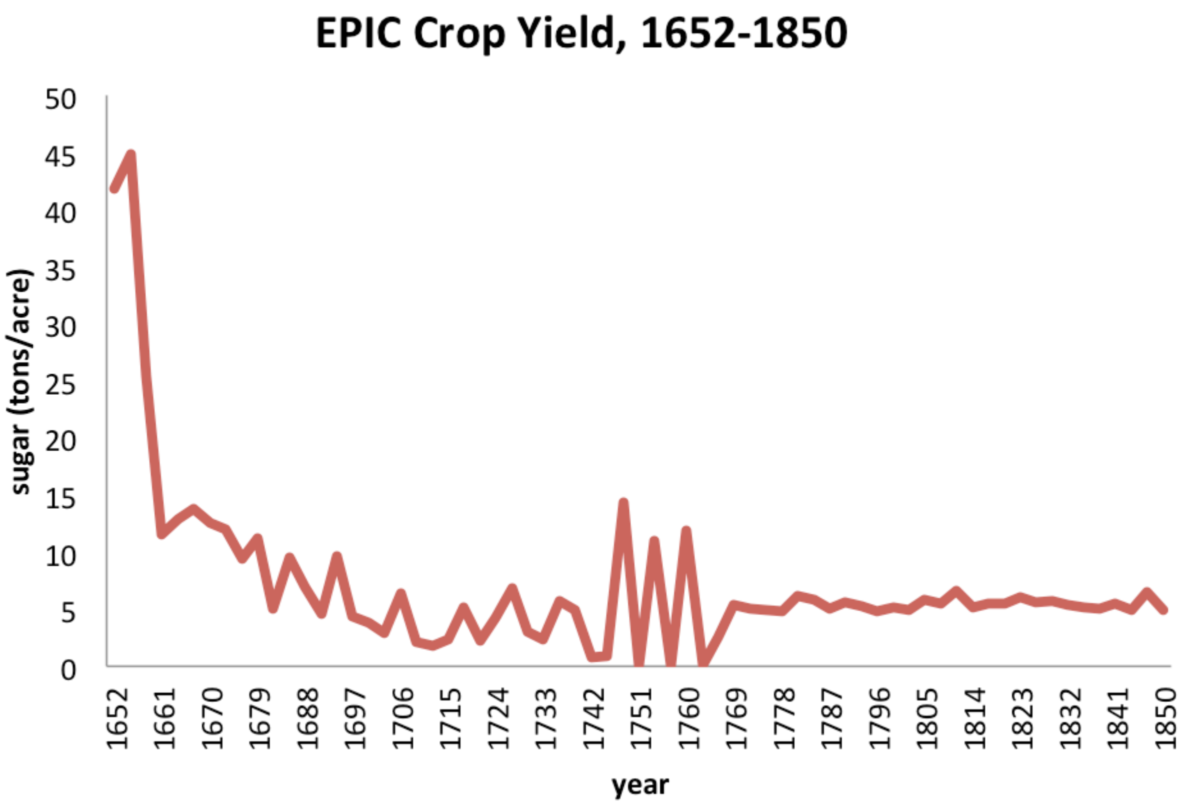


Figure 5.2. *EPIC yield bar chart. Bar chart of the EPIC-simulated sugarcane yield in tons/acre from 1650 to 2049.*



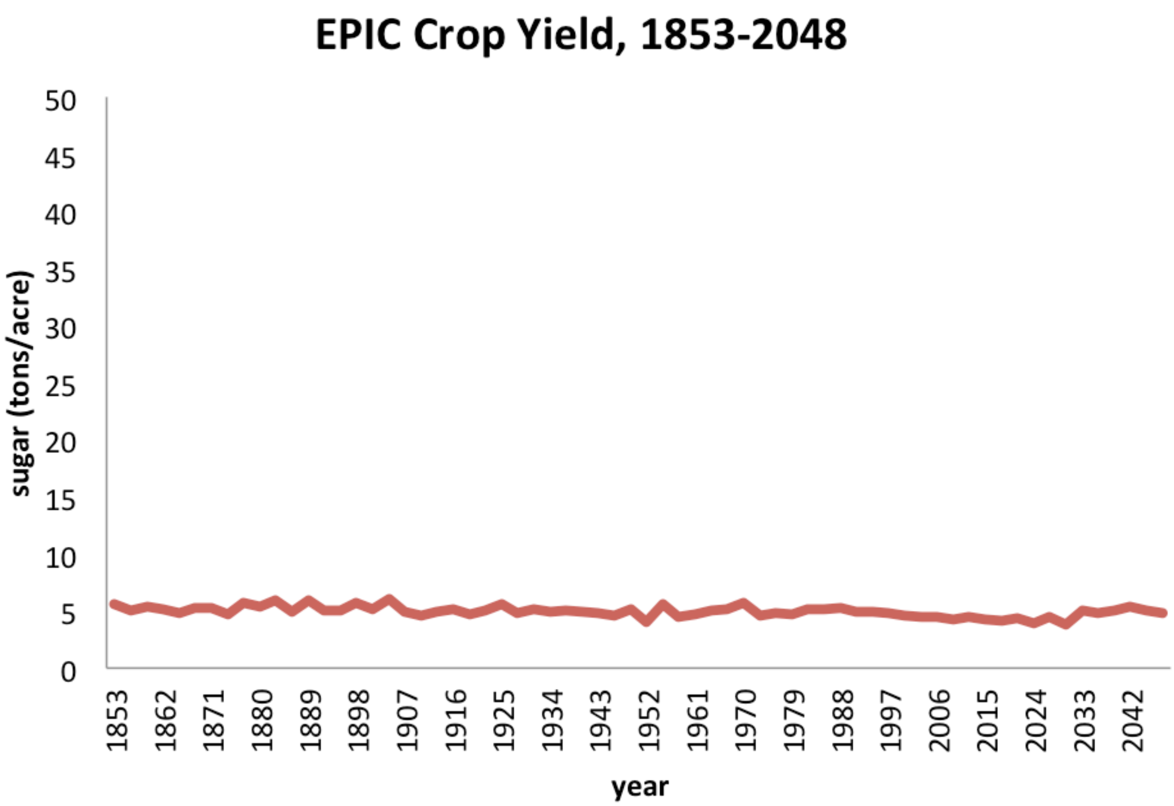


Figure 5.3. *EPIC yield line graph. Line graph of the EPIC-simulated sugarcane yield in tons/acre from 1650 to 2029.*

Although variable from crop to crop, the yield then declines steadily until 1745. From 1745 to 1766, crop yields are extremely variable, with a hypothetical yield of .84 tons/acre in 1745, 14.35 tons/acre in 1748, .05 tons/acre in 1751, 10.98 tons/acre in 1745, .05 tons/acre in 1757, 11.0 tons/acre in 1760, .15 tons/acre in 1763, and 2.57 tons/acre in 1766. Following this period of unexpected and dramatic variation, the crop yields become more regular, ranging between four and seven tons/acre from 1769 to 2048. While the post-1766 yields are significantly smaller than the yields at the beginning of the simulation, it is clear that if all soil, weather, and human variables are kept constant over time, the sugarcane yield will decline dramatically and ultimately reach a consistent reduced yield between four and seven tons/acre.

The hypothetical crop yields produced by the EPIC simulation follow the expectation that crop yields decline over time. As expected, the crop yields decline at a relatively steady rate from the beginning of the simulation to the mid-eighteenth century then are reach a smaller but consistent yield to the end of the simulation. The dramatic variation in crop yields observed from 1745 to 1766 in the simulation is unexpected, given that the model was based on constant climate, soil, and agricultural activity parameters. The period of variation does not follow the expected pattern of decreasing crop yields and does not fit with the trends of the periods before (steady decline) or after (equilibrium with limited variation). These unexpected values may be the result of the EPIC model parameters: not all parameters could be filled because EPIC is suited for modeling contemporary, not historical, agricultural activities. Although EPIC can project yields over long periods, this simulation relied on the input of only basic soil, weather, crop, and operations data and this may have affected the simulation of crop yields. Alternatively, the extreme variation during the period of 1745-1766 may be a reflection of crop yield variation in response to degraded soil caused by monoculture and a constant environment.

5.3 Sugar Yields Recorded in the Codrington Papers

Historical archaeology is unique in that it deals with documentary evidence for the human activity in the past. Historical documents and records are a “form of artifact produced under certain material conditions embedded within social and ideological systems” (Hodder 2000:112). Christopher Codrington II moved to Antigua in 1674, where he purchased land and established the 725-acre Betty’s Hope Plantation. Codrington became the Captain-General of the Leeward Islands in 1689 (Dyde 2000:28; Lowe 1951:44). Due to his distinguished career and services, he was granted the island of Barbuda in 1684, and the island remained under the control of the Codrington family for over two centuries (Lowe 1951:44). Codrington’s eldest son, also named Christopher (III), was born in 1668 and took over his father’s position as Captain-General of the Leeward Islands in 1698 (Lowe 1951:44).

The four records examined in this analysis (“Annual Statements of Total Sugar Crop 1801-1838, with Calculations of Profits from Antigua and Barbuda 1707-1830,” “Sugar Accounts of C. B. Codrington, with M. Trattle, merchant 1802-1807,” “Sugar Accounts of C. B. Codrington, with M. Trattle, merchant 1807-1813,” and “Account Sales Book of C. B. Codrington for Sugar and Wool 1824-1828”) provide exact amounts of sugar and rum produced and sold by the Codrington estates in Antigua. By comparing the hypothetical crop yield produced by the EPIC model with the amounts extrapolated from these records, this research can assess whether land degradation caused a steady decline of crop yields or if human activity staved off degradation.

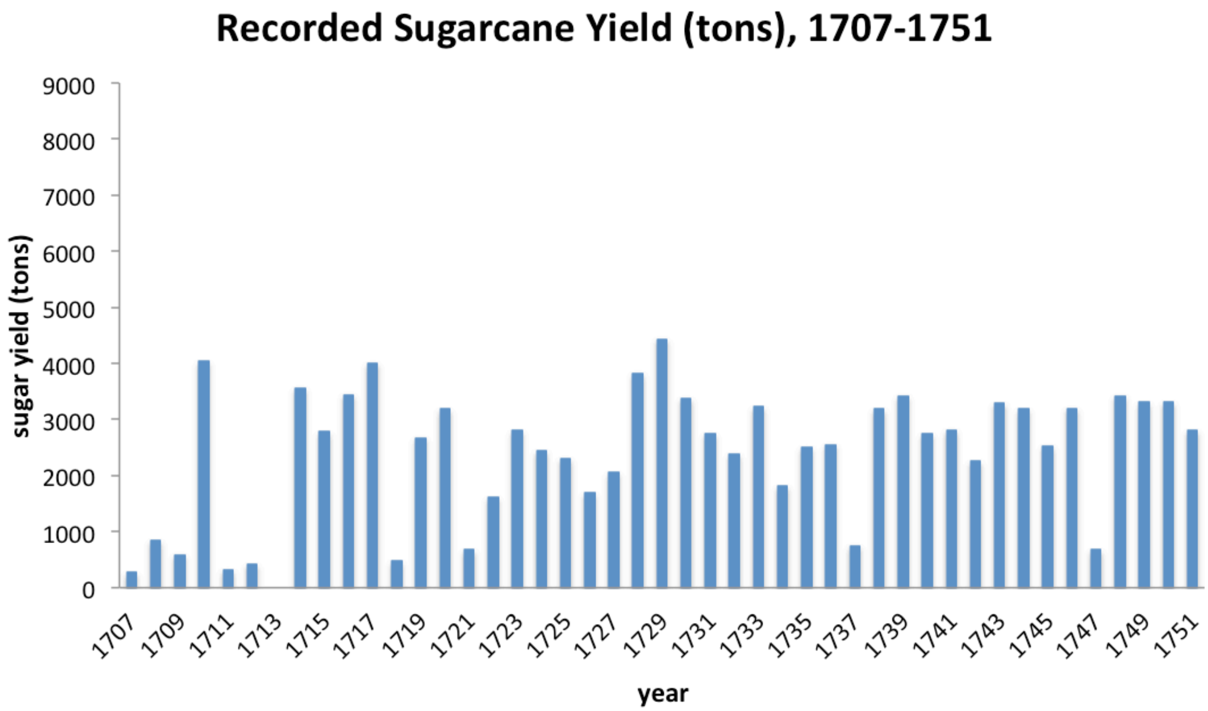
As with the EPIC model, I expect that the quantification of sugar sales and crop yields by year will corroborate the arguments that sugar production declined over time following the period of peak success in the mid-eighteenth century (Abbott 1964:1; Campbell et al. 1992;

Garside et al. 2001:16; Meyer et al. 1996; Ragatz 1928; Sheridan 1960:135; Ward 1978:198). Additionally, Lowes (1994:10) examined island-wide sugar yields from 1820 to 1877 and found that sugar production "swung wildly from one year to the next," but demonstrated an overall decline (Figure 5.1). If the Codrington estates are reflective of broader sugarcane production trends in Antigua, crop yields recorded in the Codrington Papers are expected to be relatively high in the first half of the eighteenth century, and then decline at a steady rate in the second half of the eighteenth century and into the nineteenth century. I also expect to see variation in crop yields from year to year, though overall trends should be discernable.

A bar chart of the sugar sales visually represents the annual sugarcane yield from 1707-1751, 1760-1779, 1782-1790, 1802-1814, 1817-1826, and 1828 (Figure 5.4). A line graph allows for a visual representation of the changes from year to year (Figure 5.5). Though there are periods with missing records, sugarcane yields appear to be quite steady with a small amount of annual variation in the beginning of the eighteenth century. In the second half of the eighteenth century, however, yields vary to a much greater degree, with some years displaying especially large yields and some especially low ones. The increase in yields in the second half of the century follows the expectation that sugarcane production increased over time, though the peak of the Codrington plantations sugarcane yields appears to occur after Antigua's peak in 1753. The recorded sugarcane yields also confirm the expectation that yields varied from year to year.

5.4 Comparison of Sugar Yields

A dual bar chart created in Microsoft Excel displaying the EPIC-simulated crop yields and the recorded sugar yields and sales allows for the comparison of the simulated and actual crop yields (Figure 5.6; see also Appendix II). To represent the trends in the simulated and



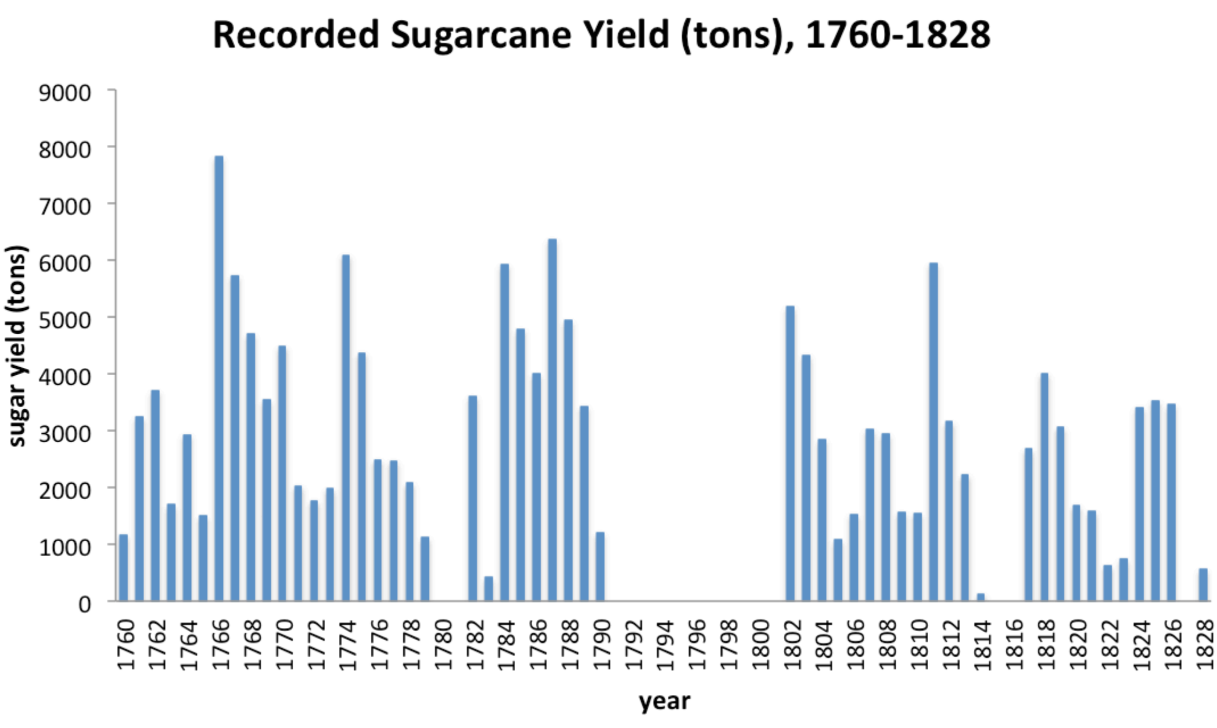


Figure 5.4. *Historic yield bar chart. Bar chart of amount of sugar produced annually from 1707-1751, 1760-1779, 1782-1790, 1802-1814, 1817-1826, and 1828.*

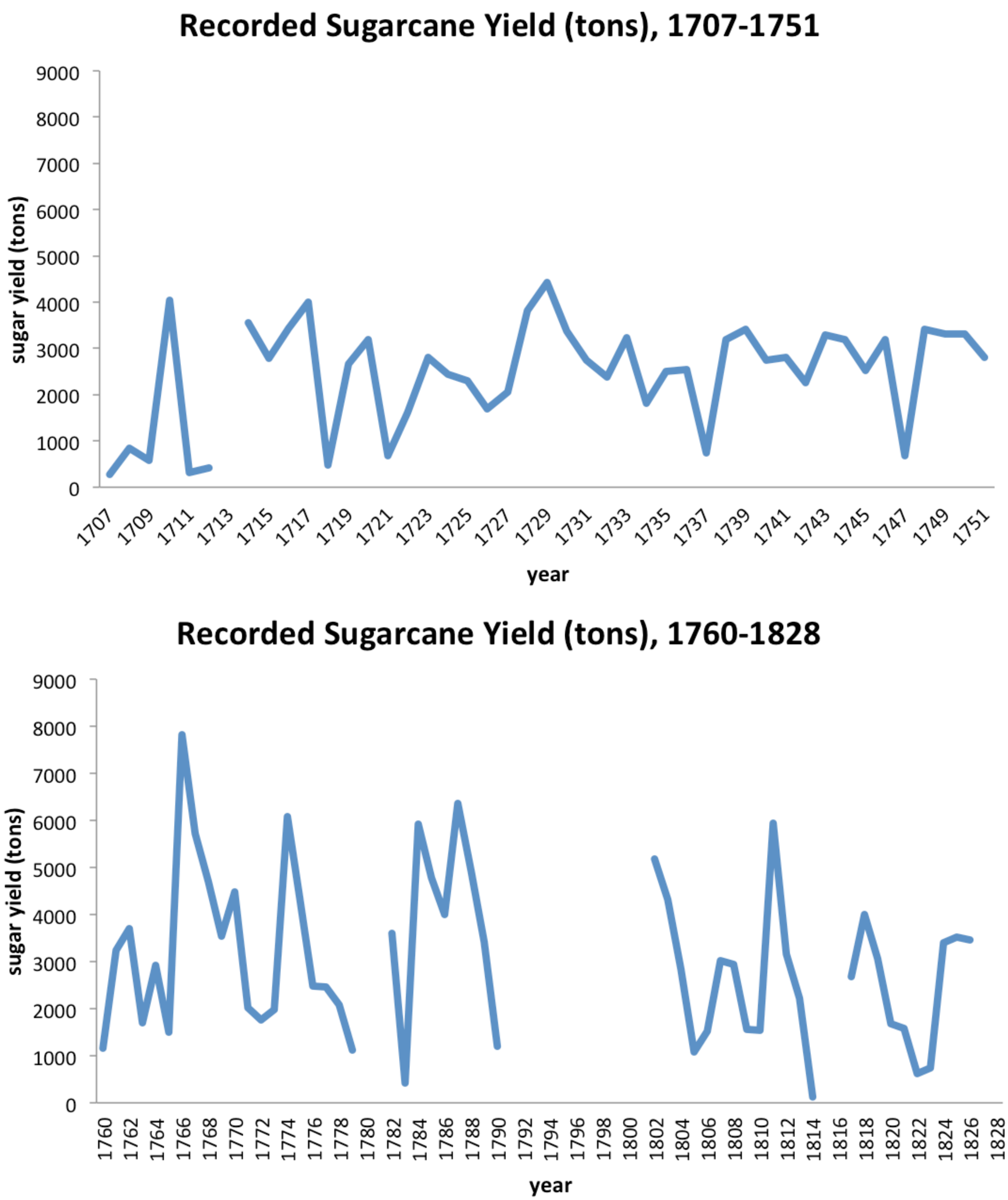


Figure 5.5. *Historic yield line gra ph. Line graph of changes in historically recorded sugarcane crop yields produced from 1707-1751, 1760-1779, 1782-1790, 1802-1814, 1817-1826, and 1828.*

historical yields visually, I multiplied the EPIC-simulated yield by 500 (to represent tons/500 acres) in order to give the simulated yields a similar scale as the historical yields so that both could be visually represented on the same chart. The comparison of the reported sugar produced and the simulated crop yield allows me to assess whether trends in the historical yield are consistent with those of the simulation. However, due to the fact that the exact amount of land cultivated by the Codrington estates is generally unknown, the changes in historically recorded sugar yields may be due to changes in the size of the sugarcane fields associated with Betty's Hope. To further compare the sugarcane yields, I created line graph to highlight the changes in yields over time (Figure 5.7).

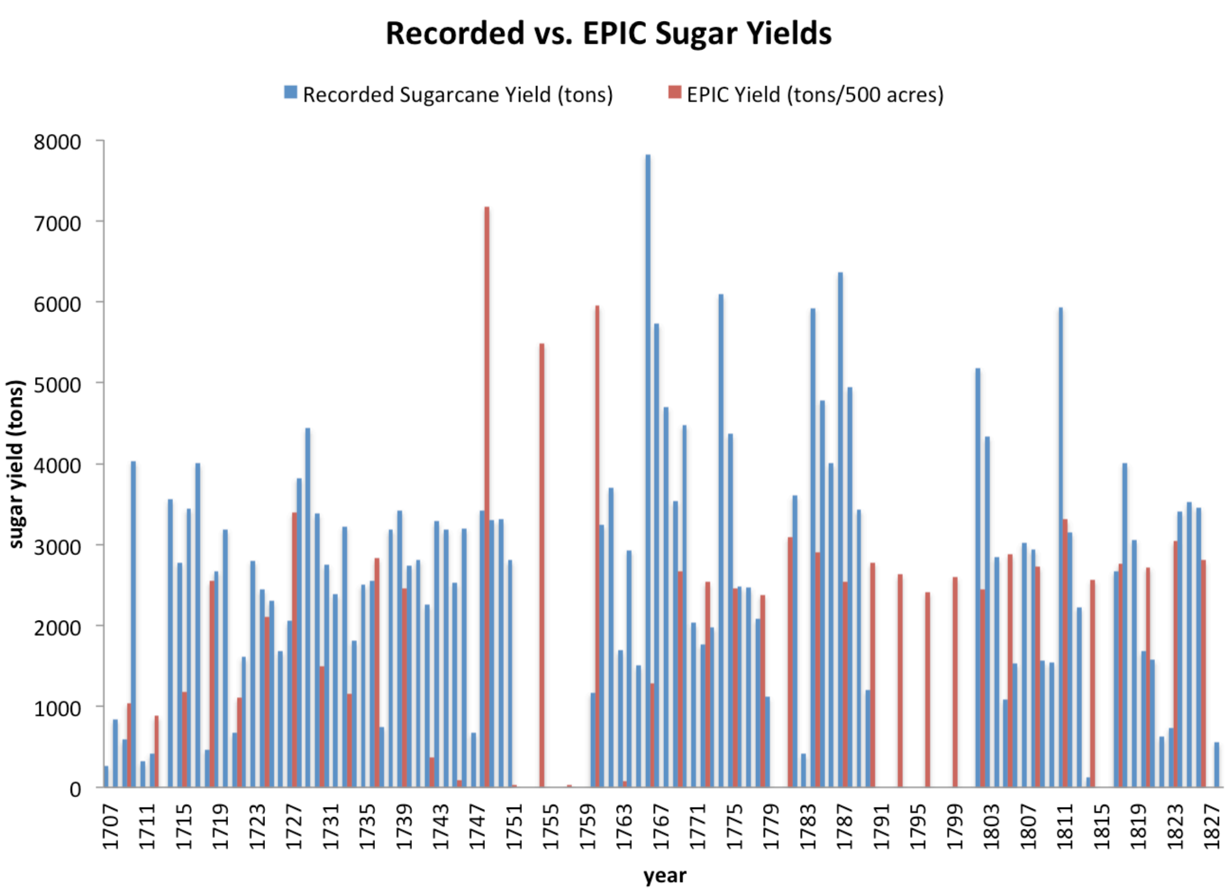


Figure 5.6. *EPIC and historic yield comparison bar chart. Bar chart comparing the historically recorded sugarcane crop yields (tons) from 1707 to 1828 to the EPIC-simulated sugarcane crop yields (tons/acre) from 1709 to 1826.*

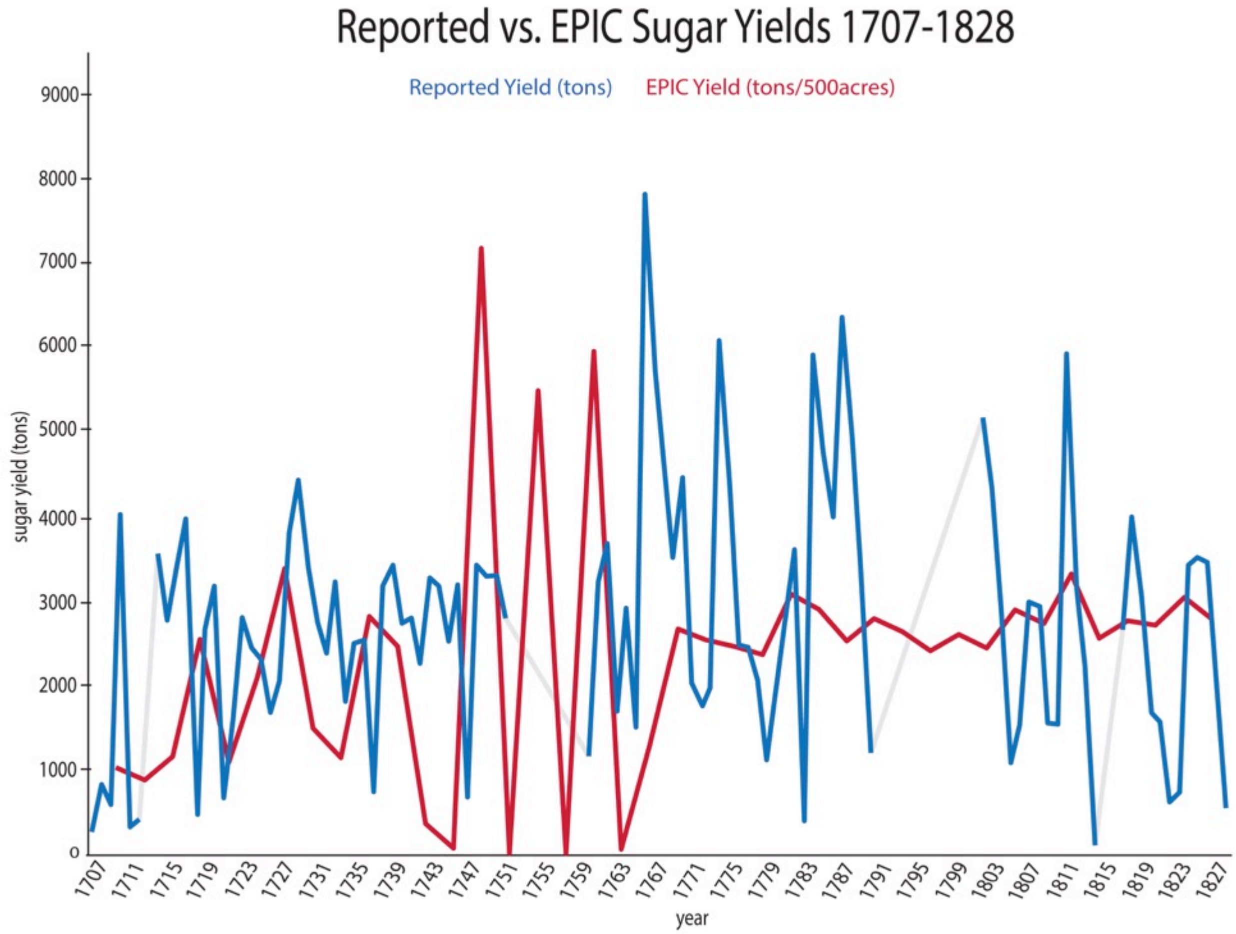


Figure 5.7. *EPIC and historic yield comparison line graph. Trends in the historically recorded sugarcane crop yields (tons) from 1707 to 1828 and the EPIC-simulated sugarcane crop yields (tons/acre) from 1709 to 1826. The light gray lines serve as a placeholder for periods for which historical crop yield data is missing.*

The sugar yields gleaned from the Codrington Papers show spikes in the crop yield a few years after the EPIC model predicted highly variable yields. However, the variable period in the simulated yields from 1745-1766 is dramatically much higher and lower than the known historical yields for the same period. This substantiates the possibility that the variation in simulated crop yield may not be an accurate representation of hypothetical yields. However, post-1766, the EPIC crop yield is relatively low and stable, fluctuating between four and seven tons per acre. The available historical data do not appear to follow this trend and historical yields display much greater annual variation. However, historical records are not present for all of these years, making it difficult to compare to the simulated yield and leaving room for interpretation of the results.

In order to smooth the variation of yearly production and assess broader trends, I computed six-year moving averages for both the historically recorded sugar yields and the EPIC-simulated yields (Figure 5.8; see also Appendix III). This follows the strategy employed by Lowes (1994), though while Lowes used five-year moving averages, I expanded the period to six years because the EPIC model produced yield estimates for every third year. The use of moving averages also helps to overcome analytical gaps: periods when data are missing from the historical records and the period in which the EPIC simulation vary dramatically. The comparison of the six-year moving averages reveals an anomalous decrease in historically recorded yields from 1755-1760 and a similar decrease in the EPIC simulated yield a few years later, from 1761-1766. Aside from the unexpected decrease, the historical yield increases steadily from 1707 to the period of 1797-1802, then decreases more sharply until 1826. This period coincides with a known expansion of the sugar trade and acreage for planting; there is likely an increase in the purchase of slaves to work increased acreage to meet the demands of the market (Georgia Fox, personal communication, February 11, 2015), though the examinations of trends in slave purchase are outside the scope of this research. The EPIC simulated yields are more variable, with a slight increase from 1707 until the unexpected decrease in 1761-1766 (coinciding with part of the period of dramatic variation in the EPIC simulation), then is relatively stable until 1826. This period of 1755-1760 also coincides with a period of absent data in the historical records (from 1752 to 1759). The unexpected declines in sugar yields in both the EPIC simulation and the historical data likely do not reflect an actual decline in crop yields

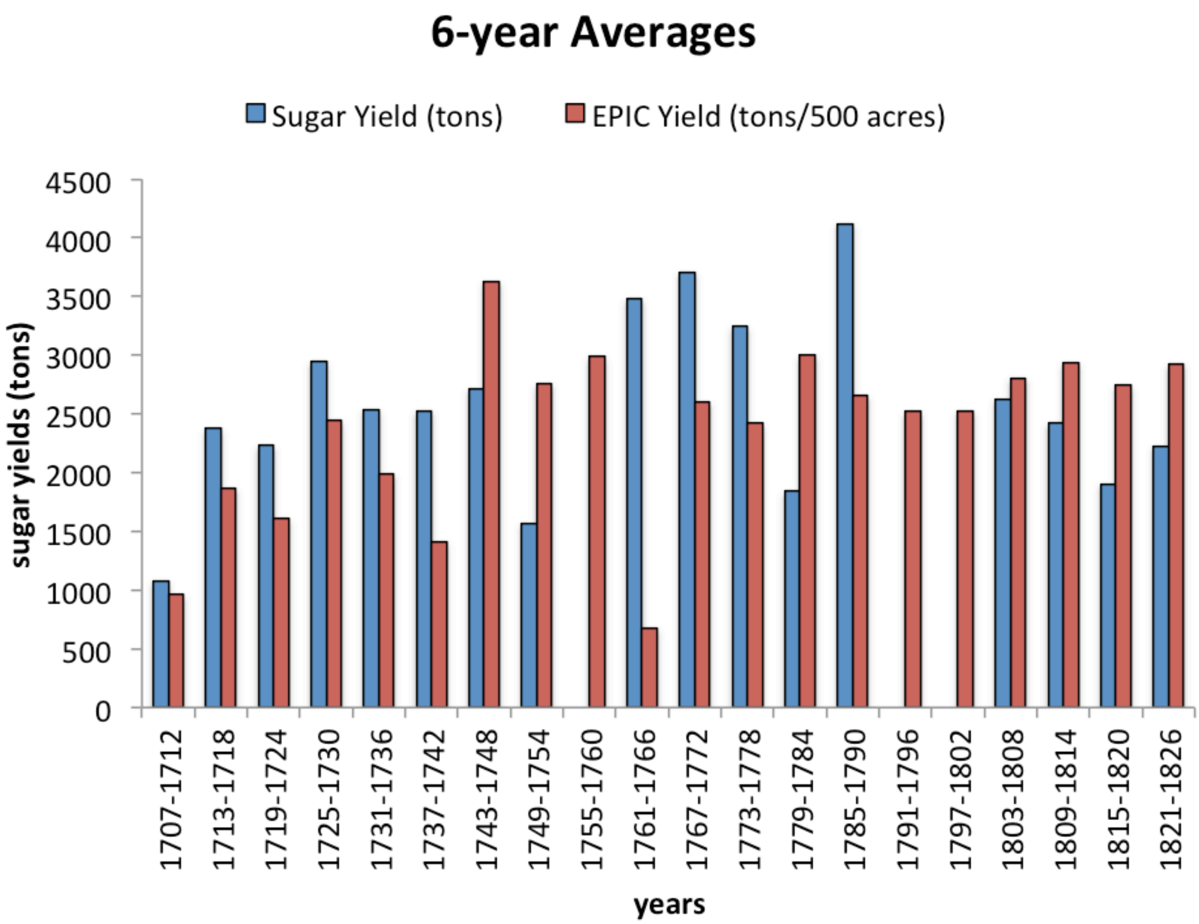


Figure 5.8. *Six-year averages bar chart. Bar chart of the average over 6 years of the historically recorded and EPIC-simulated sugarcane yields.*

during this time as the EPIC simulated yields are unexpectedly variable and historical records are missing. Additionally, the Antiguan sugar industry reached its peak during this time, thus a dramatic decline in sugar yields in the 1750s in not expected (Figure 5.9). Figure 5.10 compares the sugar yields with these periods of decline removed in order to bring further resolution to long-term trends that may be overshadowed by unexpected deviations in the overall change over time. This also helps to overcome the gaps created by missing data records the Codrington Papers and unexpected extreme variation in the EPIC simulation of crop yields.

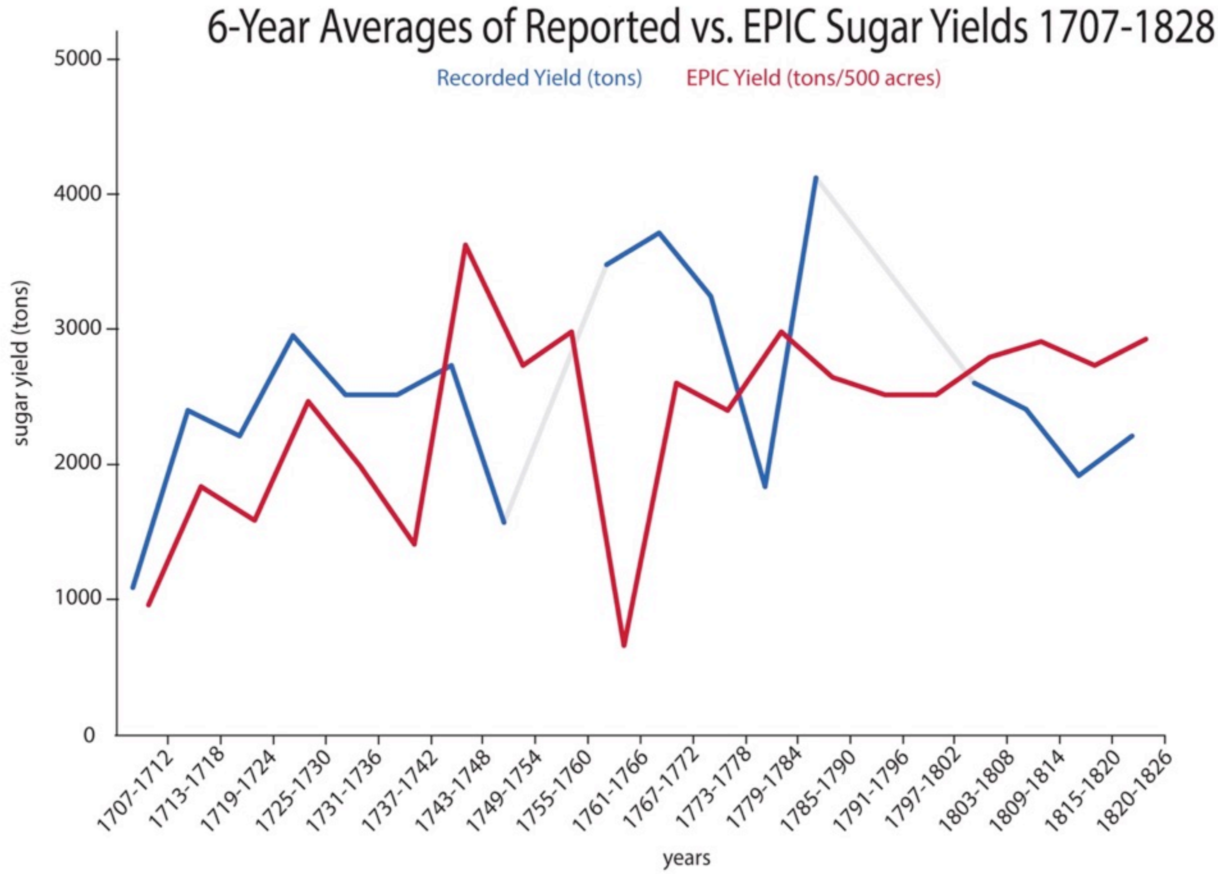


Figure 5.9. *Six-year averages line graph. Line graph of the changes in the 6-year moving average of the historically recorded and EPIC-simulated sugarcane yields. The gray lines serve as a placeholder for periods lacking data (1755-1760, 1761-1766, and 1797-1802).*

A correlation analysis conducted in SPSS revealed that there is no correlation between the 6-year moving averages of the historically recorded and the six-year moving averages of the EPIC-simulated yields (r = 0.044, n= 19, p=.05). This confirms my expectation and the results presented in the above charts: the historical yields and the EPIC simulated yields are not correlated, suggesting that the hypothetical EPIC annual yields do not accurately reflect the historical yields. From this comparison, it appears that Antiguan planters did not use the land sustainably, at least as predicted by EPIC. However, other factors must be considered in assessing the changes in historical crop yields. A number of variables may have contributed, in

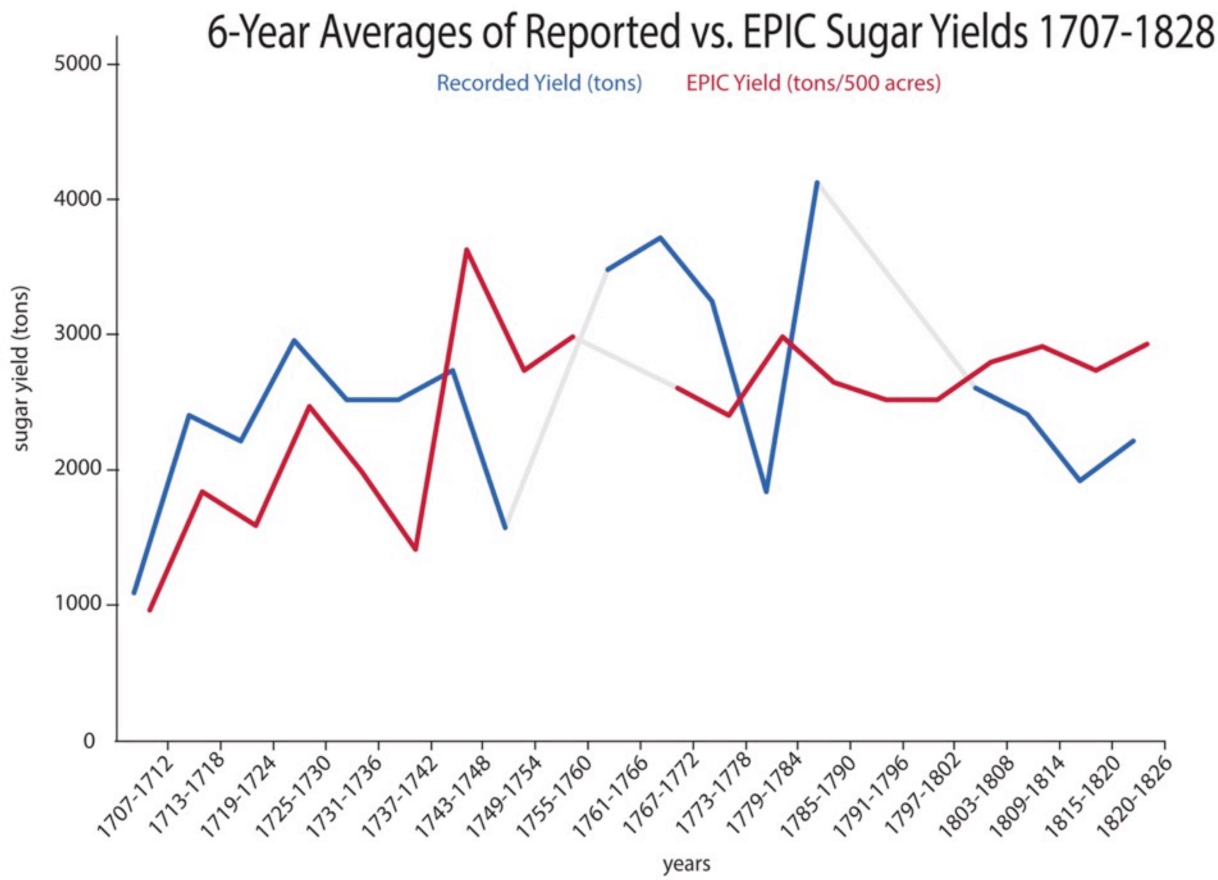


Figure 5.10. *Six-year averages with aberrations removed. Line graph of the changes in the 6-year moving average of the historically recorded and EPIC-simulated sugarcane yields with historically recorded yields from the period of 1755-1760, 1761-1766, and 1797-1802 removed and EPIC simulated yields removed from the period of 1761-1766. The gray lines serve as a placeholder for periods lacking data.*

some way or another, to the discrepancies between the EPIC-simulated crop yields and the historically recorded crop yields. Though the use of six-year averages attempts to compensate for years of missing records, it is possible that records are incomplete for other years, especially for those for which individual sales were totaled in order to obtain an annual yield. In the case of the three records detailing sugar and rum sales to Marmaduke Trattle, it is impossible to determine whether or not the records for every sale of each year survived, or if sugar was also sold to other merchants in England or elsewhere.

It is also important to reiterate that it was not possible to determine the exact amount of land cultivated for each year from 1707-1828. The size of the Codrington plantations changed over time as sugarcane monoculture took hold in Antigua, and the area cultivated each year is not recorded in the documents. As a result, the average amount of sugar produced per acre each year cannot be determined, thus this analysis compares historically produced sugar in tons and the EPIC-simulated yield in tons per acre, allowing for the assessment of general trends in sugar production over time if the area cultivated is assumed equal for all years. A more accurate measurement would compare the historical yield in tons per acre to the simulated yield in tons per ace, but this analysis is constrained by the limitations of the available historical data.

5.5 Major Historical Events of the Last Three Centuries

Sugarcane production and economic prosperity increased in Antigua from 1730 to 1770, reaching its peak in 1753 (Lowes 1994). From this point onward, sugar production never again achieved the same levels of production, declining steadily in the nineteenth century (Lowes 1994:9). In addition to this general trend of rise and fall, major factors that may have influenced the sugar yields include natural events such as droughts, floods, hurricanes, and earthquakes, and human events such as wars, epidemics, slave revolts, and political changes. The rise and fall of sugarcane's success in the West Indies was tied to other social and political developments in the Caribbean and elsewhere; colonial expansion galvanized population and environmental changes. It is important to account for the potential impact of various historical events at multiple scales in the assessment of changes to the sugar yield from the Codrington estates. Events at the local, regional, and global scale had the potential to dramatically influence the sugarcane crop yield for any given year, thus it is paramount to discuss the changes taking place in Antigua, the

Caribbean, and the world as a whole during the years for which historical records document sugarcane crop yields from the Codrington estates in Antigua.

Environmental events are perhaps the most palpable factors affecting sugarcane yields; both droughts and floods could affect crops from year to year, though Antigua's limestone bedrock lacks permanent surface water sources and was less susceptible to major floods. This points to the effects of multiple droughts that would have more dire consequences for agricultural productivity (Berland et al. 201:1341). Due to its location in the Caribbean, Antigua is subject to highly variable annual rainfall and prolonged periods of unusually high or low precipitation, which can have profound socioeconomic consequences (Berland et al. 2013:1331). Berland and colleagues (2013) reconstructed precipitation variations in Antigua for the period of 1770-1890 based on 13,250 items of documentation pertaining to Antigua, including missionary, plantation, and government papers, and contemporary scholarly publications (Berland et al. 2013:1331). They identified several periods of unusually dry or wet seasons; dry conditions create periods of drought and prevent sugarcane crops from receiving adequate water, and wet conditions can cause flooding, turning the fields to mud and drowning the crops. Antigua experienced unusually dry years in 1752 (Sheridan 1957:22), and from 1776-1780, 1782-1783, 1788-1791, 1820-1822, 1834-1837, 1862-1864, and 1871-1873 (Berland et al. 2013:1337-1338). The predominantly dry years of 1779-1789 ruined a number of Antigua's plantations (Lowe 1951:22). The island experienced unusually wet years from 1771-1774, 1833-1834, 1837-1838, 1841-1846 (interrupted by a drought year from 1844-1845), and 1878-1881 (Berland et al. 2013:1339-1340). The authors note that since these precipitation conditions are extrapolated from historical documents, it is likely that extreme precipitation was noted only when it interfered with sugarcane production. It is perhaps for this reason that more dry years were noted since unusually wet years would only have posed a problem to sugarcane production if heavy precipitation coincided with the harvesting period (Berland et al. 201:1341).

Earthquakes and hurricanes also had the potential to disrupt sugarcane crops, though to separate these events from changes in precipitation would oversimplify the relationships between singular events and their effects (Lewis 1984:190). Antigua experienced earthquakes in 1778 and 1843, causing economic setbacks as Antiguans devoted time and labor to rebuilding damaged buildings (Lewis 1984:192). In the years following the 1843 earthquake, the value of Antiguan exports decreased, indicating a decline in the island's production (Lewis 1984:193). Antigua's total sugar exports declined from 15,357 hogsheads in 1844 to 11,809 hogsheads in 1845 (Lewis 1984:193). While hurricanes brought Antigua much-needed rain, the results of such severe weather could have detrimental effects on sugarcane production (Lewis 1984:195). Severe hurricanes occurred in 1681, 1772, 1780, 1792, 1804, 1812, and 1848 (Lewis 1984:195; Lowe 1951:57).

The context of sugarcane development in the West Indies was socially, politically, and economically unpredictable; from the introduction of sugarcane in the 1620s to emancipation in the 1830s; in addition, played out their conflicts in the Caribbean region through numerous wars, skirmishes, invasions, blockades, and related activities (Watts 1990:240). Among the major conflicts affecting the Caribbean were the Third Dutch War (1672 to 1674-8 between England, France, and Holland), the War of the Grand Alliance (1688 to 1697 between England, Holland, and France), the War of Spanish Succession (1702 to 1713 between England, Holland, France, and Spain), the War of Jenkins' Ear (1739 to 1748 between England and Spain), the Seven Years' War (1756 to 1763 between France/Spain and England), the War of American Independence (1776 to 1783 between Spain, Holland, France and England), and the Napoleonic

Wars (1803 to 1815 between France and England; Watts 1990:243-253). The effects of these conflicts on Antigua's sugar industry were mixed. War caused variations in sugar supplies across the Caribbean, such that rumor of conflict "was enough to send the price of sugar up and the mere rumor of peace enough to send it down" (Pares 1956:261).

Additionally, local events may have affected annual sugar yields. Correspondence between the managers of the Codrington estates and the Codrington family in England provide insight on the effects of regional climate and political events. In 1779, George Redhead—a member of the Antigua Assembly who owned his own estates and served as an attorney for the Codrington plantations in Antigua and Barbuda—reported to Messers. Codrington and Trattle that the island was devastated by drought and that little sugar was expected that year (Lowe 1951:21-22). In 1781, Richard Oliver, then manager of the Codrington estates in Antigua, reported that the number of slaves on the estates (779) was too low for 1,100 acres producing 800-1000 hogsheads of sugar each year (Lowe 1951:26). In 1790, Joseph Lyons Walrond, manager of the Codrington estates in Antigua, reported a poor sugar crop in multiple correspondences (Lowe 1951:32). However, Walrond reported in 1791 that "rain has come at last and should improve the crop" (Lowe 1951:33). In 1812, a hurricane was reported in a letter from Langford Lovell Hodge, a Codrington attorney, estate owner, and member of the Antiguan Assembly (Lowe 1951:57). In 1813, John Osborn—who became superintendent of the Codrington estates in Antigua in 1816—reported that weather prevented good crops at the estate (meaning Betty's Hope; Lowe 1951:59). This unfortunate set of circumstances was reversed by 1817, when Osborn reported a good crop from Betty's Hope: 674 hogsheads were produced; roughly five times the anemic 1813 crop (Lowe 1951:59). In 1821, Osborne reported a severe drought (Lowe 1951:59). The drought worsened in 1822, causing the sugar crop to be unusually low; Osborne predicted a final yield of only 260 hogsheads (Lowe 1951:60). By 1823, Osborn said the prospects of a satisfactory crop were improving (Lowe 1951:60). Good fortune continued: by 1825, the Codrington estates produced 564 hogsheads of sugar. The following year, Osborne reported anticipating a crop of 800 hogsheads (Lowe 1951:62).

A timeline of natural disasters, wars, and other major events enables the understanding of how these phenomena may have affected the sugarcane production on the Codrington estates, possibly explaining increases and decreases in production. The EPIC model cannot account for natural disasters or the socio-political climate, thus it is important to examine whether or not historical events are associated with changes in Codrington sugar production. Figure 5.11 depicts a timeline of the historically recorded sugar yields with major conflicts, environmental events (earthquakes, hurricanes, and unusually dry/wet years), as well as documented details about Betty's Hope Plantation (size of the estate, number of enslaved laborers, and major construction).

5.6 Decade by Decade Comparison

The Codrington family became absentee in 1704 when they left Antigua, overseeing the plantation via correspondence with local supervisors and estate managers. Perhaps the absence of the plantation owner and his family necessitated the beginning of annual sugar production records. The first historical records of Codrington crop yields in this analysis appear in 1707, late in the first decade of the eighteenth century. Despite the few years of records present in this decade, the yields increase, paralleling the historical development of the West Indian sugarcane industry. Antigua became the lead sugarcane producer of the Leeward Islands in 1808. A major European political conflict took place during this decade: the War of Spanish Succession lasted

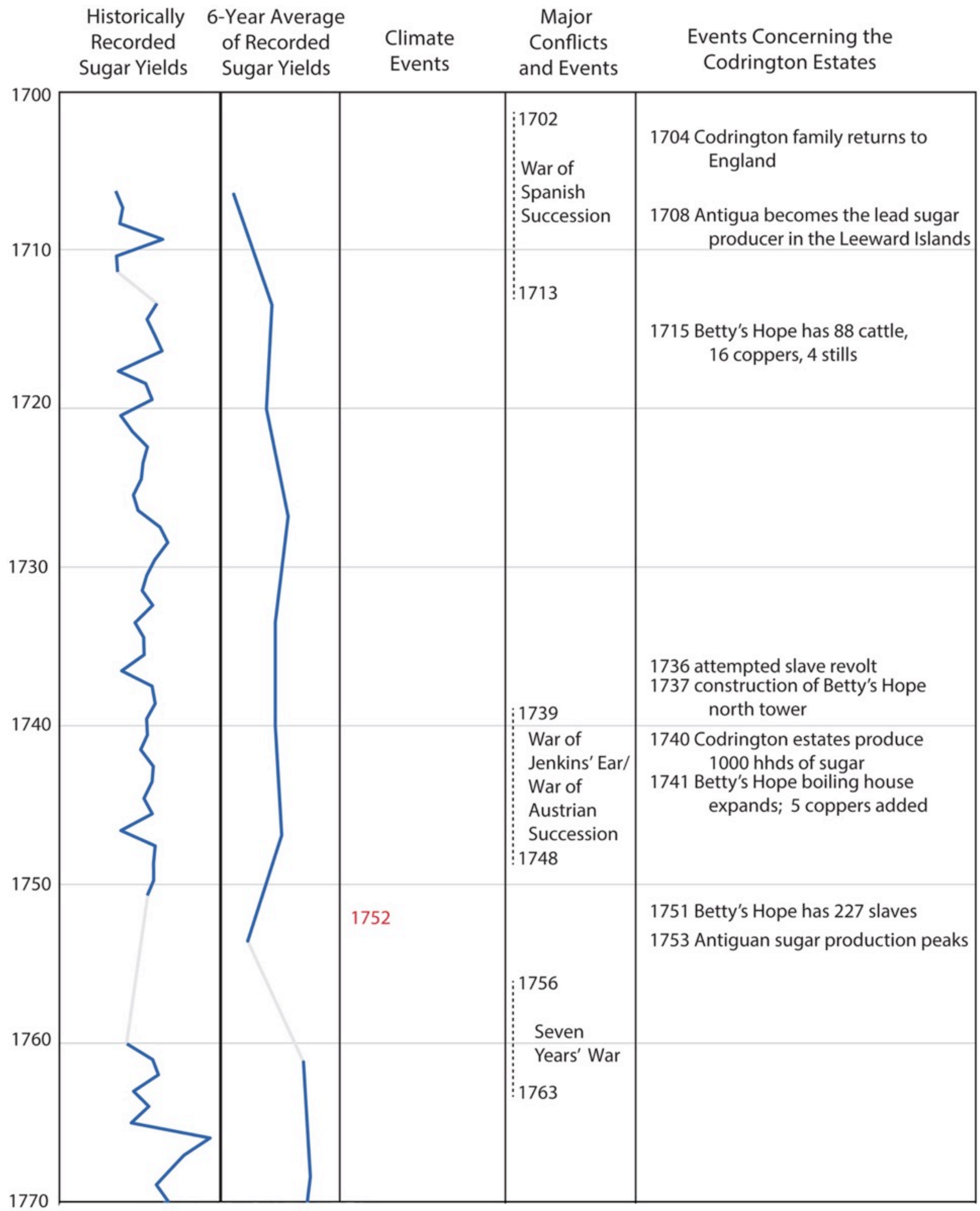


Figure 5.11. *Timeline. Historically recorded sugarcane yields, 6-year moving average of historical yields, major environmental events (dry years are red, wet years are green), historical events, and events concerning the Codrington estates from 1700 to 1850.*

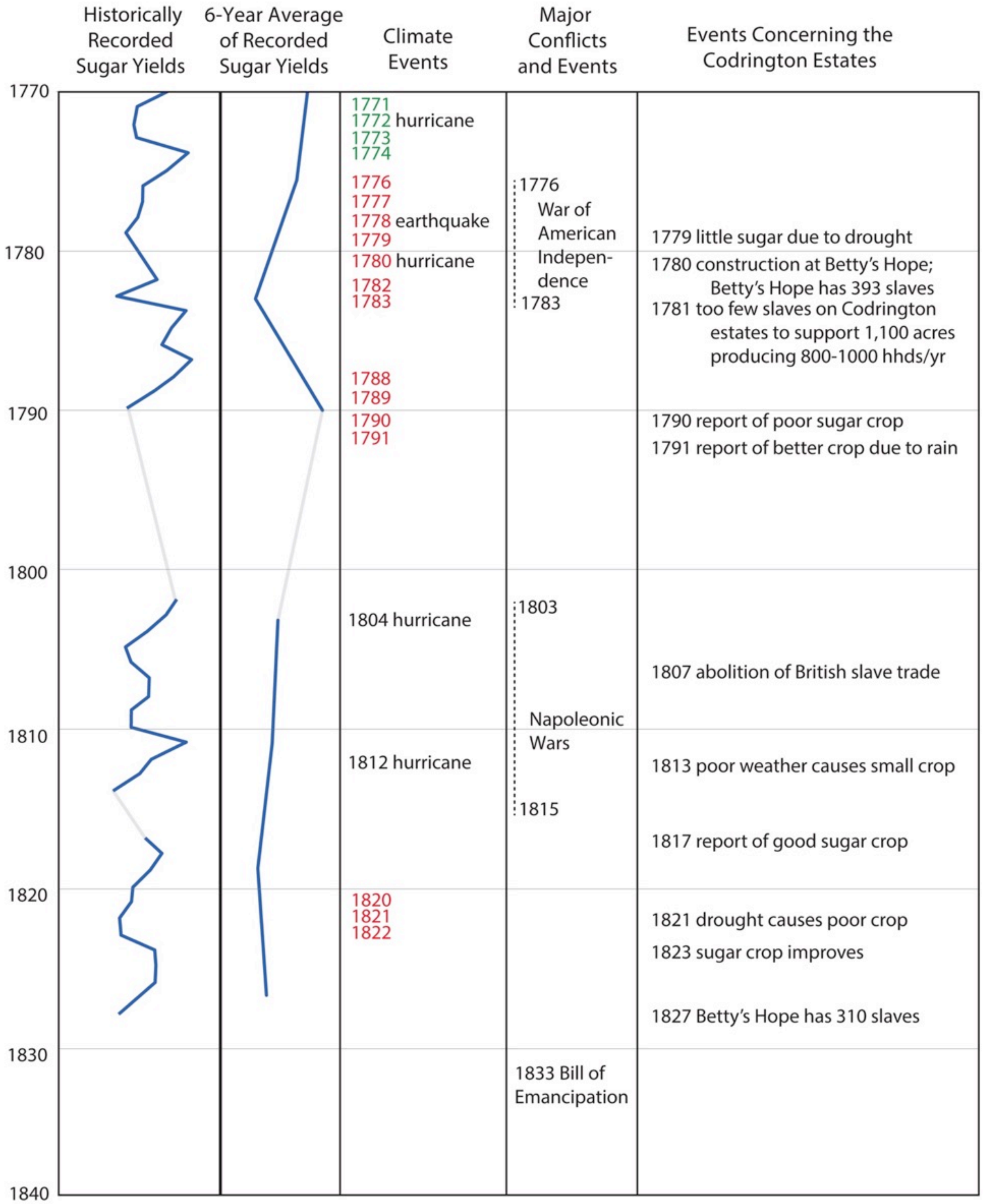


Figure 5.11 (continued). *Timeline. Historically recorded sugarcane yields, 6-year moving average of historical yields, major environmental events (dry years are red, wet years are green), historical events, and events concerning the Codrington estates from 1700 to 1850.*

from 1702 to 1713. However, despite the turmoil in Europe and the absenteeism of the Codringtons, sugar was a profitable and increasing industry in Antigua.

Codrington crop yields declined in 1711 and then increased slightly in 1712. No record of the 1713 crop is available, but yields remained relatively high for the next few years. In 1715, Betty's Hope was capable of industrial sugar production: the estate had 16 copper kettles for boiling cane juice, and four stills for distilling rum. Sugar yields continued to vary in the second half of the decade, dropping in 1718, and then increasing at the end of the decade. The six-year moving average of sugar yields reveals a trend of increase in the first half of the decade, then a slight decrease in the second half. Despite the variation in annuals yields, the Codrington estates produced roughly the same amount of sugar at the beginning and end of the 1710s.

No major climatic events or events related to the Codrington estates are known for the 1720s. Sugar yields were variable once again, though less dramatically than in the previous decade, indicating that sugar production was consistent. The six-year moving average of sugar yields indicates a slight increase in the first half and a slight decrease in the second half of the decade, though there is a small net increase in average sugar yields. Despite annual variations in the yields, sugar production remained largely constant, suggesting that land use was consistent.

No major climatic events are known for the 1730s, either. Sugar yields decline with small amounts of variation at the beginning of the decade, and a more dramatic decrease occurred in 1737. This year coincides with an attempted slave rebellion in Antigua that took place in 1736, when Prince Klass, an enslaved laborer from the Gold Coast, led a campaign to take control of the island (Brown 2002:104). This rebellion and the associated social turmoil are accompanied by a sharp decline in sugarcane yields. The year 1737 also marked a time of expansion at Betty's Hope. The construction of the north windmill tower is a sign of expanding production and the increased need to supply more power to process sugarcane into exportable products. This suggests that sugarcane yields were increasing or expected to increase and reflects Antigua's role as the dominant sugar island of the region, wholly devoted to growing a single crop. Sugarcane yields increase in the last few years of the decade. The six-year moving averages of sugar yields indicate that average yields were relatively stable during this period; this is consistent with the two previous decades. During the first half of the eighteenth century, sugar production was a growing and profitable industry in Antigua and this economic dominance of a single crop is reflected at Betty's Hope in the expansion of the sugar production capacity and in sugarcane yields that were for the most part reliable and consistent.

In the 1740s, sugarcane yields are steady with very slight annual variation at the beginning of the decade. A decline is observed in 1747, and then yields increase to approximately the same levels as earlier in the decade. The majority of the War of Jenkins Ear (and the War of Austrian Succession which subsumed it; 1739-1748) occurred in this decade, creating an atmosphere of conflict and uncertainty in the Caribbean. Despite Spanish and British forces at odds in the region, Betty's Hope appears to have been largely unaffected by these conflicts: the Codrington estates produced 1000 hogsheads of sugar in 1740. This success in sugar production is reflected in yet another expansion in 1741, when the Betty's Hope Boiling House acquired five additional copper boiling vats. Like the expansion in the 1730s, this construction reflects the increasing sugarcane processing capacity at Betty's Hope, speaking to the success and profitability of sugarcane cultivation. Despite the decline in 1747, the six-year moving averages indicate an overall increase in sugarcane yields during the 1740s. As Antigua was nearing the peak of its production, the increase in crop yields and expansion at the

Codrington estates again parallels the historic expansion and importance of sugarcane in the region.

Antiguan sugarcane reached its peak in 1753. However, records of the Codrington sugarcane yields are missing for this decade. An unusually dry year was recorded in 1752, likely affecting sugarcane yields across the island, though there is no way to determine whether this event is associated with a decline in Codringtons sugar yields. The success of Betty's Hope can be inferred, however, as the plantation had 227 enslaved laborers in 1751. Additionally, the Seven Years' War began in 1756, ushering a phase of economic prosperity for British planters as British naval forces ruled the seas, French competition was minimized, and planters could more readily access British markets (Watts 1990:276).

The Seven Years' War ended in 1763, marking the end of a highly successful and profitable period for British colonial sugar (Ragatz 1928:111). The wealthy wartime years marked the beginning of the end for British planters' wealth (Watts 1990:276). From the 1750s until the beginning of the American War of Independence, the output of sugar from the Leeward Islands became increasingly difficult to maintain at previous levels and the output from Antigua fell (Watts 1990:315). Historical sugar yields from the Codrington plantation were variable in the beginning of this decade, but overall appear relatively consistent. A large spike in yields occurred in 1766, then yields return to level similar to those of the beginning of the decade. The six-year moving averages for this decade show much higher yields than in previous decades, with an overall trend of increase. From these crop yields, it appears that even though Antigua as an island may have reached the pinnacle of its sugar productivity in 1753 (Lowes 1994), the Codrington estates continued to expand their production such that yields were higher in the 1760s than before. No major climate events are known for this decade, suggesting that a reliable climate that was never too dry or to wet created conditions favorable to a decade of successful sugarcane crops.

Multiple years of extreme weather conditions were recorded in the 1770s. The period of 1771-1774 was unusually wet, while 1776-1779 was a period of multiple droughts. In addition, an earthquake was recorded in 1778. The hurricane in 1972 was "one of the most destructive hurricanes in decades" (Ragatz 1928:134) for the Leeward Islands; buildings were flattened and crops were decimated. Correspondence from Betty's Hope to the Codrington family reported that a small sugarcane crop was expected in 1779 due to prolonged drought conditions (Lowe 1951). Sugarcane yields for this decade display much variation, possibly as a result of extreme weather. Yields are low in the first half of the decade, increase in 1774, then drop precipitously in the second half of the decade. The year 1775 had normal precipitation in Antigua, thus it follows that the transition between extremely wet and dry periods was the most successful for sugarcane. The American War of Independence (1776-1783) further exacerbated the general decline of British colonial sugar industry (Watts 1990:278-279). The implications of this conflict on the British West Indies were profound. Britain lost its command of the seas for the first time in the eighteenth century, as trade relations between the Caribbean colonies and American colonies on the mainland were disrupted, making supplies and food less available. Other consequences included increased operating costs, a decrease in sugar markets, and fewer sugar exports from the islands (Crist 1954:228; Ward 1978:209; Watts 1990:278-279). Reflecting this time of turmoil, the six-year moving averages of sugar yields for this decade show trends of decline, a contrast to the previous decades, where increase or little change in the average sugar yields was observed.

Sugar yields in the 1780s are also quite variable, but are generally higher than those in the 1770s, perhaps indicating a recovery following a decade of climatic variation and political unrest. However, the 1780s were also a decade of extremely dry weather conditions. In 1780, Antigua experienced both a drought and a hurricane: a drought occurred in 1782-1783, and another occurred in 1788-1789. These years of dry conditions are associated with declines in crop yields. Records are not available for 1780 or 1781, but yields drop in 1783, then increase in 1784 to 1787, then decline again in 1788. The declines in crop yields correspond with years of recorded drought, while the increases in the middle of the decade correspond with years of normal precipitation levels. The War of American Independence also ended in 1783, coinciding with an increased crop yield the following year. Betty's Hope also appears to have continued its expansion: in 1780, the plantation had 393 enslaved laborers (compared to 227 in 1751), indicating an increase in labor capacity. The increased number of laborers at Betty's Hope reflects an increased demand for labor investments into the plantation land and sugar production. However, it was reported in 1781 that the slave population was too low for the 1,100 acres of estate lands and for annual production of 800-1000 hogsheads of sugar. This suggests that Betty's Hope needed a larger labor force to maintain production levels. The six-year moving averages of sugarcane yields for this decade reveal that the decline in average yields from the previous decade continues then yields increase from 1785-1790, producing a net increase by the end of the decade.

Historical records are not available for the period of 1791-1801, but it is known that the drought from the end of the previous decade continues in 1790 and 1791. Correspondence from the Codrington estates in Antigua recounts poor crops in 1790 due to the drought. Correspondence also reports that rain in 1791 provided relief from the dry conditions and the expectations that good crop yields would follow. No major political events occurred in this decade. Without historical records of sugarcane crops, it is difficult to determine the changes to the Codrington estates during this decade.

Historical records return in 1802, reporting higher yields than the last recorded yield in 1790. However, yields drop significantly in the beginning of the decade. The year 1803 marked the first year of the Napoleonic Wars (1803-1815) between France and a number of opposing coalitions, including Britain, which remained involved throughout the entirety of the war. This conflict may be related to declines in sugarcane crops in 1804 and 1805. During this conflict, European consumption of government-subsidized beet sugar increased, creating competition and reducing the market for Caribbean sugar (Crist 1954:228). In 1807, British Parliament passed the Abolition of the Slave Trade Act, which abolished the slave trade in the British Empire but did not abolish slavery itself (Porter 1970). This act would have cut off the influx of new labor in the West Indies and may be related to declines in sugarcane yields in the late 1810s. While sugarcane yields for this decade were quite variable, the six-year moving averages of yields indicate an overall trend of slight decline in this decade. Although the Codrington estates did not appear to decline following Antigua's peak in the middle of the eighteenth century, it appears that crop yields are beginning to decline in the beginning of the nineteenth century.

Historical records are absent in 1815 and 1816, but sugar yields continue to indicate a decline in production in the 1810s. With the end of the Napoleonic Wars in 1815, British sugar prices dropped as French colonial production recovered, Cuban harvests grew in size, and cheap East Indian sugarcane and European sugar beet emerged on British and colonial markets (Watts 1990:282). A hurricane was recorded in 1812, possibly contributing to declines in the first half of the decade. Historic yields decline from 1810 to 1813, coinciding with John Osborne's letter to Codrington, reporting that poor weather caused a poor crop at Betty's Hope (Lowe 1951:59).

The rise in yields a few years later coincides with another letter from Osborne, reporting a good crop at Betty's Hope in 1817. The six-year moving averages from this decade indicate an overall decline in yields for the 1810s, despite annual variation.

Sugar yields continue to vary in the 1820s. A decline in the beginning of the decade coincides with a period of drought from 1820-1822. Correspondence to the Codrington family corroborates this decline, reporting that the 1821 sugar crop was small due to drought, but that yields improved in 1823. It was also reported that Betty's Hope had 310 enslaved laborers in 1827. This figure is lower than that reported in 1780 (393 enslaved laborers). Along with the declines in crop yields, the reduced number of laborers reflects a decrease in production capacity at Betty's Hope. The smaller labor force could be a product of the ban on slave trade two decades prior, which would have cut off the supply of new laborers. During this time, plantation owner absenteeism soared to approximately 70 percent during the 1820s (Sheridan 1971; Watts 1990:283), and the average estate profits fell to less than six percent (Watts 1990:283). Antiguan sugar production waned by the first few decades of the nineteenth century, and the broader island-wide trend seems to be reflected in the crop yields from the Codrington estates.

It is clear that Antigua, along with the rest of the British West Indian sugar islands experienced decline from the profitable and wealthy period of the mid-eighteenth century when Parliament passed the Bill of Emancipation in 1833, decreeing that freedom should be granted to slaves in British colonies on August first of the following year (Watts 1990:469). Interestingly, despite dire predictions to the contrary, Antigua remained prosperous after emancipation (Lowes 1994:4). The average export quantity from 1829-1833 was 12,189 hogsheads, while from 1834-1838 it increased to an average of 13,545 hogsheads (Lowes 1994:10). In the early 1840s, it was reported that despite droughts in the 1830s, sugarcane crops were larger than those before emancipation (Lowes 1994:10). However, Antigua's annual sugar exports declined steadily in the nineteenth century and the island faced a crisis in the 1890s, when a drastic decline in sugar production coupled with low prices on the world market triggered a major economic decline from which the island never recovered (Lowes 1994:4).

5.7 Conclusion

The comparison of the EPIC simulated sugar yield in tons per acre and the historical yields in tons extrapolated from historical documents reveal that there is little agreement between simulated and historical crop yields. The variation in the historically recorded yields suggests that sugarcane production was not as simple as the EPIC simulation suggests. According to the EPIC model, yields should have declined rapidly following the introduction of sugarcane, then varied dramatically in the middle of the eighteenth century, and then stabilized at a lower yield for the next few decades. The recorded yields in the Codrington Papers indicate that the actual crop yields were more dynamic. Historic yields varied dramatically from year to year, but as the six-year averaged values indicate, there appears to be a trend of yield increase from the beginning of available records in 1707 until the end of the eighteenth century, after which time the records show a decline of crop yields. These trends coincide with historical observations about Antiguan sugar production. While the records obtained from the Codrington Papers in this study only span the period of 1707-1828 (with several gaps), it appears that the records reflect the increase in Antiguan sugar yields and the subsequent decline following the historical peak of the sugarcane industry.

The EPIC simulation is useful for illustrating the hypothetical course of sugarcane productivity if agricultural practices remained constant over time, thereby illustrating the speed at which crop yield would have declined due to soil exhaustion and erosion. The simulation is a representation of the idea that intensive monoculture contributes to degradation of soil, erosion, compaction, and decline in fertility (Abbott 1964:1; Campbell et al. 1992; Garside et al. 2001:16; Meyer et al. 1996; Ragatz 1928; Sheridan 1960:135; Ward 1978:198). The historic sugar yields gleaned from the Codrington Papers indicate that crop yields on the Codrington estates deviate from the EPIC simulation, and instead varied from year to year, though broad tends are present. While some dissimilarity between the EPIC simulated and historically recorded yields can be attributed to missing historical data and the fact that historically cultivated acreage is not known, the variation in historic yields suggests that Antiguan sugarcane crops were vulnerable to factors besides soil health, including drought, hurricanes, and wars. The divergence of the historic yields also suggests that investments of landesque capital—fertilization, cane holing, drainage, liming, etc.—may have prevented the soil exhaustion and erosion causing the dramatic yield decline in the EPIC simulation. From this analysis, it is apparent that the EPIC model does not provide an accurate prediction of actual sugar yields on the Codrington estates. The annual sugar yields from 1707-1828, while inconsistent from year to year, defy the expectation that sugar yields ought to decline over time as a result of intensive monocropping. Historical yields increased gradually from 1707 until the end of the eighteenth century, then began to decline. These trends are more concordant with the known patterns of sugar production in Antigua and other British sugar islands in the West Indies.

CHAPTER SIX
RESULTS OF THE GEOARCHAEOLOGICAL ANALYSES

6.1 Introduction

Geoarchaeological approaches examine the natural landscape elements incorporated into areas of human activity in the past. The footprint of human activity—the so-called landscape legacy—can be detected through basic soil analyses (Scudder et al. 1996:8). The geoarchaeological analyses described in Chapter 4 were conducted in the Laboratory for Anthropogenic Soils Research at the University of South Florida.

6.2 Expectations

Most soils have a visibly, chemically, and/or physically distinct sequences of horizontal layers, termed horizons (Redman 1999:83). The typical O, A, E, B, C, and R horizons are the result of processes of chemical weathering, eluviation, illuviation, and organic decomposition. Multiple layers can be present in a typical soil, though not all profiles will have all horizons (Figure 6.1). Soil profiles do not necessarily have to display all horizons and may have multiple horizons of the same type. The O horizon is a surface horizon composed of large quantities of recently deposited organic material in various stages of decomposition (Redman 1999:83). The A horizon is immediately below the O horizon and consists of minerals (sand, silt, and clay) and with higher amounts of organic matter. Events, such as flooding, volcanic eruptions, landslides, and dust deposition can bury an A horizon so that it is no longer found at the surface. Buried A horizons indicate that soil and landscape processes changed in the past. The A horizon is also vulnerable to compaction and to wind and/or water erosion, which reduces its fertility or may lead to its complete elimination (Redman 1999:83). Compared to other mineral horizons (E, B, or C) in the soil profile, A horizons are rich in organic matter and thus are darker in color (Redman 1999:83). Clays and easily dissolved compounds leach out of the A horizon over time, causing A horizons to have a higher proportion of coarse particles than underlying layers. The E horizon is found between the A and B horizons and is typically lighter in color. E horizons are more common in forested areas, but can also form in lower-precipitation grasslands. The B horizon is a subsurface mineral horizon and a zone of accumulation of minerals and particles due to leaching from above and mechanical movement from above and below (Redman 1999:83). B horizons typically have accumulations of clay, soluble salts, and iron. In anthropogenic landscapes, processes such as erosion can strip away overlying horizons and leave the B horizon on the surface. The C horizon is the least weathered subsurface horizon consisting of loose parent material with little to no alteration due to the soil forming processes (Redman 1999:83). The R horizon is composed of unweathered bedrock.

Multiple processes affect the development of soil concentrations, contributing to distinct physical and chemical properties of each horizon. Soil in the tropics have developed over long periods of time such that weathering is deep and there is a high level of water penetration into the soil (Watts 1990:34). The rapid chemical weathering prevalent in most Caribbean environments causes soils to form quickly from their parent materials (Watts 1990:37). The soils of Antigua and Barbuda were first characterized in a soil survey carried out by the Regional Research Centre of the University of the West Indies in the early 1960s (Hill 1966; United Nations 2005:10). Antigua has three main geological regions: a Volcanic Region in the southwest, a Central Plain region, and a coastal Limestone Region (Day 2007:172). In his 1966 survey, Hill

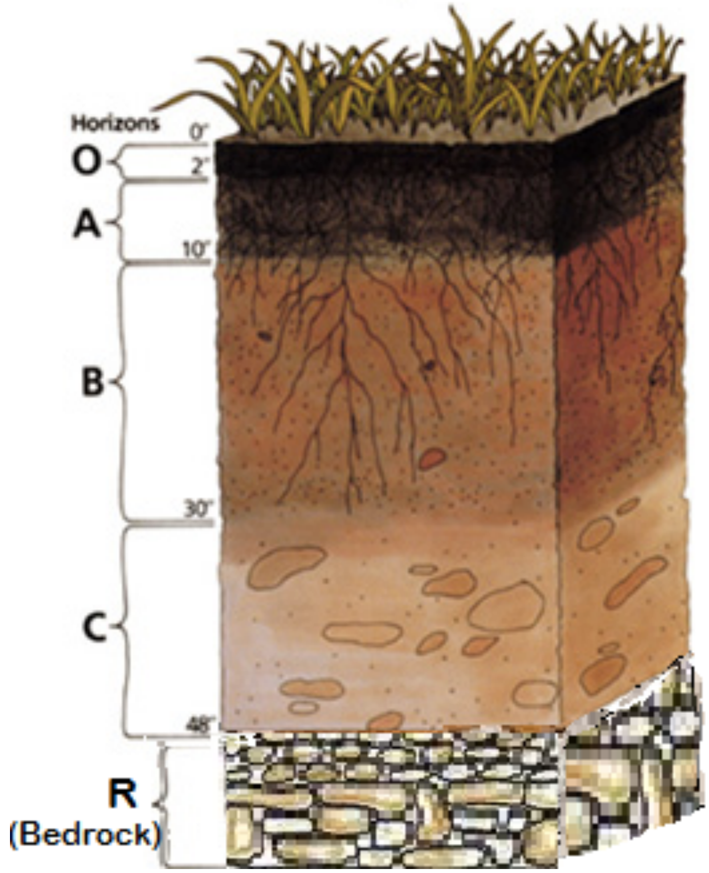


Figure 6.1. *Soil horizons present in a typical soil profile (United States Department of Agriculture 2015).*

described 33 soils that are divided into five groups based on depth and texture (United Nations 2005:10).

Betty's Hope lies within the area of soil type 2: "deep kaolinitic clay soils of the Central Plain; these are hard to work, heavy clays with impeded drainage and near neutral pH. Some are saline at various depths below the topsoil. Some calcareous clays are found in parts of this region (United Nations 2005: 10). The soil profiles are expected to display neutral clay and clay loam horizons with gradual changes in mineral concentrations and pH from the ground surface toward the bedrock. The Lesser Antilles, including Antigua, are composed of coral limestone bedrock of Plio-Pleistocene age developed on an older volcanic base (Watts 1990:12), meaning the marine carbonate bedrock foundation contributes to higher levels of strontium concentrations and calcium carbonate percentages in soil horizons nearer to the parent material.

Other gradual changes are also expected to be visible down the soil profiles. The pH values should increase and become more basic down the profile toward the bedrock. The percentage of organic carbon and the phosphate concentration are expected to decrease down the profile because organic material decays in the A horizon and phosphate bearing particles move down the profile. The concentrations of iron and manganese are expected to decline toward the bottom of the profile. All changes down the profile are expected to be gradual; dramatic changes from one horizon to the next indicates a disturbance to the profile. Figure 6.2 displays the patterns of increase and decrease expected in a normal soil profile.

Based on these expected trends for each soil characteristic, I also expect a typical soil profile to exhibit correlations between particular characteristics. Since the calcium carbonate percentage, the strontium concentration, and the pH increase down a normal profile, I expect these characteristics to correlate positively and correlate negatively with the organic carbon percentage, the iron concentration, the phosphate concentration, and the manganese concentration. Because the organic carbon percentage, the iron concentration, the phosphate concentration, and the manganese concentration decrease down the profile, I expect these characteristics to correlate positively and correlate negatively with the calcium carbonate percentage, the strontium concentration, and the pH. For each soil profile, a correlation analysis was conducted in SPSS to determine correlations at the .01 level.

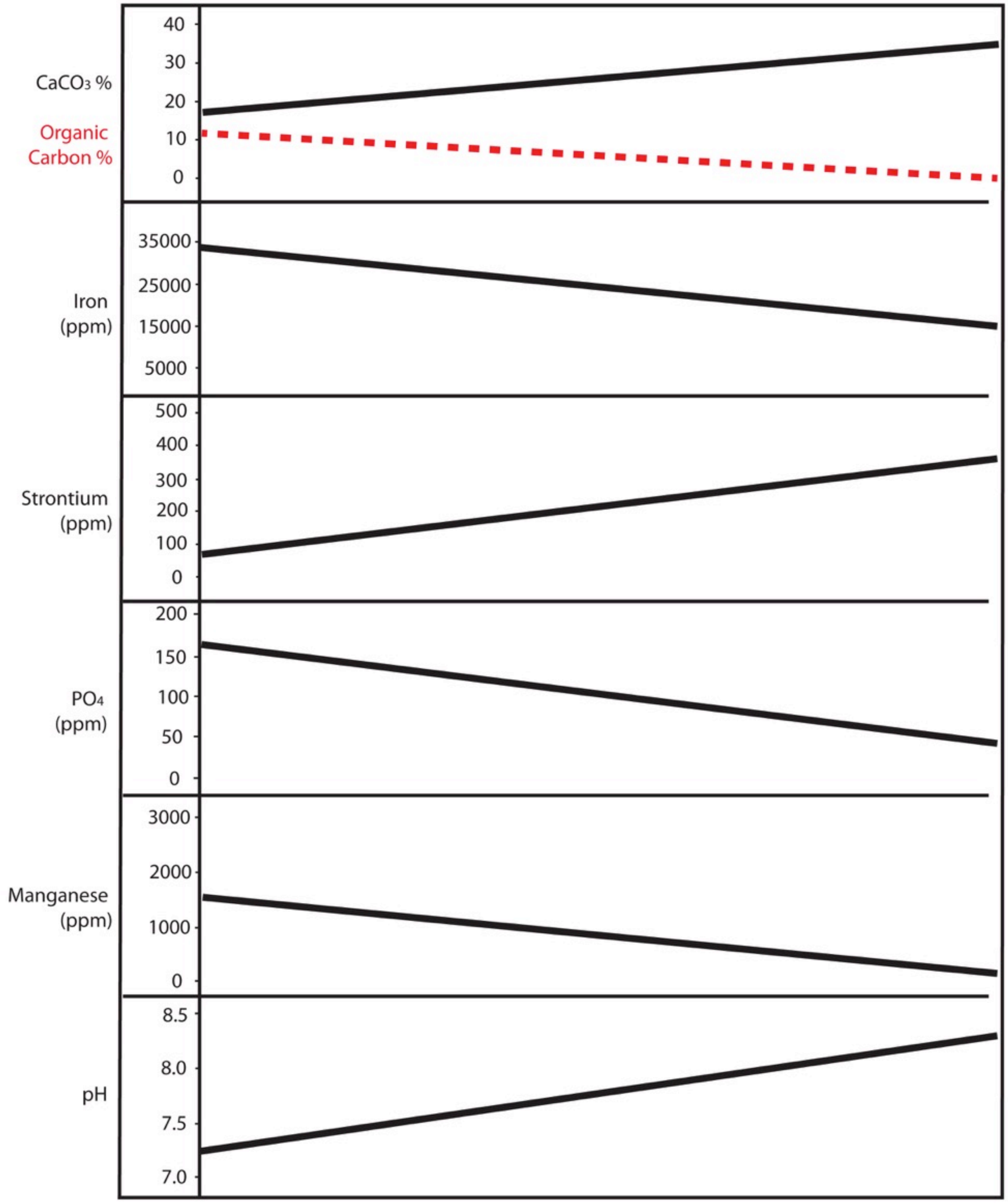


Figure 6.2. *Idealized soil profile. Graph of a normal soil profile displaying gradual increase in calcium carbonate percentage, strontium concentration, and pH and gradual decrease of organic carbon percentage, iron concentration, phosphate concentration, and manganese concentration down the profile.*

6.3 Results of Geoarchaeological Analyses

The 96 soil samples were characterized using Munsell color descriptions and soil texture descriptions. Multiple laboratory methods were used to examine the soils, including measurement of pH, acid-extractable phosphates (P), loss-on-ignition (LOI) organic matter and carbonate content, and trace element quantification using portable x-ray fluorescence (Beach et al. 2006:169; Holliday and Gartner 2007:301; Metcalfe et al. 2009; Stein 1986). Appendix V provides descriptive statistics for the iron, strontium, manganese, and phosphate concentrations, the pH, and the sand, silt, clay, organic carbon, and calcium carbonate percentages (see also Appendices IV, VII, VIII, IX, X, and XI).

Analysis of each soil profile (referred to at BHAP1-20) allows the identification of deviations from the expected patterns of soil characteristics in normal profiles, highlighting areas of the landscape that have been modified by human activity over time. To assess the landscape legacy of sugarcane monoculture at Betty's Hope, each soil profile has been analyzed individually, beginning with the profile from the top of the northern catena, then progressing down this catena to the drainage, and up the southern catena to the site of the Betty's Hope Great House. Figure 6.3 provides an illustration of the location of the profiles along each catena, with relative horizon depths and Munsell soil colors. Descriptions of the results of the laboratory analyses for each soil profile can be found in Appendix VI, beginning with the profile at the top of the northern catena (BHAP12) and moving down the catena to the drainage channel separating the two hillslopes (BHAP1 and BHAP2), then moving up the slope of the southern catena to BHAP20.

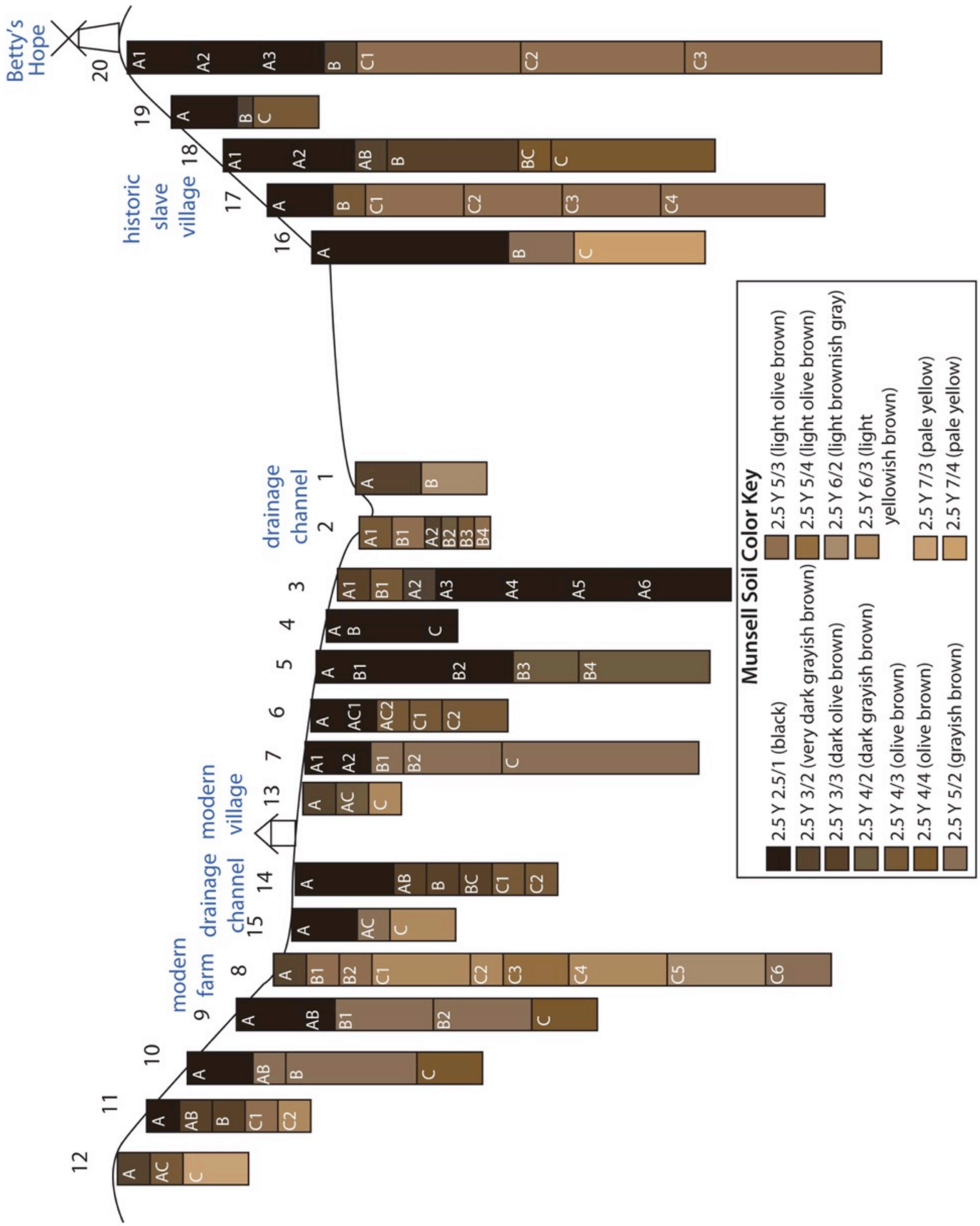


Figure 6.3. *Soil profiles. Illustration of the location of the profiles along each catena, with relative horizon depths and Munsell soil colors.*

Analyses of the soil profiles from the catenas near Betty's Hope also reveal signs of a changing-human environmental dynamic. Archaeological studies of landscape change involving soils focus on the physical, biological, and chemical effects (modification to soil structure, soil pH, aeration and water drainage, nutrient cycling, soil temperature changes, and the addition of anthropogenic materials) of different human activities reflected in contemporary soils (Wells 2006:126). Soil profiles from different auger probe locations reveal both stability and instability in the landscape, suggesting that some parts of Betty's Hope have been more susceptible to anthropogenic landscape degradation while others have remained stable. Full descriptions of the changes to each profile and the major correlations between soil characteristics can be found in Appendix IX.

The profile from auger probe 12 appears normal with no anthropogenic disturbance. The soil horizons are very thin because the profile was located on the crown of the northern catena and sediment moves downslope, leaving the profile at the highest elevation shallow. There is no B horizon, but the soil constituents exhibit gradual change down the profile with no unexpected values. This suggests that the land around auger probe 12 is relatively stable, but not particularly suited to agriculture, given the lack of a B horizon and the thin (10 cm) A horizon. There is little evidence for past agricultural activity in this profile, though the lack of a B horizon and shallow profile suggests that sediment from the top of the catena has moved down the hill slope.

Similar to the profile from auger probe 12, the profile from auger probe 11 is also quite shallow since it is from the top of the catena. The horizons are thin, but there is a B horizon present in this profile. Unexpectedly, the organic carbon percentage increases in the C1 and C2 horizons, suggesting a now-buried deposition of organic material. The C horizons are also very low in iron, while the overlying horizons all share relatively high iron concentrations. This suggests that the A, AB, and B horizons may possibly be recently deposited sediments eroded from the upper slopes of the catena. However, the horizons in this profile are quite distinct, indicating that they have developed over a long period. The A, AB, and B horizons (each 10 cm thick) appear to be relatively fertile. Like the profile from auger probe 12, this soil profile appears relatively stable, though possible too shallow to be an ideal location for intensive agriculture.

The soil profile in auger probe 10 does not display unexpected changes in soil characteristics other than a change in the soil texture. While the A, AB, and C horizons are clay, the B horizon is sandy loam. The changes in other soil characteristics are gradual down the profile. The organic carbon percentage is higher in the A horizon and the iron concentration is high throughout the profile suggesting that the upper horizons are more fertile and better suited to be cultivated. The B horizon is quite thick (40 cm) and this profile is also deeper than those higher on the catena, suggesting that this location is less susceptible to erosion and likely is the location of deposition of sediment from the upper slopes.

Auger probe 9 was removed from a now-fallow field that was cultivated in the past. Accordingly, the AB horizon appears to be a now-buried area of activity, displaying a slight dip in pH and increase in manganese and phosphate concentrations. The uppermost A horizon is thicker (20 cm) than those from higher on the slope, but bears no evidence of having been cultivated, suggesting this horizon is a layer of sediment eroded from above, deposited after the AB horizon was cultivated. The B1 and B2 horizons are similar to the A horizon and the B horizon is very thick (60 cm total). This indicated that the area from which auger probe 9 was removed is very stable and suited for agriculture.

The soil profile in auger probe 8 was removed from an actively cultivated field. As a result of constant cultivation, the soil profile is quite deep and exhibits a high level of variation, though the organic carbon percentage is consistently low throughout the entire profile. The A, B1, and B2 horizons are affected by the current cultivation, displaying steady change in soil characteristics. Underneath this active area, the 30 cm thick C1 horizon appears similar to the C horizons nearest to the bedrock. However, the C2 and C3 horizons (60-90 cm below the surface) may represent a buried cultivation surface: the changes in soil characteristics match those found in the currently cultivated horizons. This profile provides an example of an active and healthy farm with evidence of past cultivation and a fallow period before the current cultivation period. The A horizon displays fertile soil with anthropogenic changes evident in the decrease in calcium carbonate percentage and increases in pH and iron and manganese concentrations.

The soil profile in auger probe 15 was extracted near a drainage channel below the active farm. Unlike that from auger probe 8, this soil profile is very shallow, possibly because the water channel carries easily moved settlement downstream. The high calcium carbonate percentages in this profile suggest that the horizons have high levels of particles derived from the bedrock. The A horizon is relatively thick (20 cm) with high concentrations of iron and manganese. Particles containing heavy metals are suspended in water channels; when these flood, much of the suspended sediment in the water is deposited in nearby alluvial soils (Alloway 2012:28), thus the high concentrations or iron and manganese can be attributed to sediments being washed down to the drainage from the farm of auger probe 8. While the A horizon is fertile, this soil profile lacks a B horizon, suggesting that the location near the drainage channel is conducive to washing sediment away. The shallowness of the profile suggests that it is susceptible to unexpected events: there is no B horizon, the profile is sediment washed down from the upper slopes of the catena lying atop a C horizon of weathered bedrock.

The soil profile in auger probe 14 was samples near the present-day village of Pares. This profile has a thick A horizon (30 cm) with a high percentage of organic carbon and a high phosphate concentration consistent with continuous human occupation. Although the effect of human occupation is evident in the A horizon, the underlying horizons appear relatively normal and do not display unexpected changes that might indicate erosion or other degradation. This soil profile is very stable due to the side effect of maintenance that occurs as a result of human occupation.

The profile from auger probe 13 was removed from an unoccupied field near the modern village of Pares. Despite being located near an area of occupation, the profile displays very little organic carbon throughout the profile and a very high percentage of calcium carbonate. The profile is quite shallow (30 cm), but appears normal. The thinness of the horizons suggests that this soil profile may be vulnerable to unexpected events, such as drought. With a thin A horizon and virtually no B horizon, this profile is probably not well suited for agriculture. The A horizon is likely a recently deposited horizon composed of sediment washed eroded from the upper slope of the catena.

The profile from auger probe 7 was removed from an empty field. This profile is deeper (120 cm) than that of auger probe 13. The A1, B2, and C horizons appear to be quite similar, but disturbance is present in the A2 and B1 horizons. These horizons display changes in pH and manganese, possibly indicating cultivation or other activity in the past that has now been covered by a thin A1 horizon composed of sediment eroded from the upper hill slope.

Like that of auger probe 7, the profile from auger probe 6 was removed from an empty field on terrace two. This profile displays thick A and AC1 horizons (20 cm each) but lacks a B horizon. The A and AC1 horizons appear physically and chemically identical, with low calcium carbonate percentages, high organic carbon percentages, high iron, phosphate, and manganese concentrations, and low pH. This profile displays no evidence of past disturbance. The thick upper horizons appear to be fertile and this location is likely suited to productive agriculture. As with the profile from auger probe 7, the A horizon may be composed of sediment recently eroded from higher on the catena.

The profile from auger probe 5 was removed from an empty field on terrace two. This profile is the best example of a buried A horizon and recent decline in phosphate concentration. The recent decline could be due to an erosional event or a slow-moving process like continuous monoculture. The B2 horizon may represent a buried A horizon, evidenced by a change in soil texture and a decline in manganese and an increase in iron. The entire profile exhibits low and consistent percentages of calcium carbonate and organic carbon. The buried A horizon is buried deep (40 cm) under A and B1 horizons that are physically and chemically quite similar. The consistency and depth of these horizons indicates that these thick horizons were deposited relatively fast, suggesting that that sediment from the slopes above this auger probe location eroded quickly to accumulate in formerly cultivated fields on the lower slopes.

The soil profile in auger probe 4 is very shallow (40 cm). While A, B, and C horizons are present, they are very similar, with high iron concentrations, consistent organic carbon and calcium carbonate concentrations, constant pH, and gradually declining manganese and phosphate concentrations. This soil profile likely represents an accumulation of sediment eroded from the upper slopes of the catena. Since the horizons are not distinctly formed, it is likely that these represent very recently deposited sediment, suggestive of sudden erosional activity.

The soil profile in auger probe 3 was extracted from terrace one, near to the drainage channel between the two catenas. This profile is quite deep (130 cm) and displays another buried A2 horizon at 30 cm below the surface. The buried A2 horizon is not as fertile as the horizons overlying is, suggesting perhaps that this horizon was depleted by past cultivation. The B1 horizon is slightly more enriched than both the underlying buried A2 horizon and the uppermost A1 horizon. This suggests that the A1 and B1 horizons are composed of sediment eroded from the upper slopes, making them more fertile than the buried A2. As lower terraces are typically more fertile than upper ones, it follows that this field was subject to longer-term cultivation enriched this profile.

The soil profile in auger probe 2 was removed from terrace one on the north side of the drainage channel between the catenas. The profile is very shallow (40 cm) with thin horizons. The majority of the soil characteristics are relatively stable, but the iron concentrations increase in the lower horizons and the calcium carbonate percentages decrease, both defying the expected pattern. This suggests that the iron and other minerals in the upper horizons are washed away by the water in the drainage channel, leaving only a larger than normal quantity of weathered bedrock. The thin but invariable horizons are alluvial, representing sediment eroded from the above catena with nutrients washed away by the water activity near the drainage channel.

The soil profile in auger probe 1 was removed from the south side of the drainage channel. Like the profile from auger probe 2, this profile is also very shallow (40 cm), but only displays two horizons. The A and B horizons are alluvial sediments with little variation. As water moves particles bearing heavy metals and phosphates, the nutrients from the A horizon may be washed away by the activity of the water in the drainage channel.

The soil profile in auger probe 16 was removed from a fallow field on the hill slope of terrace one on the southern catena. As a result of having been farmed in the recent past, the A horizon is very thick (60 cm) and fertile. Soil characteristics change gradually in the B and C horizons as expected, and the soil texture transitions from clay to clay loam. This profile represents a normal soil profile well suited to agriculture. There is no evidence of landscape change in this profile; rather, it represents what an ideal, stable soil profile should be with recent anthropogenic investment into the landscape to maintain soil fertility and productivity in the A horizon.

The soil profile in auger probe 17 was removed from the site of the historical slave village. The historic living surface dates to the mid-eighteenth century and is immediately identifiable in the profile: the organic carbon percentage increase dramatically in the C1 horizon, accompanied by an increase in pH, a decrease in the manganese concentration, and a change in soil texture. The A and B horizons overlying the historic occupation surface are composed of sediment eroded from the upper slopes following the occupation of the area. These horizons are also shallow compared to the others in the profile, suggesting they have been deposited more recently with less time to develop. The B horizon also displays an increase in phosphate concentration, representing an aberration from the otherwise normal gradual decrease in phosphate concentration in this profile. The C horizons below the occupation surface are physically and chemically consistent, suggesting that these horizons are free from anthropogenic disturbance. This profile indicates roughly 25 cm of sediment deposition. The fact that there are two distinct horizons over the historic occupation surface suggests that either the deposition occurred a long time ago, allowing the sediment to develop into two horizons, or that the B horizon is older and the A horizon is more recent deposition and the product of recent erosional activity.

The soil profile in auger probe 18 was removed near the site of the historic village. Unlike the profile from auger probe 17, this profile does not display dramatic spikes in organic carbon percentages, but the A horizon is very thick (40 cm) and nutrient rich, with a high phosphate concentration. There is little evidence for erosion in this soil profile, suggesting that it is quite stable.

The soil profile in auger probe 19 was removed near the crown of the southern catena. The profile is shallower than previous profiles, suggesting that since this auger probe was removed nearer the top of the catena, the horizons are thinner because sediment erodes down the slopes. Despite this, the A horizon is relatively thick (20 cm) and there is a shallow (5 cm) B horizon present. Given that this area is between the location of the historic slave village and the plantation Great House, it may not have been subjected to intensive agriculture, therefore is currently less degraded than former cultivation areas. This is corroborated by the hypothesis that there was a historic road and slave village may have been located near this location (Georgia Fox, personal communication, February 11, 2015).

The soil profile in auger probe 20 was removed from the crown of the southern catena near the site of the Betty's Hope Great House. The profile is very deep (230 cm), though the three C horizons appear physically and chemically consistent. The three A horizons are thick (20 cm each), and the B horizon is present, though shallow (10 cm). The A horizons display gradual changes in organic carbon percentages and pH. The C1 horizon bears evidence of past human occupation, with an increase in organic carbon percentage and pH. Aside from the anthropogenic disturbance from the occupation period, the profile seems relatively stable with no signs of recent or long-term degradation. The A horizon is thick, suggesting that the upper horizons of this area were less susceptible to erosion down the slopes.

There exists considerable variation in the soil profiles removed from different areas of the two catenas. Some of this is attributable to the natural archaeological stratigraphy of slope units, wherein upper slopes have shallower soils that may show evidence of erosion, mid-slopes have eroded and over thickened soil horizons, lower slopes are the location of colluvial deposition, and valleys are characterized by colluvial and alluvial deposits (Goldberg and Macphail 2006:77-78). The understanding of the natural variation in soil profiles on different parts of the catena facilitates the identification and interpretation of past anthropogenic landscape construction and degradation processes.

6.4 Conclusion

The keys to reconstructing the landscape are preserved in the sediments, soils, and erosional contacts marking up the archaeological site matrix (Waters 1992:91). Studies of soils can reveal how humans in the past used the landscape and defined space through their activities (Walkington 2010:122). By analyzing soil profiles from different areas on the two catenas near Betty's Hope, this research seeks to reconstruct the changes to the landscape since the introduction of sugarcane. By identifying aberrations from normal changes in a soil profile, a geoarchaeological analysis highlights areas of possible human disturbance. Soils preserve evidence of landscape stability, and erosional nonconformities preserve evidence of landscape degradation, allowing for the unraveling of the spatio-temporal record of landscape aggradation, stability, and degradation (Waters 1992:91).

CHAPTER SEVEN:
DISCUSSION

7.1 Introduction

As stated in Chapters 1 and 4, there are three possible explanations for modern degradation at Betty's Hope Plantation: 1) landscape degradation is predominantly anthropogenic; 2) landscape degradation is the product of natural environmental processes; or 3) degradation is linked to both human and natural factors. If landscape degradation is mostly anthropogenic, it can be concluded that humans overused the land until it failed. If landscape degradation is the product of natural environmental processes, then it can be concluded that natural events such as climate-induced flooding or drought have contributed to current land degradation. If land degradation is linked to both human and natural factors, it can be concluded that the "abandoning the garden" hypothesis is correct: long-term investment of landesque capital to maximize agricultural yields crated a landscape dependent on human maintenance to be successful.

The analysis of the sugar yields recorded in the Codrington Papers and the soil profiles sampled in 2014 provide new insight into historical and contemporary landscape degradation. The legacy of sugarcane monoculture on the landscape of Betty's Hope Plantation can be elucidated through the concurrent examination of these two lines of evidence, revealing the complexity of the human-environmental dynamic over time for a single sugarcane plantation.

7.2 Results Summary

The comparison of historically recorded sugarcane yields extrapolated from annual sugar sales in the Codrington Papers with a timeline of significant climatic, political, and local events in Antigua reveals that the effects of these events were felt in annual sugar yields. The annual crop yields simulated by the EPIC model serve as a hypothetical baseline for expected sugar yields if the soil conditions, weather conditions, and cultivation strategies remain constant over time. The EPIC model cannot account for unexpectedly wet or dry years, political and social unrest, or slave labor (or, after, 1824, free labor). The EPIC-simulated crop yields suggest that the sugarcane yield per acre declines nearly immediately if all conditions are constant. After a century of consistent monoculture, the simulated crop stabilizes at a much lower yield per acre with limited annual variation. Without taking into account variation caused by external event or human activity, the crop yields at Betty's Hope should to have declined dramatically following the domination of sugarcane cultivation in Antigua in the early 1700s. If the historically recorded yields match the simulated yields, it can be concluded that the Codrington family used their estates sustainably. The simulated crop yields provide a basis for comparison of historically recorded yields; deviation in the actual yields in the past from the pattern presented by the EPIC model suggests the effects of external events and human activity in creating a more or less productive landscape than is hypothesized to occur if all conditions are held constant over time.

The examination of historical crop yields and the subsequent comparison with the simulated yield/acre provided by the EPIC model reveals that the EPIC model *does not* reflect accurately the changes in historical yields. The EPIC model predicts that yields should to decline dramatically, and, ultimately stabilize at a much lower yield, but recorded historical yields defied this pattern and continued to exhibit growth long after the takeover of sugarcane monoculture.

The records show annual variation with a trend of yield increase from the beginning of available records in 1707 until the end of the eighteenth century, and then a subsequent a decline in yields after 1800.

The deviation of historical yields from the simulated yields suggests that the Codrington plantations *pushed the landscape to the limit* to produce as much sugarcane as possible from their land. Unexpectedly high and expanding crop yields suggest that not only did Betty's Hope expand the area of cultivation area as much as possible, they also used the land unsustainably. The expansion of sugarcane at Betty's Hope mirrors the takeover of the crop throughout the rest of the island; roughly ninety percent of Antigua's available land was devoted to sugarcane in the 1750s during the peak of the island's sugar industry. The expansion and overuse of Codrington land at Betty's Hope may have been part of island-wide patterns of land use. The Codrington plantations cultivated sugarcane in an unsustainable manner, creating a situation in which the short term crop yields were high, but the land was overused and made more vulnerable to later decline and landscape degradation.

The historical yields also display variation associated with major political and climatic events. The effects of extreme wet or dry periods coincide with periods of sharp increases and decreases in sugar yields. These effects are particularly acute in the 1770s and 1780s, when alternating years of too little and too much precipitation coupled with the disruption caused by the American War of Independence coincide with two decades of wildly swinging sugarcane yields. Despite the increase in annual variation during this period, the six-year averages from these decades reveal that average sugar production was actually higher in these years than in the beginning of the century. It is also during this time that Betty's Hope's sugar works underwent another expansion and the slave population continued to grow. It is clear from the historical records that sugarcane cultivation was beginning to destabilize, because although more sugar was produced than in previous decades, crop yields were becoming unpredictable due to unexpected environmental and political events. In 1781, in the middle of this period of dramatic crop variation, a letter from the supervisor of Betty's Hope to the Codrington family in England reported that the Codrington estates collectively had too few slaves to support 1100 acres of fields producing 800-1000 hogsheads of sugar each year. Although there were 393 slaves working at Betty's Hope at this time, the sugar production on the Codrington states was too massive to be sustained by the available labor force. Given the amount of human effort put into the land to prepare the fields, plant the cane, tend to the cane, and harvest the cane, the struggle to maintain consistently high levels of sugar production suggests increasing instability in the human-environmental system.

Since the annual historical sugar yields appear to be generally larger but more variable in the later half of the eighteenth century after the Antiguan sugarcane industry reached its historic peak in 1833, I conducted a brief analysis to assess the degree to which yields varied before and after the industry's height. I calculated basic descriptive statistics in SPSS for the historical sugarcane yields from 1707-1753 (before the peak of Antigua's sugarcane industry) and 1754-1828 (following the peak of Antigua's sugar industry) (Table 7.1). The mean annual yield for the period of 1707-1753 yields is 2423.39 tons, while the mean annual yield for the period of 1754-1828 is 3026.43 tons. The larger yields in the second half of the century may be due to the expansion of Codrington estates over time, contributing to larger sugarcane fields and thus larger annual yields. If the productivity of the land continued to be approximately the same throughout the eighteenth century, crop yields are expected to display the same amount of annual variation no matter the size of the cultivated area.

Table 7.1 Yield Variation Before and After the Peak of the Sugarcane Industry

	1707-1753	1754-1828
Mean	2423.39	3026.43
Median	2707.75	2939.42
Mode	3185.58	4003.84
Standard Deviation	1158.44	1712.76
Coefficient of Variation	0.48	0.57
Range	4166.24	7695.37

The standard deviation of yields following the peak of the sugarcane industry (1712.76 tons) is significantly larger than that of the beginning of the eighteenth century (1158.44 tons). However, the coefficient of variation is a more useful way to determine how much the yields vary because the standard deviation must always be understood relative to the mean of the data. In order to compare datasets with different means, such as the annual yields before and after the peak of the sugar industry, the coefficient of variation provides a more accurate representation of variation than the standard deviation. The coefficient of variation for sugarcane yields from 1707-1753 is .48, while the coefficient of variation for the yields from 1754-1828 is .57. While it is clear that yields varied quite a bit in the early years of the sugar industry, the greater variation observed after the historic peak suggests that sugarcane cultivation may have been larger, but was also becoming less stable and annual yields less predictable. The greater variation in later years of the Codrington sugar records suggests that despite higher yields on average, sugarcane cultivation was becoming less stable, perhaps indicating a more vulnerable landscape.

The examination of the 20 soil profiles from the site of Betty's Hope Plantation helps to elucidate the changes to the landscape over time. Several findings come to light, especially the identification of stable and unstable parts of the landscape. Two types of stable locations are present: those located higher on the hillslopes of each catena and those located near areas of continuous human activity. Locations on the upper slopes or near the crows of the catenas are inherently more stable than those below; these areas are subject to natural erosion of sediment down the slope and consequently have thinner A horizons and absent or thin B horizons. Although the horizons are shallow and these areas are prone to sediment loss, they are also subject to less depositional activity and less vulnerable to the effects of changes in the drainage channels. These parts of the landscape are less suitable for agriculture, given the thin A and B horizons and proclivity for erosion, but are overall more stable and reliable that the more dynamic lower slopes of the catenas. Areas where human activity has persisted also appear to be more stable. The auger probes located near the modern village of Pares, the historic slave village, or active and recently fallowed farms all display thick and A horizons, suggesting that continuous human activity has contributed to the intentional or unintentional stability of these locations. In the case of auger probes 8 and 16 (active and recently fallow fields respectively), the thick A horizons with high mineral contents indicate that these parts of the landscape are still relatively productive agricultural areas.

Auger probes from the lower slopes of the catenas, especially those in close proximity to drainage channels, suggest that these areas are more fertile than upper slopes, but also in a more dynamic part of the landscape. The lower parts of the landscape are simultaneously more suited for agriculture due to their thicker and more fertile A horizons, but more unstable. The lower slopes are subject to sediment deposition as particles erode from the upper slopes and accumulate on the lower parts of the catenas; this is apparent in the presence of buried A horizons in many auger probes removed from the lower slopes. The location near water channels also makes lower parts of the catenas more unstable because water activity can wash away sediment and soil nutrients. The 20 auger probes from the site of Betty's Hope reveal that the landscape is a dynamic one, with some areas more and less suited for agriculture.

7.3 Sugarcane Landscape Legacies at Betty's Hope

Based on the historical records of sugar yields and the discrete geographic area covered by the auger probes, it is clear that the legacy of sugarcane present in the contemporary landscape is complex. Landscapes are the multi-dimensional product of historically determined structures and contingent processes; the product of long-term human-environmental coevolution (McGlade 1995, 2003). The assessment of the impact of sugarcane monoculture on the landscape at Betty's Hope focuses specifically on the cultural soilscape and soilscape legacy of the Antiguan sugarcane industry, which reflects the effects of both human and natural processes over time (Wells 2006:125).

The landscape around Betty's Hope was subjected to multiple investments of landesque capital over time. It is known that the Codrington estates, like the majority of Antiguan plantations, manured their fields to increase productivity and fields were rotated between sugarcane and fallow, allowing the soil a reprieve from constant farming (Museum of Antigua and Barbuda 2014; Martin 1784; Sheridan 1960:133; Watts 1990:425). These two agricultural strategies are inherently investments of landesque capital in that they increase the health and productivity of the land. As previously discussed, landesque capital is the "purposive land management designed to secure future production" that "once created persists with the need only of maintenance," thus the initial investment is intended to benefit future crop cycles beyond a single season (Blaikie and Brookfield 1987:9; Brookfield 1984). Through continued investments intended to improve sugarcane crop yields, Antiguan plantations over time drastically altered the landscape in order to make it ideal for sugarcane growth and subsequently dependent on human activity for its maintenance. Through the continuous investments of landesque capital required for sugarcane cultivation, Antiguan planters can be thought of as constructing a niche. The human action of clearing the island of its natural forest, for example, created new environmental conditions wherein the land was less fertile and more prone to soil erosion without natural vegetation; Antiguan planters then to adapt their agricultural methods to overcome this anthropogenic change to the environment. Although the exact investments of landesque capital are unknown for the period for which sugar yield records were available, it can be assumed that such strategies forestalled the rapid decline in sugarcane yields predicted by the EPIC model.

However, despite the efforts of Antiguan planters to stave off decreasing yields over time (Sheridan 1960), the sugar industry ultimately did reach a point after which production levels could not be sustained (Watts 1990). Though sugar was never again as productive or profitable as it was in 1753, sugarcane cultivation persisted in Antigua until 1972. The long-term adherence to the sugar industry can be explained by the concept of path dependency. As described in Chapter 2, path-dependent societies continue to follow a course of action based on tradition and practice—or short-term "least cost"—even if other alternatives are possible and potentially more desirable in the long-term (Chase and Chase 2014:143). The commitment to sugarcane monoculture in the early eighteenth century profoundly set Antigua on a course of pursuing great wealth at a high cost, as the island's economy subsisted on the production and export of sugar and its byproducts; the island relied on the importation of necessary supplies from elsewhere. Even after Antigua reached the pinnacle of sugarcane productivity, Antiguan plantations continued to produce sugar even as annual yields progressively declined in the latter half of the eighteenth century, with sharper declines from the 1890s until the end sugarcane cultivation in the early 1970s. Although sugarcane cultivation was no longer as productive or profitable after 1753, Antiguan planters continued to grow the crop for another two centuries.

The adherence to sugarcane monoculture is visible in the examination of the sugar yields recorded in the Codrington Papers. Although Antiguan sugarcane peaked in the mid-1700s, the Codrington plantations continued to produce sugar at higher quantities; according to the Codrington Papers, the year 1766 was the peak for sugar production. Additionally, the sugar yields extrapolated from the Codrington Papers indicate that sugar yields in the second half of the eighteenth century were larger than those from the first half. This suggests that although the heyday of sugar production may have been over for Antigua, the Codringtons continued to expand their production capability by expanding sugar processing facilities, increasing the number of enslaved laborers, and producing larger annual quantities of sugar and sugarcane byproducts, such as rum. In doing so, it appears that the Codrington estates overused their land: not only were the numbers of laborers too low to sustain high levels of sugar production, the consistent pressure on the landscape to maintain high levels of fertility made it reliant on constant human maintenance and more susceptible to destabilization caused by disruptions to the human-environmental system. This is evident in the dramatic changes to sugar yields in the 1770s and 1780s, when climatic and political events created an unpredictable context for sugarcane cultivation.

The northern catena bears more evidence for land degradation than the southern catena. The profiles at the top of the catena have thin A horizons, but the A horizons thicken on lower slopes, suggesting that sediment consistently erodes from the upper slopes to the lower. The material accumulated at the foot of a hillslope indicates possible locations of buried land surfaces and stratigraphic records of human activity where erosion has been active (Goldberg and Macphail 2006:76). Soil profiles at the foot of the catena have thicker A horizons which overlie older A horizons, representing episodes of recent (post-1972) sediment accumulation on the lower portions of the catena. Fewer auger probes were removed from the southern catena, but the soil profiles suggest that these areas are more stable and possibly not cultivated as heavily (or at all) in the past, evidenced by thicker A horizons, and the presence of B horizons on upper slopes. Out of all soil profiles, those from auger probes 8 and 16 are particularly interesting, as they represent a currently farmed field and a recently fallowed field respectively. These soil profiles indicate that the former Betty's Hope landscape can sustain successful agriculture when given proper maintenance. Soil profiles taken from empty fields on the lower slopes of the northern catena indicate that older A horizons—farmed in the past—have been buried by sediment eroded from the top of the hill slope. The thicker horizons on the lower slopes of the catena suggest that lower areas were more suitable for agriculture, given the increased fertility and consistent addition of new sediment through natural erosion. However, given that long-term monoculture may have created the necessary conditions for failure in the wake of an unexpected event (e.g. extreme drought or the cessation of sugarcane cultivation), slopes near drainage channels appear to be at a greater risk for catastrophic failure. Higher slopes on the catena are more stable but less fertile, since sediments erode from the slopes, creating thin soil horizons. Lower slopes by the drainage channel are part of a more dynamic landscape; they are rich and fertile but more susceptible to disaster.

Soil profiles near areas of human occupation or continuous human maintenance (modern village, historic village, Great House site, active farm, recently fallowed field) display less evidence of land degradation. Anthropogenic impacts are visible in buried occupation surfaces as reflected in the relatively high percentages organic carbon in the topsoil. These profiles also have thick and fertile A horizons and B horizons, suggesting a relatively stable landscape with healthy fertile soil lying atop a B horizon. The continuous human activity at these locations is reflected in the disturbances to changes in a normal soil profile as well as in the continued stability of these areas compared to those with a less visible human presence in the cultural soilscape.

Phosphate concentration is an indicator of soil productivity; increases in the concentration indicate the effects of landesque capital investments, such as the addition of fertilizer, manure, or letting fields lay fallow. Decreased productivity over time should be reflected in reduced phosphate concentration in the B horizons of previously cultivated areas, thus the agrarian legacy may be visible in the profiles with no disturbances. Phosphate concentrations should decrease gradually down normal soil profiles, as is the case in auger probes 9, 12, 14, 16, 17, 18, and 19. However, the soil profiles from auger probes 4, 5, 6, 7, 10, and 11 exhibit declines of phosphate concentrations in the B horizons, then increases in the C horizons, indicating a depletion of the phosphate concentration in the past. The higher concentration in the A horizons indicate recent enrichment due to eroded sediment accumulating in the A horizons. The observed decline in phosphate concentrations in the B horizons supports the hypothesis that the declining sugar production observed for the entire island of Antigua after 1753—and recorded in the Codrington Papers at the end of the eighteenth and beginning of the nineteenth centuries—was caused by a decline of soil fertility due to long term monoculture. Despite the efforts to allow fields to lie fallow and to apply manure and lime, the Codrington plantations could not maintain the level of sugar production over time. As the concept of path dependence suggests, once the commitment to sugarcane monoculture took its hold, Antiguan planters would not be so easily swayed from their ways even when their actions became progressively less successful. The desire for short-term profit and wealth won over long-term sustainable planning, leading to eventual disaster in the form of land degradation.

In contrast, areas at the top of the northern catena appear stable but much less fertile and there is evidence of downward erosion in the gradually thickening A horizons as soil profiles move down the slope. The erosion appears relatively recent; old cultivation surfaces are visible in empty fields (formerly part of the Betty's Hope land), buried under 20 cm or more of A horizon sediments. In some cases, such as with auger probe 4, the entire soil profile is composed of a thick layer of enriched material that was deposited from upper slopes. The drainage channels indicate leaching of heavy metals and other minerals, suggesting that soil nutrients have been washed away between the catenas, leaving higher amounts of heavy particles, such as sand and weathered bedrock. The lower slopes of the catenas appear to have been farmed in the past, suggesting that lower slopes closer to drainage channels were more conducive to agriculture. However, these areas are also more dynamic than the tops of the catenas, as they are subject to flooding due to the proximity to drainage channels and as they receive sediment deposition through erosion from the higher slopes.

Erosion has occurred in the landscape since the fields near Betty's Hope were cultivated. This recent erosion is evidenced by the buried A horizons in empty fields on lower slopes of the northern catena. The last Antiguan sugar refinery closed and sugar production all but stopped in 1972, suggesting that the recent erosional process observed in the former Betty's Hope fields began at roughly this time (Weaver 1988:321). The cessation of island-wide sugarcane cultivation appears to have tipped off the erosion of A horizon sediments from the upper slopes of the catena, which subsequently buried the A horizons of previously cultivated fields. The A horizons are thick on the lower portion of the catena (auger probes 7, 6, 5, and 4), suggesting that since approximately 1972, upwards of 20 cm of sediment has accumulated on the lower slopes. The buried A horizons are also thick, indicating that this area was conducive to agriculture.

The soil profiles from the two catenas indicate that erosion has occurred in the recent past, likely coinciding with the dramatic decline of the one-dominant sugarcane industry. It is clear that areas with long histories of recurrent human activity—villages and active fields—appear to be the most stable locations on the catenas, even while areas nearby are subject to sediment erosion and deposition.

7.4 Conclusion

The annual sugarcane yields recorded in the Codrington papers indicate that historical crop yields were more dynamic than those predicted by the EPIC model. The deviation of historical yields from the simulated yields suggests that the Codringtons may have been pushing their plantations to the limit. Consistent overuse of the landscape, while initially could have provided increased sugar yields, can create the conditions necessary for later degradation. As Fisher's abandoning the garden hypothesis suggests, highly anthropogenic landscapes require constant human maintenance in order to remain stable. Sugarcane agriculture, by virtue of requiring large amounts of labor to plant, tend, and harvest, required an increasing amount of human labor and landesque capital investments into the Antiguan landscape as plantation owners struggled to extract as much sugar from their plantations as possible. Chronic overuse of plantation lands for decades created a landscape dependent on human labor to remain stable enough for cultivation. The consolidation of Antiguan sugar estates in the mid-twentieth century represents the "abandonment" of the island's plantation sugary industry. The abrupt cessation of large-scale sugarcane cultivation—and the accompanying labor inputs into the landscape—may have tipped off recently observed land degradation in Antigua, though the causes of such degradation can be attributed to events decades before. Heavy investment into the Antiguan landscape to maintain the largest sugarcane crops possible created a landscape progressively less stable and more dependent on human maintenance. By 1972, the landscape was reliant on landesque capital investments and the sudden and dramatic reduction to those investments caused rapid destabilization of a long-vulnerable landscape.

CHAPTER EIGHT:
CONCLUSION

In many parts of the world, landscapes are being transformed at an unprecedented rate. In these regions, land management often attempts to reduce the rate of landscape change and to direct it in more desirable directions (Bürgi et al. 2004:861). Studying landscape persistence and constraints to landscape change deserves the same attention as the analysis of landscape change itself (Bürgi et al. 2004:861). In all studies, it is pivotal to distinguish between correlation and causality (Bürgi et al. 2004:864). This study sheds light on associations between environmental events and changes to historical sugarcane yields as well as the correlation between recently observed land degradation and eroded sediment burying former sugarcane fields.

The legacies of three centuries of monoculture in Antigua continue to be felt today; the anthropogenic landscape is currently changing in response to both the conditions created by long-term sugarcane cultivation and by the cessation of such intensive agriculture. The major findings of this research indicate that erosion has occurred since fields near Betty's Hope Plantation were cultivated. This indicates that since the cessation of the sugarcane industry, the landscape has destabilized. The decline in phosphate concentrations in the buried A and B horizons of soil profiles with recent colluvial topsoil on the lower slopes of the northern catena suggests that depletion of soil nutrients occurred in the past and that the higher phosphate concentrations observed in the A horizons represent enrichment since the end of sugarcane monoculture. Locations in the landscape with more consistent human activity—the historic and modern villages, and the active and recently active fields—are more stable and appear to have suffered less recent erosion and/or deposition. The increase in sugarcane yields during the eighteenth century indicates that the highly anthropogenic environment was pushed to the limits of its capacity; unpredictable yields toward the end of the eighteenth century suggest that the landscape was beginning to destabilize and the consistent sugarcane yields became more difficult to maintain. The continuation of sugarcane cultivation until 1972, coupled with observed soil nutrient loss in buried cultivation surfaces and recent erosion from upper slopes of the catenas suggests that without constant human maintenance, the engineered landscape was vulnerable to unexpected and undesired changes.

Archaeology is uniquely suited for assessing the landscape legacies and the relationship between human and the environment in the past due to its deep time perspective and ability to identify emerging change (Redman and Kinzig 2003; Redman et al. 2009). Archaeology's inherent deep-time perspective allows for the examination of information about the past over a long period facilitates the identification of subtle underlying causes of system change and collapse. The archaeological record reveals multiple human modifications to the environment and can show how the accumulation of these changes leads to shifting environmental conditions (Redman and Kinzig 2003; Redman et al. 2009). The span of information over multiple decades, centuries, or millennia can yield insight into the way short-term changes to the human-environmental system (such as the investment of landesque capital) can create long-term unanticipated changes (such as delay of land degradation). Archaeology also facilitates the identification of emergent features in the trajectories of societies. The archaeological record may provide information about the development of indicators of undesirable change, how such emergence is affected by characteristics of human and ecological systems, and how the indicators change over time (Redman and Kinzig 2003; Redman et al. 2009). Identification of the root causes of undesirable environmental changes in the past can serve as warnings about potential negative changes occurring in contemporary human-environmental systems and help to understand the origin of current problems. Archaeological approaches to landscape change can explore the diversity of human action in creating and responding to changing environmental conditions in both the past and the present and apply this knowledge to preventing or alleviating current environmental crises (Redman and Kinzig 2003; Redman et al. 2009).

At a time when environmental research is growing in importance, archaeological studies are more valuable than ever. Redman (2014:5) emphasizes the past as a "laboratory for innovations," since history contains nearly limitless experiments of resource management, adaptive responses, reactions to climate change, impacts of new technology, and a multitude of human and environmental interactions. However, despite the importance of history in creating present contexts, few studies of human-environmental interactions have incorporated effectively historical knowledge or long-term perspectives into current research (Redman 2014:5). This research at Betty's Hope provides a case study of human-environmental interactions in the recent past and sheds light on how particular human actions affect the environment and vice versa. The knowledge of the impact of long-term sugarcane monoculture on contemporary landscapes imparts a greater understanding of the complex human-environmental dynamics over time. Redman warns that we ought not oversimplify the past when designing the future, thus historical geoarchaeological studies such as this one can unravel the specific context of a localized environmental problem.

The research at Betty's Hope answers Redman's call for contributions to the "database of changing conditions, stresses or shocks, the responses to them, and the respective outcomes" using evidence from the past that may improve predictions of the desirability of future adaptive responses (Redman 2014:5). To create sustainable human-environmental systems, research must delve into the connected human and environmental factors contributing to contemporary environmental and sustainability issues. This research serves as a pilot study for the viability of assessing anthropogenic landscape change based on simulated yields, historical records, and geoarchaeological analyses.

The exploration of the landscape legacy of sugarcane at Betty's Hope also provides an example of the combination of multiple theoretical approaches for understanding how humans change their environment over time. The particular landscape legacy of sugarcane monoculture is visible through the study of archaeological soils, drawing upon the concept of cultural soilscapes ("soil bodies that have been physically and chemically altered as a direct result of human behavior"; Wells et al. 2013:24) and soilscape legacies ("the long-term socioecological consequences of human interactions"; Wells et al. 2013:23). Landscape legacy further draws upon niche construction theory, landesque capital, and path dependence to understand how people and the environment change each other and how human actions in regard to the environment persist over time. Niche construction theory contributes to the "understanding of how agricultural production and associated human activities create both intended and unintended changes to the landscape, as three centuries of intensive monoculture at Betty's Hope created a number of new selective pressures" (Fox 2014:36). While the evolutionary consequences of sugarcane monoculture are not the focus of this research, it is important to understand that agricultural practices changed and were changed by the island's environment, shaping the trajectory of the sugarcane industry. Landesque capital provides a descriptive term for the human actions that transformed the landscape; agricultural techniques such as drainage, tilling, fertilization, cane holing and others are investments of landesque capital that helped to create a landscape reliant on human labor for stability and continued agricultural success. These investments into the landscape can be considered a form of niche construction in that they alter the landscape such that new environmental pressures emerge to shape future inputs of landesque capital. Path dependence helps to explain how past human decisions, such as the switch to exclusive sugarcane cultivation or large-scale deforestation, constrain the possibilities for future decisions. Antiguan planters devoted their efforts solely to sugarcane, investing huge amounts of human labor and landesque capital to fundamentally alter the island's landscape, committing themselves to a path of sugarcane monoculture that lasted three centuries. While Antigua's sugarcane industry ended in the 1970s, the effects of such long-term, intensive agriculture are still visible in the landscape today. As this research suggests, recent land degradation is not merely the product of land use change as the numbers of grazing animals increase, but is also the result of the destabilization of an engineered landscape.

The analysis of sugar records from the Codrington Papers and geoarchaeological data obtained from 20 soil profiles has revealed the complexity of the human-environmental dynamic during the last three centuries at Betty's Hope Plantation. However, more research is needed to further unravel the course and causes of landscape change in regard to sugarcane production and investments of landesque capital in an anthropogenic landscape. Many possibilities exist for future courses of research. First, much investigation remains to be done at Betty's Hope to reconstruct the historic landscape and further assess the changes that occurred as a result of long-term sugarcane monoculture. Future research can delve deeper into the historical records and/or analyze a greater number of soil samples in order to assess more fully the changes to the landscape over time. The landscape legacy of sugarcane at Betty's Hope formed over three and a half centuries, thus it is too complex to be unraveled fully in this small pilot study.

The legacy of the sugar industry continues to be felt in the Caribbean. The collapse of the sugar plantation economy left many Caribbean nations struggling "with the post-colonial realities of transitioning from sugar to tourism and other industries" (Fox 2014:40). The results of this study may to be representative of other islands with similar land use histories, especially other islands of the British West Indies, such as Barbados. By identifying the long- and short-term causes of contemporary landscape degradation, this research may help inform future land use policies in Antigua and other former Caribbean sugar islands in order to prevent further undesirable landscape change. The conceptualization of the sugarcane landscape legacy draws attention to the myriad ways in which long-term intensive monoculture has affected the landscape of a plantation from the beginning of sugarcane cultivation to the present. This study can help make inferences about landscape degradation related to sugarcane production on the rest of Antigua and other Caribbean sugar islands; if the landscape at Betty's Hope is representative of the rest of the island, the conclusion that sugarcane cultivation was overdone can be extended to other Antiguan plantations. As Betty's Hope was one of the oldest and largest sugar plantations on the island, it is likely that the observed trends in sugarcane yield and landscape change were repeated at other sugarcane plantations. If these findings are representative of other parts of Antigua, they suggest that current erosion and degradation experienced today cannot be attributed to intensive plantation agriculture alone, but rather are part of a complex mosaic of human-environmental interactions that included abandonment of engineered landscapes.

REFERENCES CITED

Abbott, George C.
1964 The West Indian sugar industry, with some long term projections of supply to 1975. *Social and Economic Studies* 13(1):1-37.

Abernethy, Virginia D.
2005 Ester Boserup and agricultural development. *Society* 42(5):55-58.

Adderley, Roseanne
2004 West Indies. In *Encyclopedia of Contemporary Latin American and Caribbean Cultures 1900-2003*, edited by Daniel Balderston, Mike Gonzalez, and Ana M. Lopez, pp. 1584. Routledge, New York.

Anderson-Córdova, Karen Frances
1990 *Hispaniola and Puerto Rico: Indian Acculturation and Heterogeneity 1492-1550*. Ph.D. dissertation, Department of Anthropology, Yale University. New Haven, Connecticut.

Arthur, W. Brian
1988 Urban systems and historical path dependence. In *Cities and their Vital Systems Infrastructure: past, present, and future,* edited by J.H. Ausubel and R. Herman, pp. 85-97. Washington, DC, National Academy Press.

Aruna, P, A. Ajitha, and V. Uma Maheshwar Rao
2014 X-ray fluorescence. *International Journal of Pharmaceutical Research and Analysis* 4(4):222-228.

Auchinleck, Gilbert G., and Antigua Sugar Association
1956 *The Rainfall of Antigua and Barbuda: Compiled from Available Records*. Antigua Sugar Association, St. Johns, Antigua.

Bakker, Henk
1999 *Sugar Cane Cultivation and Management*. Springer Science and Business Media, New York.

Beach, Timothy, Nicholas Dunning, Sheryl Luzzadder-Beach, Duncan E. Cook, and Jon Lohse
2006 Impacts of the ancient Maya on soils and soil erosion in the central Maya Lowlands. *Catena* 65(2):166-178.

Bement, Leland C., Brian J. Carter, RA Varney, Linda S. Cummings, and J. B. Sudbury
2007 Paleo-environmental reconstruction and bio-stratigraphy, Oklahoma Panhandle, USA. *Quaternary international* 169:39-50.

Berland, Alexander J., Sarah E. Metcalfe, and Georgina H. Endfield
2013 Documentary-derived chronologies of rainfall variability in Antigua, Lesser Antilles, 1770-1890. *Climate of the Past* 9(3):1331-1343.

Blacklands Research and Extension Center
2014 Environmental policy integrated climate model: user's manual version 0810. Electronic document, http://epicapex.tamu.edu/files/2013/02/EPIC.0810-User-Manual.pdf, accessed September 15, 2014.

Blaikie, Piers, and Harold Brookfield
1987 *Land Degradation and Society*. Methuen, London.

Boserup, Ester
1965 *The Conditions of Agricultural Growth: The Conditions of Agricultural Growth*. Transaction Publishers, London

1975 The impact of population growth on agricultural output. *The Quarterly Journal of Economics* 89(2):257-270.

1976 Environment, population, and technology in primitive societies. *Population and Development Review* 2(1):21-36.

1983 The impact of scarcity and plenty on development. *Journal of Interdisciplinary History* 14(2):383-407.

Bremer, Francis J.
2012 *First Founders: American Puritans and Puritanism in an Atlantic World*. University of New Hampshire Press, Durham, New Hampshire.

Brookfield, Harold C.
2001 Intensification, and alternative approaches to agricultural change. *Asia Pacific Viewpoint* 42(2–3):181-192.

1984 Intensification revisited. *Pacific Viewpoint* 25(1):15-44.

Brown, Amos, P.
1913 Notes on the geology of the island of Antigua. *Proceedings of the Academy of Natural Sciences of Philadelphia* pp. 584-616.

Brown, Laurence
2002 Monuments to freedom, monuments to nation: The politics of emancipation and remembrance in the eastern Caribbean. *Slavery and Abolition* 23(3):93-116.

Bürgi, Matthias, Anna M. Hersperger, and Nina Schneeberger
2004 Driving forces of landscape change—current and new directions. *Landscape Ecology* 19(8):857-868.

Bushnell, Thomas M.
1943 Some aspects of the soil catena concept. *Soil Science Society of America Journal* 7(C):466-476.

Butzer, Karl W.
1971 *Environment and Archeology: An Ecological Approach to Prehistory*. Vol. 703. Aldine Publishing Co., Chicago, Illinois.

1982 *Archaeology as Human Ecology: Method and Theory for a Contextual Approach*. Cambridge University Press, Cambridge.

Campbell, JC, John Radke, JT Gless, and RM Wirtshafter
1992 An application of linear programming and geographic information systems: cropland allocation in Antigua. *Environment and Planning A* 24(4):535-549.

Chase, Arlen F., and Vernon Scarborough
2014 Diversity, resiliency, and IHOPE-Maya: using the past to inform the present. *Archeological Papers of the American Anthropological Association* 24(1):1-10.

Chase, Diane Z., and Arlen F. Chase
2014 Path dependency in the rise and denouement of a Classic Maya city: the case of Caracol, Belize. In *Archeological Papers of the American Anthropological Association* 24(1):142-154.

Clark, Eric, and Huei-Min Tsai
2012 *Islands: Ecologically Unequal Exchange and Landesque Capital*. Routledge, London.

Codrington Papers, West Indies Correspondence
1807 *Sugar Accounts of C. B. Codrington, with M. Trattle, merchant 1802-1807*. Simon Fraser University Library, Microfilm 440, Section 16, D1610 A60/1.

1813 *Sugar Accounts of C. B. Codrington, with M. Trattle, merchant 1807-1813*. Simon Fraser University Library, Microfilm 441, Section 1, D1610 A60/2.

1828 *Account Sales Book of C. B. Codrington for Sugar and Wool 1824-1828*. Simon Fraser University Library, Microfilm 441, Section 2, D1610 A61.

1838 *Annual Statements of Total Sugar Crop 1801-1838, with Calculations of Profits from Antigua and Barbuda 1707-1830, etc*. Simon Fraser University Library, Microfilm 441, Section 3, D1610 A62.

Cowton, Christopher J., and Andrew J. O'Shaughnessy
1991 Absentee control of sugar plantations in the British West Indies. *Accounting and Business Research* 22(85):33-45.

Crist, Raymond E.
1954 Changing cultural landscapes in Antigua, BWI. *American Journal of Economics and Sociology* 13(3):225-232.

Crumley, Carole L., and William H. Marquardt
2010 Landscape: a unifying concept in regional analysis. *Interpreting Space: GIS and Archaeolog*y: 73-79.

Day, Michael
2007 The karstlands of Antigua, their land use and conservation. *The Geographical Journal* 173(2):170-185.

Deagan, Kathleen A.
1988 Neither history nor prehistory: the questions that count in historical archaeology. *Historical Archaeology* 22(1):7-12.

Deetz, James
1988 American historical archeology: methods and results. *Science (New York, N.Y.)* 239(4838):362-367.

Denevan, William M.
1992 The pristine myth: the landscape of the Americas in 1492. *Annals of the Association of American Geographers* 82(3):369-385.

Dodonov, AE, TA Sadchikova, SN Sedov, AN Simakova, and LP Zhou
2006 Multidisciplinary approach for paleoenvironmental reconstruction in loess-paleosol studies of the Darai Kalon section, Southern Tajikistan. *Quaternary international* 152:48-58.

Doolittle, William E.
1984 Agricultural change as an incremental process. *Annals of the Association of American Geographers* 74(1):124-137.

Dunn, Richard S.
1972 *Sugar and Slaves: The Rise of the Planter Class in the English West Indies, 1624-1713*. Published for the Omohundro Institute of Early American History and Culture Williamsburg Virginia by the University of North Carolina Press, Chapel Hill.

Dyde, Brian
2000 *A History of Antigua: The Unsuspected Isle*. MacMillan Caribbean, London.

Easterling, William E., Norman J. Rosenberg, Mary S. McKenney, C. Allan Jones, Paul T. Dyke, and JR Williams
1992 Preparing the erosion productivity impact calculator (EPIC) model to simulate crop response to climate change and the direct effects of CO_2. *Agricultural and Forest Meteorology* 59(1):17-34.

EDAX Smart Insight
2014 Elemental Analysis through a Plastic Barrier. Application Note—Micro-XRF. Electronic document, http://www.edax.com/download/Elemental_Analysis_ Through_ Plastic_Barrier_HR.pdf, access January 15, 2015.

Erickson, Clark L., and John H. Walker
2009 Pre-Columbian causeways and canals as landesque capital. In *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective*, edited by James Snead, Clark Erickson, and Andy Darling, pp. 232-252. Penn Museum Press and the University of Pennsylvania Press, Philadelphia, Pennsylvania

Farrand, William R.
1975 Sediment analysis of a prehistoric rock shelter: the Abri Pataud. *Journal of Quaternary Research* 5(1):1-26.

Fisher, Christopher T., and Tina L. Thurston
1999 Dynamic landscapes and socio-political process: the topography of anthropogenic environments in global perspective. *Antiquity* 73(281):630-631.

Fisher, Christopher T., Helen P. Pollard, Isabel Israde-Alcantara, Victor H. Garduño-Monroy, and Subir K. Banerjee
2003 A reexamination of human-induced environmental change within the Lake Patzcuaro Basin, Michoacan, Mexico. *Proceedings of the National Academy of Sciences of the United States of America* 100(8):4957-4962.

Fisher, Christopher T., and Gary M. Feinman
2005 Introduction to “landscapes over time.” *American Anthropologist* 107(1):62-69.

Fisher, Christopher, T., J. Brett Hill, and Gary M. Feinman
2009 *The Archaeology of Environmental Change: Socionatural Legacies of Degradation and Resilience*. University of Arizona Press, Tucson.

Flannery, Kent V.
1968 Archaeological systems theory and early Mesoamerica. *Anthropological Archaeology in the Americas* 67:67-87.

Fox, Georgia L.
2013 Betty's Hope archaeological site report, 2007-2012. Prepared for Dr. Reginald Murphy, Principal Oversight, Betty's Hope Trust. California State University, Chico.

2014 Archaeological investigations at Betty's Hope Plantation, Antigua: some preliminary thoughts on theory. In *Bitasion Archaeologie Des Habitations—Plantations Des Petites Antilles*, edited by Kenneth Kelly and Benoit Berard, pp. 33-41. Sidestone Press, Leiden.

Garside, AL, MJ Bell, and RC Magarey
2001 Monoculture yield decline—fact not fiction. *Proceedings of the International Society of Sugar Cane Technology* 24:16-21.

Gassman, Philip W., Jimmy R. Williams, Verel W. Benson, R. C. Izaurralde, Larry M. Hauck, C. A. Jones, Jay D. Atwood, James R. Kiniry, and Joan D. Flowers
2005 *Historical Development and Applications of the EPIC and APEX Models*. Center for Agricultural and Rural Development, Iowa State University.

Gladfelter, Bruce G.
1977 Geoarchaeology: the geomorphologist and archaeology. *American Antiquity* 42(4):519-538.

1981 Developments and directions in geoarchaeology. *Advances in Archaeological Method and Theory* 4:343-364.

Goldberg, Paul, and Richard I. Macphail
2009 *Practical and Theoretical Geoarchaeology*. John Wiley and Sons, Malden, Massachusetts

Gonzalez-Scollard, Edith
2008 *Raising Cane: Sugar, people and the environment in nineteenth-century Antigua, West Indies*. Ph.D. dissertation. Department of Anthropology. City University of New York, New York.

Goodwin, Conrad M.
1987 *Sugar, time and Englishmen: a study of management strategies on Caribbean plantations*. Ph.D. dissertation. Boston University, Boston, MA.

1994 Betty's Hope windmill: An unexpected problem. *Historical Archaeology* 1:99-110.

Great Britain
1824 *The Statutes of the United Kingdom of Great Britain and Ireland*. His Majesty's statute and law printers, London, pp. 339—354

Great Britain Public Record Office
1661-8 Colonial calendar of state papers, 1661-1668. Electronic document, https://archive.org/details/calendarofstatep166168grea, accessed February 28, 2015.

Grigg, David
1979 Ester Boserup's theory of agrarian change: a critical review. *Progress in Human Geography* 3(1), 64-84.

Gunderson, Lance. H., and Crawford. S. Holling, eds.
2002 *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press, Washington, D.C.

Håkansson, N. Thomas, and Mats Widgren
2014 *Landesque Capital: The Historical Ecology of Enduring Landscape Modifications*. Vol. 5, Left Coast Press, Walnut Creek, California.

2007 Labour and landscapes: the political economy of landesque capital in nineteenth century Tanganyika. *Geografiska Annaler: Series B, Human Geography* 89(3):233-248.

Hall, Douglas
1962 Slaves and slavery in the British West Indies. *Social and Economic Studies* 11(4):305-318.

Hill, J. Brett
2004 Land use and an archaeological perspective on socio-natural studies in the Wadi Al-Hasa, west-central Jordan. *American Antiquity* 69(3):389-412.

Hodder, Ian
2000 *The Interpretation of Documents and Material Culture*. Sage Publications, California.

Holliday, Vance T.
2004 *Soils in Archaeological Research*. Oxford University Press, Oxford.

Holliday, Vance T., and William G. Gartner
2007 Methods of soil P analysis in archaeology. *Journal of Archaeological Science* 34(2):301-333.

Hornburg, Alf, and Carole Crumley, eds.
2007 *The World System and the Earth System: Global Socioenvironmental Change and Sustainability since the Neolithic*. Left Coast Press, Walnut Creek, California.

Huang, Mingyan, Jacques Gallichand, T. Dang, and M. Shao
2006 An evaluation of EPIC soil water and yield components in the gully region of Loess Plateau, China. *The Journal of Agricultural Science* 144(04):339-348.

Kendal, Jeremy, Jamshid J. Tehrani, and John Odling-Smee
2011 Human niche construction in interdisciplinary focus. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 366(1566):785-792.

Kirch, Patrick V.
2005 Archaeology and global change: the Holocene record. *Annual Review of Environment and Resources* 30:409-440.

Kirch, Patrick V., Anthony S. Hartshorn, Oliver A. Chadwick, Peter M. Vitousek, David R. Sherrod, James Coil, Lisa Holm, and Warren D. Sharp
2004 Environment, agriculture, and settlement patterns in a marginal Polynesian landscape. *Proceedings of the National Academy of Sciences of the United States of America* 101(26):9936-9941.

Laland, Kevin N., and Gillian R. Brown
2006 Niche construction, human behavior, and the adaptive-lag hypothesis. *Evolutionary Anthropology: Issues, News, and Reviews* 15(3):95-104.

Laland, Kevin N., and Michael J. O'Brien
2010 Niche construction theory and archaeology. *Journal of Archaeological Method and Theory* 17(4):303-322.

Lentz, David L., and Brian Hockaday
2009 Tikal timbers and temples: Ancient Maya agroforestry and the end of time. *Journal of Archaeological Science* 36(7):1342-1353.

Lewis, David B., Jason P. Kaye, Corinna Gries, Ann P. Kinzig, and Charles L. Redman
2006 Agrarian legacy in soil nutrient pools of urbanizing arid lands. *Global Change Biology* 12:703-709.

Lewis, James
1984 A multi-hazard history of Antigua. *Disasters* 8(3):190-197.

Lewontin, Richard C.
1982 Organism and environment. In *Learning, Development and Culture: Essays in Evolutionary Epistemology,* edited by H. C. Plotkin, pp. 151-170. John Wiley and Sons, New York.

2000 Path dependence. In *Encyclopedia of Law and Economics, Volume I. The History and Methodology of Law and Economic*, edited by Boudewijn Bouckaert and Gerrit De Geest, pp. 981-998. Edward Elgar, Cheltenham, England.

Lincoln, Yvonna S., and Egon G. Guba
1985 *Naturalistic Inquiry*. Vol. 75, Sage, Beverly Hills, California.

Lombardo, U., S. Denier, and H. Veit1
2015 Soil properties and pre-Columbian settlement patterns in the Monumental Mounds Region of the Llanos de Moxos, Bolivian Amazon. *SOIL* 1: 65-81.

Lowe, Robson
1951 *The Codrington Correspondence, 1743-1851*. Robson Lowe, Ltd., London.

Lowes, Susan
1994 *The Peculiar Class: The Formation, Collapse, and Reformation of the Middle Class in Antigua, West Indies, 1834-1940*. Ph.D. dissertation, Columbia University, New York.

Malthus, Thomas R.
1798 *An Essay on the Principle of Population*. Printed for J. Johnson, in St. Paul's Church-Yard, London.

Marquardt, William H., and Carole L. Crumley
1987 Theoretical issues in the analysis of spatial patterning. In *Regional Dynamics: Burgundian Landscapes in Historical Perspective*, edited by Carole Crumley, pp. 1-18. Academic Press Inc., San Diego, California.

Martin, Samuel
1784 An essay upon plantership. In *Annals of Agriculture and Other Useful Arts,* Volume 18, edited by Arthur Young, Bury St. Edmunds, Suffold, England, pp. 236-320.

McCauley, Ann, Clain Jones, and Jeff Jacobsen
2005 Basic soil properties, soil and water management modules. Electronic document, http://landresources.montana.edu/%20SWM/PDF/Final_proof_SW1.pdf, accessed December 10, 2014.

McGlade, James
2003 Archaeology and the evolution of cultural landscapes: towards an interdisciplinary research agenda. In *The Archaeology and Anthropology of*

Landscape: Shaping Your Landscape, edited by Robert Layton and Peter Ucko, pp. 459-480. Routledge, London.

Meide, Chuck
2003 The sugar factory in the colonial west indies: an Archaeological and historical comparative analysis. Electronic document, https://www.academia.edu/3258102/The_Sugar_Factory_in_the_Colonial_West_Indies_an_Archaeological_and_Historical_Comparitive_Analysis, accessed November 1, 2014.

Meltzer, David J.
2003 Lessons in landscape learning. In *Colonization of Unfamiliar Landscapes: The Archaeology of Adaptation,* edited by J. Rockman and J. Steele, pp. 222-241. Routledge, London.

Menard, Russell, R.
2006 *Sweet Negotiations: Sugar, Slavery, and Plantation Agriculture in Early Barbados*. University of Virginia Press, Charlottesville, Virginia.

Metcalfe, Sarah, Ann Breen, Malcolm Murray, Peter Furley, Anthony Fallick, and Angus McKenzie
2009 Environmental change in northern Belize since the latest Pleistocene. *Journal of Quaternary Science* 24(6):627-641.

Meyer, Jan H., Rianto Van Antwerpen, and Eddie Meyer
1996 A review of soil degradation and management research under intensive sugarcane cropping. Proceedings of the South African Sugar Technology Association 70:22-28.

Midgett, Douglas K.
1984 Distorted development: the resuscitation of the Antiguan sugar industry. *Studies in Comparative International Development (SCID)* 19(2):33-58.

Miller, Susan
1991 The high price of sugar. *Newsweek* 118(10):70-73.

Mintz, Sidney W.
1985 S*weetness and Power: the Place of Sugar in Modern History*. Viking, New York.

2007 *Caribbean Transformations*. Reprinted. Transaction Publishers. Originally published 1974, Aldine Publishing Co., Chicago.

Morrison, Kathleen D.
2014 Capital-esque landscapes: long-term histories of enduring landscape modifications. In *Landesque Capital: The Historical Ecology of Enduring Landscape Modifications,* edited by N.T. Håkansson and Mats Widgren, pp. 49-74. Vol. 5, Left Coast Press.

Mulcahy, Matthew
2004 Weathering the storms: hurricanes and the risk in the British greater Caribbean. *The Business History Review* 78(4):635-663.

Murphy, Arthur Reginald
1999 *The Prehistory of Antigua, Ceramic Age: Subsistence, Settlement, Culture and Adaptation Within an Insular Environment*. Ph.D. dissertation, Department of Anthropology, University of Calgary, Alberta, Canada.

Museum of Antigua and Barbuda
2014 Betty's Hope. Electronic document, http://antiguahistory.net/Museum/bettyshope.htm, accessed November 15, 2014.

Neff, Hector, Barbara Voorhies, and Federico Paredes Umaña
2012 Handheld XRF elemental analysis of archaeological sediments: some examples. In *Handheld XRF for Art and Archaeology*, Vol. 3, edited by Aaron N. Shugar and Jennifer L. Mass, Leuven University Press, Leuven, Belgium, pp. 379-400.

Nelson, Donald R., W. Neil Adger, and Katrina Brown.
2007 Adaptation to environmental change: contributions of a resilience framework. *Annual Review of Environment and Resources* 32:395-419.

Odling-Smee, John, Kevin N. Laland, and Marcus W. Feldman
1996 Niche construction. *American Naturalist* 147(4):641-648.

Odling-Smee, John, Douglas H. Erwin, Eric P. Palkovacs, Marcus W. Feldman, and Kevin N. Laland
2013 Niche construction theory: a practical guide for ecologists. *The Quarterly Review of Biology* 88(1):3-28.

Oliver, Vere Langford
1894 *The History of the Island of Antigua*. Mitchell and Hughes, London.

Orser, Charles, E.
1996 *A Historical Archaeology of the Modern World*. Springer Science and Business Media, New York.

Pares, Richard
1953 *A West-India Fortune*. Longmans, Green and Co., New York.

1956 The London sugar market, 1740-1769. *The Economic History Review* 9(2):254-270.

Porter, Dale H.
1970 *The Abolition of the Slave Trade in England, 1784-1807*. Archon Books Hamden, Connecticut.

Ragatz, Lowell J.
1928 *Fall of the Planter Class in the British Caribbean, 1763-1833*. The Century Co., New York.

Rapp, George R., and Christopher L. Hill
2006 *Geoarchaeology: the Earth-Science Approach to Archaeological Interpretation*. Yale University Press, New Haven, Connecticut.

Redman, Charles L.
1999 *Human Impact on Ancient Environments*. University of Arizona Press, Tucson, Arizona.

2005 Resilience theory in archaeology. *American Anthropologist* 107(1):70-77.

2014 Should sustainability and resilience be combined or remain distinct pursuits? *Ecology and Society* 19(2):37.

Roe, Mark J.
1996 Chaos and evolution in law and economics. *Harvard Law Review* 109(3):641-668.

Rogozinski, Jan
1992 *A Brief History of the Caribbean: From the Arawak and the Carib to the Present*. Plume, New York.

Rouse, Irving
1989 Peopling and repeopling of the West Indies. *Biogeography of the West Indies: Past, Present, and Future*: 119-136.

Saunders, Nicholas J.
2005 *The Peoples of the Caribbean: An Encyclopedia of Archeology and Traditional Culture*. ABC-CLIO, Santa Barbara, California.

Scudder, Sylvia J., John E. Foss, and Mary E. Collins
1996 Soil science and archaeology. *Advances in Agronomy* 57:1-76.

Sen, Amartya K.
1959 The choice of agricultural techniques in underdeveloped countries. *Economic Development and Cultural Change* 7(3):279-285.

Shackley, M. Steven
2011 An introduction to X-ray fluorescence (XRF) analysis in archaeology. In *X-ray Fluorescence Spectrometry (XRF) in Geoarchaeology,* edited By M. Steven Shackley, pp. 7-44. Springer, New York.

Sheridan, Richard B.
1957 Letters from a sugar plantation in Antigua, 1739-1758. *Agricultural History 31(3)*:3-23.

1960 Samuel Martin, innovating sugar planter of Antigua 1750-1776. *Agricultural History* 34(3):126-139.

Simpson, Ian A., Andrew J. Dugmore, Amanda Thomson, and Orri Vesteinsson
2001 Crossing the thresholds: human ecology and historical patterns of landscape degradation. *Catena* 42(2):175-192.

Simpson, Ian A., W. P. Adderley, Garðar Guðmundsson, Margrét Hallsdóttir, Magnús Á. Sigurgeirsson, and Mjöll Snæsdóttir
2002 Soil limitations to agrarian land production in premodern Iceland. *Human Ecology* 30(4):423-443.

Shugar, Aaron N., and Jennifer L. Mass, eds.
2012 *Handheld XRF for Art and Archaeology*. Vol. 3. Leuven University Press, Leuven, Belgium.

Smith, Frederick Harold
2005 *Caribbean Rum: A Social and Economic History*. University Press of Florida, Gainesville, Florida.

Stein, Julie K.
1986 Coring archaeological sites. *American Antiquity* 51(3):505-527.

Stein, Julie K., William R. Farrand, eds.
2001 *Sediments in Archaeological Context*. University of Utah Press, Salt Lake City, Utah.

Steward, Julian H.
1955 *Theory of Culture Change*. University of Illinois Press, Urbana, Illinois.

Stone, Glen Davis.
2001 Theory of the square chicken: Advances in agricultural intensification theory. *Asia Pacific Viewpoint* 42(2-3):163-180.

Taylor, Stanley Arthur Goodwin
1969 *The Western Design: An Account of Cromwell's Expedition to the Caribbean*. Solstice Productions, London

Texas AandM Agrilife Research
2014 EPIC and APEX models. Electronic document, < http://epicapex.tamu.edu/epic/>, accessed September 10, 2014.

Timpson, Michael E., and John E. Foss
1993 The use of particle-size analysis as a tool in pedological investigations of archaeological sites. In *Proceedings of the First International Conference on Pedo-Archaeology, Special Publication*, pp. 93-03, University of Tennessee, Knoxville, Tennessee.

Trigger, Bruce G.
1989 *A History of Archaeological Thought*. Cambridge University Press, Cambridge.

Turner, B.L., Robert Q. Hanham, and Anthony V. Portararo.
1977 Population pressure and agricultural intensity. *Annals of the Association of American Geographers* 67(3): 384-396.

United Nations Technical Advisory Committee
2005 United Nations convention to combat desertification draft national action plan for Antigua and Barbuda. Electronic document, http://www.unccd.int/ActionProgrammes/antigua_and_barbuda-eng2005.pdf, accessed August 15, 2014.

United States Department of Agriculture
2015 A soil profile. Electronic document, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/kthru6/?cid=nrcs142p2_054308, access March 1, 2015.

Van der Leeuw, Sander E.
2014 Transforming lessons from the past into lessons for the future. *Archeological Papers of the American Anthropological Association* 24(1):215-231.

2009 What is an "environmental crisis" to an archaeologist? In *The Archaeology of Environmental Change: Socionatural Legacies of Degradation and Resilience*, edited by C. T. Fisher, J. B. Hill, and G. M. Feinman, pp. 40–61. University of Arizona Press, Tucson.

Van der Leeuw, Sander E., and Charles L. Redman
2002 Placing archaeology at the center of socio-natural studies. *American Antiquity* 67(4):597-605.

Vellend, Mark, Carissa D. Brown, Heather M. Kharouba, Jenny L. McCune, and Isla H. Myers-Smith
2013 Historical ecology: using unconventional data sources to test for effects of global environmental change. *American Journal of Botany* 100(7):1294-1305.

Vereș, Daniel S.
2012 A comparative study between loss on ignition and total carbon analysis on mineralogenic sediments. *Studia UBB, Geologia* 47(1):171-182.

Vitousek, Peter M., Thegn N. Ladefoged, Patrick V. Kirch, Anthony S. Hartshorn, Michael W. Graves, Sara C. Hotchkiss, Shripad Tuljapurkar, and Oliver A. Chadwick
2004 Soils, agriculture, and society in precontact Hawai'i. *Science* 304(5677):1665-1669.

Ward, John R.
1978 The profitability of sugar planting in the British West Indies, 1650–1834. *The Economic History Review* 31(2):197-213.

Walkington, Helen
2010 Soil science applications in archaeological contexts: a review of key challenges. *Earth-Science Reviews* 103(3):122-134.

Waters, Michael R.
1992 *Principles of Geoarchaeology: A North American perspective*. University of Arizona Press, Tucson.

Waterston, William
1859 *A Manual of Commerce*. Oliver and Boyd, Edinburgh.

Watts, David
1990 *The West Indies: Patterns of Development, Culture and Environmental Change since 1492*. Vol. 8, Cambridge University Press, Cambridge.

WeatherSpark
2014 Average weather for Saint John's, Antigua and Barbuda. Electronic document, <https://weatherspark.com/averages/33713/Saint-John-s-Antigua-Antigua-And-Barbuda-Antigua-and-Barbuda>, accessed November 3, 2014.

Weaver, David B.
1988 The evolution of a 'plantation' tourism landscape on the Caribbean island of Antigua. *Tijdschrift voor economische en sociale geografie* 79(5):319-331.

Weiss, Malcolm P.
1994 Oligocene limestones of Antigua, West Indies: Neptune succeeds Vulcan. *Caribbean Journal of Science* 30(1-2):1-29

Wells, E. Christian
2006 Cultural soilscapes. In *Function of Soils for Human Societies and the Environment Geological Society, Special Publication No. 266*, edited by E. Frossard, W.E.H. Blum, and B.P. Warkentin, pp. 125-132, The Geological Society, London.

2014 Simple and inexpensive analytical techniques for archaeological prospection. Unpublished document. Cultural Soilscapes Research Group, University of South Florida, Tampa, Florida.

Wells, E. Christian, Karla L. Davis-Salazar, and David D. Kuehn
2013 Soilscape legacies: historical and emerging consequences of socioecological interactions in Honduras. In *Soils, Climate and Society: Archaeological Investigations in Ancient America,* edited by John D. Wingard and Sue E. Hayes, pp. 21- 59. University Press of Colorado, Boulder, Colorado.

Widgren, Mats
2007 Pre-colonial landesque capital: a global perspective. *Rethinking environmental history*. In *World System History and Global Environmental Change,* edited by Alf Hornborg, John Robert McNeill, and Juan Martínez Alier, pp. 61-77. Altamira Press, Lantham, Maryland.

2012 Landscape research in a world of domesticated landscapes: The role of values, theory, and concepts. *Quaternary International* 251:117-124.

Williams, Jimmy R., and Vijay P. Singh
1995 The EPIC model. In *Computer Models of Watershed Hydrology*, edited by Vijay P. Singh, pp. 909-1000. Water Resources Publications, Colorado.

Williams, Jimmy R.
1990 The erosion-productivity impact calculator (EPIC) model: a case history. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 329(1255):421-428.

Williams, Jimmy R., C. Allan Jones, and P.T. Dyke
1984 The EPIC model and its application. *Proceedings of the International Symposium on Minimum Data Sets for Agrotechnology Transfer,* ISCRAT Center, Patancheru, India.

Wilson, Lucy
2011 The role of geoarchaeology in extending our perspective. *Geological Society, London, Special Publications* 352(1):1-9.

Wilson, Samuel, M.
1990 *Hispaniola: Caribbean Chiefdoms in the Age of Columbus*, Volume 45879. University of Alabama Press, Tuscaloosa, Alabama.

2007 *The Archaeology of the Caribbean*. Cambridge University Press, Cambridge.

Wingard, John D., and Sue E. Hayes
2013 *Soils, Climate and Society: Archaeological Investigations in Ancient America*. University Press of Colorado, Boulder, Colorado.

APPENDICES

Appendix I. EPIC Output

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1650	0	398.84	293.11	264.41	373.89	0	0	40.32	209.13	0
1651	0	181.09	200.51	192.01	340.69	0	0	36.96	0.02	0
1652	41.76	93.86	200.38	202.62	340.43	0	0	41.3	0	0.6
1653	0	0	240.44	224.67	143.82	0	0	41.56	0	0
1654	0	0	154.16	154.62	465.32	0	0	34.45	0	0.04
1655	44.89	0	115.08	131.86	410.08	0	0	39.82	0	0.02
1656	0	0	152.35	144.07	137.09	0	0	36.07	0	0.01
1657	0	0	113.03	112.46	471.13	0	0	28.72	0	0.03
1658	25.3	0	88.01	98.18	405.88	0	0	32.15	0	0.04
1659	0	0	110.92	105.23	145.1	0	0	27.97	0	0
1660	0	0	88.43	87.7	483.35	0	0	23.35	0	0.09
1661	11.55	0	82.26	83.99	392.04	0	0	24.48	0	0.02
1662	0	0	90.18	85.86	145.15	0	0	22.35	0	0
1663	0	11.81	60.73	62.86	468.92	0	0	17.27	0	0
1664	12.9	46.22	66.66	70.45	302.58	0	0	21.19	0	0.01
1665	0	25.92	77.57	74.87	148.17	0	0	19.98	0.02	0
1666	0	165.4	60.3	58.16	352.03	0	0	13.3	0.39	0
1667	13.74	39.51	41.21	54.14	290.48	0	0	24.19	0	0.01
1668	0	0	64.56	63.99	142.1	0	0	18.6	0	0
1669	0	0	39.27	41.75	564.59	0	0	12.33	0	0
1670	12.55	0.19	24.96	39.49	348.96	0	0	22.36	0	0.01
1671	0	0	52.45	52.85	145.43	0	0	17.04	0	0
1672	0	0	31.79	35.73	571.87	0	0	10.94	0	0
1673	11.96	0.13	22.54	35.25	351.69	0	0	20.26	0	0.02
1674	0	0	45.83	46.37	143.94	0	0	14.82	0	0
1675	0	0.96	30.82	35.28	495.93	0	0	10.54	0	0
1676	9.37	7.42	24.32	33.67	268.02	0	0	18.11	0	0.02
1677	0	0.01	44.62	45.01	148.28	0	0	12.84	0	0
1678	0	112.69	37.12	36.62	454	0	0	7.93	0.36	0
1679	11.16	72.57	20.45	31.83	260.65	0	0	15.87	0	0

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1680	0	0	40.97	41.9	144.15	0	0	12.2	0	0
1681	0	0.37	27.57	30.32	528.21	0	0	8.2	0	0
1682	5.07	89.35	28.81	33.56	362.96	0	0	12.3	0.03	0.01
1683	0	0	35.42	36.41	180.67	0	0	11.1	0	0
1684	0	103.89	27.83	28.7	473.04	0	0	6.37	2.86	0
1685	9.47	73.44	19.04	27.46	291.5	0	0	11.1	0.02	0.01
1686	0	15.19	32.93	35.38	148.58	0	0	9.79	0	0
1687	0	181.45	32.04	30.42	450.95	0	0	5.31	3.54	0
1688	7	85.9	19.46	26.88	364.99	0	0	11.27	0.04	0
1689	0	0	29.89	31.75	152.16	0	0	8.5	0	0
1690	0	81.33	18.34	19.95	493.41	0	0	4.65	2.8	0
1691	4.58	62.19	18.33	24.84	306.96	0	0	9	0.26	0
1692	0	46.58	28.04	30.03	158.74	0	0	8.17	0.44	0
1693	0	188.07	24.74	24.97	375.52	0	0	4.37	1.92	0
1694	9.67	53.33	14.21	23.41	284.92	0	0	11.48	0	0.01
1695	0	0	24	26.79	148.76	0	0	7.72	0	0
1696	0	67.7	15.58	17.82	507.21	0	0	4.53	0.87	0
1697	4.42	73.56	15.61	23.07	285.93	0	0	10.97	0.23	0
1698	0	0.73	22.8	25.53	152.51	0	0	7.51	0	0
1699	0	134.5	20.92	20.77	428.9	0	0	4.04	4.05	0
1700	3.84	71.97	15.13	22.09	321.42	0	0	9.71	0.44	0.01
1701	0	10.96	20.84	24.16	160.45	0	0	6.98	0	0
1702	0	171.6	22.76	21.67	423.98	0	0	3.68	7.32	0
1703	2.88	63.05	14.35	20.58	296.1	0	0	8.8	0.85	0
1704	0	17.85	19.58	22.55	166.53	0	0	6.52	0.12	0
1705	0	177.3	18.89	19.62	418.9	0	0	3.81	3.54	0
1706	6.39	45.07	10.74	18.2	223.49	0	0	9.03	0.03	0
1707	0	9.34	17.78	21.32	158.02	0	0	6.14	0	0
1708	0	170.54	19.26	18.35	490.16	0	0	3.23	8.97	0
1709	2.08	71.07	12.79	18.25	309.13	0	0	6.99	1.37	0
1680	0	0	40.97	41.9	144.15	0	0	12.2	0	0
1681	0	0.37	27.57	30.32	528.21	0	0	8.2	0	0
1682	5.07	89.35	28.81	33.56	362.96	0	0	12.3	0.03	0.01
1683	0	0	35.42	36.41	180.67	0	0	11.1	0	0
1684	0	103.89	27.83	28.7	473.04	0	0	6.37	2.86	0
1685	9.47	73.44	19.04	27.46	291.5	0	0	11.1	0.02	0.01

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1716	0	31.74	13.54	17.25	205.21	0	0	5.81	0.77	0
1717	0	169.74	15.22	14.8	399.04	0	0	2.7	16.15	0
1718	5.1	100.58	6.55	13.28	317.75	0	0	6	1.23	0
1719	0	23.04	13.29	16.8	175.08	0	0	5.41	0.29	0
1720	0	165.05	14.02	13.76	434.81	0	0	2.62	15.04	0
1721	2.22	169.82	11.14	12.96	316.29	0	0	3.7	10.21	0
1722	0	13.05	12.9	15.26	300.16	0	0	5.5	0.91	0
1723	0	128.32	8.36	9.88	438.6	0	0	2.12	22.91	0
1724	4.22	161.86	8.24	11.66	305.44	0	0	2.92	7.91	0
1725	0	143.05	12.23	15.44	394.48	0	0	4.42	38.51	0
1726	0	174.14	10.45	10.97	343.31	0	0	1.95	15.51	0
1727	6.8	93.89	3.26	9.98	346.59	0	0	4.53	0.5	0
1728	0	85.58	11.02	14.67	187.11	0	0	4.29	2.66	0
1729	0	187.03	14.2	13.22	188.89	0	0	1.84	20.22	0
1730	2.99	183.53	7.11	9.66	313.41	0	0	2.77	9.05	0
1731	0	10.32	9.98	13.09	300.25	0	0	4.73	0.44	0
1732	0	120.71	6.31	8.33	464.61	0	0	1.8	22.81	0
1733	2.3	170.75	8.23	10.68	312.27	0	0	2.45	22	0
1734	0	181.68	11.34	13.73	393.23	0	0	3.83	52.69	0
1735	0	216.17	9.72	10.43	407.27	0	0	1.95	19.67	0
1736	5.66	97.28	2.74	8.5	312.47	0	0	3.73	0.76	0
1737	0	144.56	9.15	12.7	231.96	0	0	3.61	13.75	0
1738	0	190.69	10.67	10.94	363.27	0	0	1.83	14.04	0
1739	4.92	85.18	3.34	9.2	358.84	0	0	4.18	0.23	0
1740	0	36.79	8.35	12.11	186.78	0	0	3.61	0.47	0
1741	0	171.48	10.22	10.14	420.97	0	0	1.7	20.11	0
1742	0.74	165.13	8.17	9.67	310.84	0	0	2.15	16.08	0
1743	0	58.93	7.11	11.58	374.01	0	0	3.83	8.61	0
1744	0	218.74	9.79	9.48	427.73	0	0	1.42	61.51	0
1745	0.84	201.73	6.67	7.8	339.58	0	0	1.95	44.37	0
1716	0	31.74	13.54	17.25	205.21	0	0	5.81	0.77	0
1717	0	169.74	15.22	14.8	399.04	0	0	2.7	16.15	0
1718	5.1	100.58	6.55	13.28	317.75	0	0	6	1.23	0
1719	0	23.04	13.29	16.8	175.08	0	0	5.41	0.29	0
1720	0	165.05	14.02	13.76	434.81	0	0	2.62	15.04	0
1721	2.22	169.82	11.14	12.96	316.29	0	0	3.7	10.21	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1752	0	145.71	6.01	9.82	370.44	0	0	2.43	39.27	0
1753	0	192.67	3.19	6.13	352.22	0	0	1.66	1.34	0
1754	10.98	100.66	1.53	7.2	350.87	0	0	2.83	0	0
1755	0	28.57	5.18	9.11	236.87	0	0	2.69	0.78	0
1756	0	149.46	7.25	7.56	407.42	0	0	1.29	26.39	0
1757	0.05	200.64	6.68	6.79	347.9	0	0	1.4	36.83	0
1758	0	166.43	6.01	9.48	390.47	0	0	2.35	51.09	0
1759	0	232.66	2.32	5.58	372.67	0	0	1.59	1.02	0
1760	11.9	76.58	0.15	6.22	366.85	0	0	2.81	0	0
1761	0	11.98	4.5	8.4	202.28	0	0	2.61	0.04	0
1762	0	157.22	6.49	7.47	463.82	0	0	1.26	23.31	0
1763	0.15	168.49	8.73	9.06	322.67	0	0	1.56	22	0
1764	0	129.31	6.35	10	419.66	0	0	2.7	32.95	0
1765	0	201.03	6.5	7.09	387.23	0	0	1.05	28.5	0
1766	2.57	182.66	6.55	7.63	356.62	0	0	1.81	5.26	0
1767	0	172.97	7.58	9.47	393.96	0	0	2.14	49.95	0
1768	0	213.04	4.15	5.93	390.06	0	0	1.19	13.91	0
1769	5.33	182.7	4.99	6.61	288.09	0	0	1.79	0.73	0
1770	0	135.31	5.54	8.78	400.43	0	0	2.12	24.81	0
1771	0	236.69	5.36	6.68	428.48	0	0	1.22	16.19	0
1772	5.08	204.29	5.64	7.15	337.94	0	0	1.92	0.51	0
1773	0	101.84	5.07	8.32	374.01	0	0	2.01	17.67	0
1774	0	186.23	3.59	5.3	375.36	0	0	0.88	12.22	0
1775	4.92	197.67	5.15	6.62	343.77	0	0	1.52	0.4	0
1776	0	127.29	5.55	8.49	371.4	0	0	1.86	26.03	0
1777	0	201.05	5.54	6.46	416.94	0	0	1.11	16.24	0
1778	4.76	196.62	4.28	6.24	334.85	0	0	1.61	0.67	0
1779	0	138.66	5.13	8.03	391.38	0	0	1.76	30.11	0
1780	0	240.05	3.6	5.68	417.8	0	0	1.09	11.5	0
1781	6.19	190.78	4.7	6.21	337.97	0	0	1.47	0.26	0
1752	0	145.71	6.01	9.82	370.44	0	0	2.43	39.27	0
1753	0	192.67	3.19	6.13	352.22	0	0	1.66	1.34	0
1754	10.98	100.66	1.53	7.2	350.87	0	0	2.83	0	0
1755	0	28.57	5.18	9.11	236.87	0	0	2.69	0.78	0
1756	0	149.46	7.25	7.56	407.42	0	0	1.29	26.39	0
1757	0.05	200.64	6.68	6.79	347.9	0	0	1.4	36.83	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1788	0	113.81	4.45	7.54	368.19	0	0	1.53	18.81	0
1789	0	171.18	3.63	5.35	378.33	0	0	0.83	7.42	0
1790	5.56	192.85	4.1	6.06	325.79	0	0	1.31	0.69	0
1791	0	84.13	4.12	7.15	356.58	0	0	1.45	12	0
1792	0	168.2	3.37	5.18	359.43	0	0	0.74	8.76	0
1793	5.26	211.76	4.46	6.1	357.39	0	0	1.26	0.6	0
1794	0	103.4	4.26	7.31	380.88	0	0	1.43	14.04	0
1795	0	164.96	3.57	5.23	362.23	0	0	0.77	8.78	0
1796	4.82	169.51	4.79	6.11	298.58	0	0	1.12	0.55	0
1797	0	112.3	4.48	7.34	364.79	0	0	1.35	15.16	0
1798	0	180.35	3.16	5.02	381.26	0	0	0.76	6.52	0
1799	5.2	205.64	4.96	6.21	332.02	0	0	1.18	0.16	0
1800	0	124.08	3.9	7.04	381.31	0	0	1.31	25.74	0
1801	0	177.9	3.21	5.05	376.36	0	0	0.74	7.4	0
1802	4.9	149.47	4.19	5.55	287.83	0	0	1.15	0.14	0
1803	0	117.76	3.73	6.87	393.55	0	0	1.3	17.97	0
1804	0	195.76	2.97	4.92	393.95	0	0	0.74	7.57	0
1805	5.77	163	3.9	5.51	288.61	0	0	1.06	0.07	0
1806	0	121.95	3.09	6.54	376.34	0	0	1.19	20.97	0
1807	0	212.34	3.44	5.21	414.8	0	0	0.71	9.01	0
1808	5.46	163.91	3.78	5.33	283.72	0	0	1.03	0.37	0
1809	0	122.2	3.31	6.61	372.59	0	0	1.19	18.57	0
1810	0	189.48	2.89	4.95	400.39	0	0	0.64	8.27	0
1811	6.62	161.47	1.62	4.04	283.02	0	0	1.02	0.34	0
1812	0	84.91	2.75	6.39	356.59	0	0	1.17	12.7	0
1813	0	174.67	4.17	5.44	383.41	0	0	0.59	10.26	0
1814	5.13	192.45	3.28	5.25	316.99	0	0	1.02	0.2	0
1815	0	113.31	3.23	6.51	375.39	0	0	1.08	17.67	0
1816	0	174.13	2.98	4.92	370.2	0	0	0.6	6.39	0
1817	5.53	154.61	3.78	5.2	288.04	0	0	0.94	0.08	0
1788	0	113.81	4.45	7.54	368.19	0	0	1.53	18.81	0
1789	0	171.18	3.63	5.35	378.33	0	0	0.83	7.42	0
1790	5.56	192.85	4.1	6.06	325.79	0	0	1.31	0.69	0
1791	0	84.13	4.12	7.15	356.58	0	0	1.45	12	0
1792	0	168.2	3.37	5.18	359.43	0	0	0.74	8.76	0
1793	5.26	211.76	4.46	6.1	357.39	0	0	1.26	0.6	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1824	0	127.96	2.52	6.16	372.11	0	0	0.99	20.27	0
1825	0	171.24	2.56	4.54	364.97	0	0	0.49	4.44	0
1826	5.62	205.66	3.96	5.51	327.89	0	0	0.88	0.43	0
1827	0	104.35	2.8	6.2	361.23	0	0	0.93	16.57	0
1828	0	217.79	3.93	5.43	454.64	0	0	0.53	12.58	0
1829	5.67	160.03	2.11	4.4	311.4	0	0	0.89	0.11	0
1830	0	95.74	2.57	6	370.43	0	0	0.93	13.03	0
1831	0	169.12	2.8	4.6	367.4	0	0	0.44	6.11	0
1832	5.32	165.03	3.49	5.2	309.91	0	0	0.86	0.32	0
1833	0	114.34	2.8	6.19	373.91	0	0	0.89	18.24	0
1834	0	150.62	3.79	4.98	366.88	0	0	0.44	6.36	0
1835	5.11	157.11	2.15	4.4	311.25	0	0	0.83	0.25	0
1836	0	74.77	2.88	5.94	255.99	0	0	0.86	7.06	0
1837	0	159.08	3.3	4.73	376.66	0	0	0.41	6.85	0
1838	5.05	189.23	3.11	4.91	347.08	0	0	0.85	0.27	0
1839	0	102.89	2.65	5.94	376.22	0	0	0.86	16.96	0
1840	0	214.41	2.6	4.51	404.5	0	0	0.43	7.25	0
1841	5.53	181.16	3.61	5.15	335.03	0	0	0.77	0.09	0
1842	0	105.89	2.46	5.81	363.37	0	0	0.78	13.88	0
1843	0	182.21	2.65	4.56	402.75	0	0	0.41	5.5	0
1844	4.89	163.52	3.79	5.23	316.55	0	0	0.75	0.25	0
1845	0	143.23	2.7	5.99	388.62	0	0	0.78	23.81	0
1846	0	227.69	1.93	4.27	434.09	0	0	0.45	5.12	0
1847	6.51	186.26	2.87	4.64	338.34	0	0	0.71	0.02	0
1848	0	113.79	1.77	5.62	353.61	0	0	0.73	19.62	0
1849	0	180.86	3.76	4.92	421.21	0	0	0.36	10.04	0
1850	4.93	180.28	2.09	4.36	297.56	0	0	0.72	0.34	0
1851	0	112.35	2.65	5.79	372.97	0	0	0.71	17.66	0
1852	0	188.38	2.26	4.29	374.7	0	0	0.36	6.32	0
1853	5.61	189.84	3.01	4.74	325.6	0	0	0.7	0.41	0
1824	0	127.96	2.52	6.16	372.11	0	0	0.99	20.27	0
1825	0	171.24	2.56	4.54	364.97	0	0	0.49	4.44	0
1826	5.62	205.66	3.96	5.51	327.89	0	0	0.88	0.43	0
1827	0	104.35	2.8	6.2	361.23	0	0	0.93	16.57	0
1828	0	217.79	3.93	5.43	454.64	0	0	0.53	12.58	0
1829	5.67	160.03	2.11	4.4	311.4	0	0	0.89	0.11	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1860	0	102.87	2.11	5.53	376.06	0	0	0.64	17.69	0
1861	0	186.73	2.48	4.33	386.82	0	0	0.31	8.28	0
1862	5.2	196.8	3.17	4.71	351.47	0	0	0.69	0.46	0
1863	0	101.61	2.15	5.51	370.97	0	0	0.63	14.68	0
1864	0	184.7	2.56	4.36	393.97	0	0	0.29	11.44	0
1865	4.82	177.45	3.31	4.88	338.47	0	0	0.64	0.33	0
1866	0	120.1	2.34	5.54	377.3	0	0	0.6	19.6	0
1867	0	189.85	2.16	4.04	371.14	0	0	0.27	8.41	0
1868	5.26	183.76	2.94	4.58	292.94	0	0	0.63	0.34	0
1869	0	100.35	2.15	5.39	380.42	0	0	0.58	13.37	0
1870	0	209.04	3.18	4.72	427.55	0	0	0.28	9.64	0
1871	5.23	167.87	2.06	4.2	322.1	0	0	0.63	0.23	0
1872	0	113.03	2.44	5.53	360.95	0	0	0.58	22.11	0
1873	0	170.43	3.36	4.5	375.89	0	0	0.26	11.14	0
1874	4.74	176.13	2.24	4.3	330.5	0	0	0.62	0.29	0
1875	0	163.59	2.53	5.68	389.98	0	0	0.57	31.54	0
1876	0	181.5	1.34	3.64	385.97	0	0	0.27	4.25	0
1877	5.68	188.98	3.63	4.84	331.44	0	0	0.55	0.07	0
1878	0	114.72	1.5	5.19	375.09	0	0	0.5	17.86	0
1879	0	191.43	2.38	4.22	397.59	0	0	0.23	7.83	0
1880	5.32	175.58	2.45	4.38	316.29	0	0	0.57	1.25	0
1881	0	96.37	2.17	5.4	359.28	0	0	0.51	15.37	0
1882	0	192.36	2.43	4.31	406.93	0	0	0.24	9.84	0
1883	5.92	147.55	1.53	3.69	287.01	0	0	0.59	0.06	0
1884	0	108.73	1.8	5.39	355.67	0	0	0.53	15.98	0
1885	0	207.88	3.19	4.82	434.1	0	0	0.22	9.77	0
1886	4.88	195.74	3.01	4.74	320.71	0	0	0.52	0.43	0
1887	0	135.08	2.14	5.48	382.11	0	0	0.46	25.4	0
1888	0	203.72	1.84	4.07	394.31	0	0	0.22	5.48	0
1889	5.99	188.7	2.81	4.49	329.09	0	0	0.53	0.06	0
1860	0	102.87	2.11	5.53	376.06	0	0	0.64	17.69	0
1861	0	186.73	2.48	4.33	386.82	0	0	0.31	8.28	0
1862	5.2	196.8	3.17	4.71	351.47	0	0	0.69	0.46	0
1863	0	101.61	2.15	5.51	370.97	0	0	0.63	14.68	0
1864	0	184.7	2.56	4.36	393.97	0	0	0.29	11.44	0
1865	4.82	177.45	3.31	4.88	338.47	0	0	0.64	0.33	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1896	0	119.75	2.3	5.46	366.16	0	0	0.41	20.49	0
1897	0	192.97	2.06	4.13	385.54	0	0	0.18	8.94	0
1898	5.69	195.18	2.77	4.47	331.96	0	0	0.48	0.12	0
1899	0	118.37	1.57	5.28	366.93	0	0	0.4	19.28	0
1900	0	198.6	3.17	4.64	411.75	0	0	0.17	11.11	0
1901	5.15	177.28	2.2	4.25	312.29	0	0	0.54	0.56	0
1902	0	121.31	1.94	5.43	382.46	0	0	0.43	18.21	0
1903	0	181.02	1.4	3.88	379.58	0	0	0.15	3.91	0
1904	6	172.62	2.73	4.41	304.17	0	0	0.45	0.05	0
1905	0	74.19	1.79	5.35	355.26	0	0	0.38	8.06	0
1906	0	188.5	3.84	4.83	407.52	0	0	0.15	13.81	0
1907	4.95	173.38	1.37	3.7	302.2	0	0	0.49	0.61	0
1908	0	139.16	2.18	5.51	329.23	0	0	0.4	24.02	0
1909	0	192.15	2.99	4.5	383.17	0	0	0.16	7.94	0
1910	4.64	162.83	3.29	4.75	273	0	0	0.45	1.29	0
1911	0	140.29	2.45	5.55	390.14	0	0	0.37	24.87	0
1912	0	196	1.95	3.87	377.49	0	0	0.15	6.85	0
1913	4.97	169.4	3.38	4.65	312.21	0	0	0.46	0.31	0
1914	0	108.24	2.03	5.35	363.76	0	0	0.36	17.1	0
1915	0	172.41	2.78	4.23	379.25	0	0	0.13	12.67	0
1916	5.11	190.52	1.74	3.95	340.34	0	0	0.48	0.31	0
1917	0	108.69	1.86	5.23	368.49	0	0	0.32	15.48	0
1918	0	156.79	2.28	4.1	341	0	0	0.12	5.55	0
1919	4.74	172.97	3.21	4.66	326.75	0	0	0.47	0.72	0
1920	0	116.77	2.34	5.5	374.41	0	0	0.36	19.55	0
1921	0	194.08	2.77	4.4	395.11	0	0	0.13	10.56	0
1922	4.99	179.44	2.55	4.33	316.22	0	0	0.38	0.18	0
1923	0	158.91	1.92	5.35	393.91	0	0	0.3	26.78	0
1924	0	196.77	1.91	4.02	373.86	0	0	0.13	5.89	0
1925	5.59	176.03	3.25	4.62	312.12	0	0	0.4	0.39	0
1896	0	119.75	2.3	5.46	366.16	0	0	0.41	20.49	0
1897	0	192.97	2.06	4.13	385.54	0	0	0.18	8.94	0
1898	5.69	195.18	2.77	4.47	331.96	0	0	0.48	0.12	0
1899	0	118.37	1.57	5.28	366.93	0	0	0.4	19.28	0
1900	0	198.6	3.17	4.64	411.75	0	0	0.17	11.11	0
1901	5.15	177.28	2.2	4.25	312.29	0	0	0.54	0.56	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1932	0	153.81	2.3	5.57	389.23	0	0	0.34	22.48	0
1933	0	201.99	2.7	4.42	392.65	0	0	0.12	7.77	0
1934	4.94	175.04	3.17	4.64	309.87	0	0	0.42	0.16	0
1935	0	128.36	2.38	5.53	376.55	0	0	0.31	23.36	0
1936	0	196.94	2.98	4.66	413.77	0	0	0.1	10.39	0
1937	5.07	226.98	2.55	4.53	337.29	0	0	0.46	0.7	0
1938	0	108.25	2.16	5.32	362.94	0	0	0.32	17.95	0
1939	0	212.97	3.64	4.68	419.54	0	0	0.09	15.85	0
1940	4.96	184.24	1.23	3.78	312.59	0	0	0.44	0.59	0
1941	0	100.4	2.32	5.4	373.13	0	0	0.31	12.66	0
1942	0	141.52	2.9	4.23	328.82	0	0	0.08	9.08	0
1943	4.8	219.34	2	4.25	349.98	0	0	0.44	0.61	0
1944	0	137.18	2.53	5.61	384.57	0	0	0.31	22.19	0
1945	0	186.85	2.76	4.48	384.21	0	0	0.09	6.03	0
1946	4.64	150.08	3.64	4.83	308.34	0	0	0.42	0.49	0
1947	0	147.24	2.46	5.63	387.66	0	0	0.3	27.84	0
1948	0	199.95	3	4.45	398.84	0	0	0.09	11.46	0
1949	5.13	177.17	1.81	4.05	300.48	0	0	0.42	0.32	0
1950	0	122.22	2.36	5.52	365.14	0	0	0.29	18.83	0
1951	0	177.43	2.54	4.33	379.25	0	0	0.08	12.22	0
1952	4.07	199.5	4.03	4.91	386.14	0	0	0.4	0.53	0
1953	0	160.75	2.61	5.59	393.96	0	0	0.28	30.54	0
1954	0	229.33	2.04	4.06	400.05	0	0	0.09	8.82	0
1955	5.65	201.46	2.83	4.44	321.8	0	0	0.33	0.11	0
1956	0	110.11	1.89	5.4	351.95	0	0	0.23	17.05	0
1957	0	160.06	3.44	4.59	367.27	0	0	0.07	10.31	0
1958	4.47	178.12	2.21	4.22	323.04	0	0	0.37	0.47	0
1959	0	128.04	2.7	5.75	391.76	0	0	0.26	20.68	0
1960	0	221.23	2.67	4.44	403.56	0	0	0.07	9.36	0
1961	4.7	172.43	3.52	4.83	310.14	0	0	0.39	0.23	0
1932	0	153.81	2.3	5.57	389.23	0	0	0.34	22.48	0
1933	0	201.99	2.7	4.42	392.65	0	0	0.12	7.77	0
1934	4.94	175.04	3.17	4.64	309.87	0	0	0.42	0.16	0
1935	0	128.36	2.38	5.53	376.55	0	0	0.31	23.36	0
1936	0	196.94	2.98	4.66	413.77	0	0	0.1	10.39	0
1937	5.07	226.98	2.55	4.53	337.29	0	0	0.46	0.7	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
1968	0	140.65	2.35	5.76	388.23	0	0	0.28	22.9	0
1969	0	220.1	2.21	4.37	390.12	0	0	0.07	6.22	0
1970	5.67	178.1	3.23	4.66	397.82	0	0	0.33	0.23	0
1971	0	90.3	2.06	5.76	364.18	0	0	0.22	13.77	0
1972	0	180.69	1.65	4.92	371.43	0	0	0.06	11.36	0
1973	4.63	203.79	2.58	4.6	350.56	0	0	0.39	0.58	0
1974	0	141.17	2.82	5.82	371.33	0	0	0.25	24.14	0
1975	0	179.86	2.76	4.5	375.61	0	0	0.06	7.83	0
1976	4.78	192.57	3.03	4.77	310.62	0	0	0.3	0.27	0
1977	0	159.04	2.99	5.99	381.63	0	0	0.2	30.06	0
1978	0	186.87	2.71	4.4	392.39	0	0	0.05	6.74	0
1979	4.71	194.78	3.74	5.04	342.83	0	0	0.38	0.47	0
1980	0	116.94	2.67	5.79	360.14	0	0	0.23	21.38	0
1981	0	191.71	3.28	4.72	408.36	0	0	0.05	10.78	0
1982	5.17	205.85	1.9	4.24	342.08	0	0	0.43	0.62	0
1983	0	121.67	2.61	5.76	370.72	0	0	0.26	17.65	0
1984	0	203.42	3.04	4.67	401.2	0	0	0.05	9.66	0
1985	5.12	193.39	2.64	4.64	323	0	0	0.3	0.34	0
1986	0	112.16	2.56	5.83	360.85	0	0	0.2	15.71	0
1987	0	212.24	3.61	4.92	409.6	0	0	0.05	13.37	0
1988	5.24	144.13	1.42	3.74	282.11	0	0	0.38	0.19	0
1989	0	102.78	2.65	5.95	361.22	0	0	0.24	16.83	0
1990	0	182.69	3.31	4.69	383.65	0	0	0.04	11.15	0
1991	4.97	219.13	2.31	4.47	331.2	0	0	0.35	1.28	0
1992	0	113.26	3.02	6.07	360.69	0	0	0.22	16.73	0
1993	0	191.84	3.75	4.95	401.47	0	0	0.04	11.77	0
1994	4.91	193.12	2.27	4.37	339.53	0	0	0.37	0.51	0
1995	0	129.56	3.01	6.15	363.63	0	0	0.23	21.51	0
1996	0	206.05	3.42	4.94	402.89	0	0	0.04	11.71	0
1997	4.86	233.23	3.47	5.14	365.96	0	0	0.32	0.51	0
1968	0	140.65	2.35	5.76	388.23	0	0	0.28	22.9	0
1969	0	220.1	2.21	4.37	390.12	0	0	0.07	6.22	0
1970	5.67	178.1	3.23	4.66	397.82	0	0	0.33	0.23	0
1971	0	90.3	2.06	5.76	364.18	0	0	0.22	13.77	0
1972	0	180.69	1.65	4.92	371.43	0	0	0.06	11.36	0
1973	4.63	203.79	2.58	4.6	350.56	0	0	0.39	0.58	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
2004	0	126.83	3.29	6.12	370.68	0	0	0.21	20.45	0
2005	0	177.11	2.99	4.5	384.92	0	0	0.04	10.9	0
2006	4.51	176.92	2.66	4.63	341.71	0	0	0.36	0.35	0
2007	0	145.69	3.47	6.14	372.1	0	0	0.21	29.07	0
2008	0	204.07	3.12	4.63	411.83	0	0	0.04	11.37	0
2009	4.3	215.38	3.86	5.19	347.97	0	0	0.32	0.9	0
2010	0	184.96	3.61	6.29	405.8	0	0	0.18	37.34	0
2011	0	182.12	2.55	4.28	378.76	0	0	0.04	6.34	0
2012	4.43	157.45	3.57	4.79	322.01	0	0	0.22	0.59	0
2013	0	143.44	3.3	6.04	385.94	0	0	0.18	27.72	0
2014	0	161.02	3.13	4.35	351.41	0	0	0.03	8.39	0
2015	4.24	201.78	2.99	4.69	342.04	0	0	0.36	0.83	0
2016	0	118.62	3.39	6.13	364.5	0	0	0.2	17.93	0
2017	0	217.99	3.13	4.63	424.57	0	0	0.03	14.73	0
2018	4.17	180.57	3.11	4.64	323.98	0	0	0.33	0.63	0
2019	0	154.2	3.44	6.14	406.05	0	0	0.19	25.87	0
2020	0	217.99	2.99	4.47	407.14	0	0	0.03	9.54	0
2021	4.39	180.57	3.18	4.44	317.49	0	0	0.36	0.34	0
2022	0	127.15	3.23	6.15	374.01	0	0	0.2	22.92	0
2023	0	180.65	3.25	4.52	381.81	0	0	0.03	14.19	0
2024	3.87	182.94	3.04	4.59	330.46	0	0	0.38	1.07	0
2025	0	175.97	3.97	6.34	394.68	0	0	0.21	36.93	0
2026	0	230.37	2.99	4.55	437.54	0	0	0.04	10.87	0
2027	4.46	201.51	2.28	4	325.84	0	0	0.4	0.88	0
2028	0	116.82	3.15	5.84	363.51	0	0	0.22	20.14	0
2029	0	218.96	3.48	4.82	415	0	0	0.04	14.13	0
2030	3.79	176.86	3.61	4.89	307.22	0	0	0.33	1.07	0
2031	0	152.7	3.7	6.04	385.55	0	0	0.18	29.27	0
2032	0	171.5	2.48	4.45	359.46	0	0	0.03	9.21	0
2033	5.08	175.26	2.11	4.27	297.68	0	0	0.33	0.5	0
2004	0	126.83	3.29	6.12	370.68	0	0	0.21	20.45	0
2005	0	177.11	2.99	4.5	384.92	0	0	0.04	10.9	0
2006	4.51	176.92	2.66	4.63	341.71	0	0	0.36	0.35	0
2007	0	145.69	3.47	6.14	372.1	0	0	0.21	29.07	0
2008	0	204.07	3.12	4.63	411.83	0	0	0.04	11.37	0
2009	4.3	215.38	3.86	5.19	347.97	0	0	0.32	0.9	0

Appendix I. EPIC Output (continued)

Year	SUGC	Runoff (inches)	Humus mineralization (pounds/acre)	Nitrification (pounds/acre)	Evapotrans-piration (inches)	Labile P loss in runoff	N mineralized (pounds/acre)	P mineralized (pounds/acre)	Water erosion	NO_3 leached
2040	0	111.99	3.11	6.19	366.07	0	0	0.22	18.54	0
2041	0	206.26	3.01	4.91	399.3	0	0	0.03	11.36	0
2042	5.33	208.93	2.92	4.83	302.32	0	0	0.34	0.22	0
2043	0	128.29	2.82	6.2	376.82	0	0	0.2	19.19	0
2044	0	191.73	3.05	5.03	393.71	0	0	0.04	5.72	0
2045	5.02	171.53	3.52	5.02	296.54	0	0	0.3	0.34	0
2046	0	129.69	3.32	6.36	360.79	0	0	0.18	23.14	0
2047	0	162.39	3.57	4.92	385.56	0	0	0.03	13.58	0
2048	4.84	186.83	2.61	4.59	327.06	0	0	0.36	0.29	0
2049	0	111.45	3.11	6.22	358.88	0	0	0.21	18.89	0

Appendix II. Recorded Sugar Sales, Sugarcane Yield, and EPIC Yield

Year	Recorded Hogsheads (hhds) of Sugar	Sugar in Pounds (hhds*1456)	Sugar in Tons (pounds/2000)	Sugarcane Yield in Tons (sugar in tons*8.58)	EPIC Yield (tons/500 acres)
1707	43	62608	31.30	268.59	
1708	135	196560	98.28	843.24	
1709	94	136864	68.43	587.15	1040
1710	646	940576	470.29	4035.07	
1711	51	74256	37.13	318.56	
1712	67	97552	48.78	418.50	880
1713	No data	No data	No data	No data	
1714	570	829920	414.96	3560.36	
1715	445	647920	323.96	2779.58	1180
1716	551	802256	401.13	3441.68	
1717	641	933296	466.65	4003.84	
1718	75	109200	54.60	468.47	2550
1719	428	623168	311.58	2673.39	
1720	510	742560	371.28	3185.58	
1721	108	157248	78.62	674.59	1110
1722	258	375648	187.82	1611.53	
1723	448	652288	326.14	2798.32	
1724	391	569296	284.65	2442.28	2110
1725	369	537264	268.63	2304.86	
1726	270	393120	196.56	1686.48	
1727	329	479024	239.51	2055.01	3400
1728	612	891072	445.54	3822.70	
1729	710	1033760	516.88	4434.83	
1730	541	787696	393.85	3379.22	1495
1731	440	640640	320.32	2748.35	
1732	382	556192	278.10	2386.06	
1733	516	751296	375.65	3223.06	1150
1734	290	422240	211.12	1811.41	
1735	401	583856	291.93	2504.74	
1736	408	594048	297.02	2548.47	2830
1737	120	174720	87.36	749.55	
1738	510	742560	371.28	3185.58	
1739	548	797888	398.94	3422.94	2460
1740	439	639184	319.59	2742.10	
1741	450	655200	327.60	2810.81	
1742	361	525616	262.81	2254.89	370
1743	526	765856	382.93	3285.52	
1744	510	742560	371.28	3185.58	

Appendix II. Recorded Sugar Sales, Sugarcane Yield, and EPIC Yield (continued

Year	Recorded Hogsheads (hhds) of Sugar	Sugar in Pounds (hhds*1456)	Sugar in Tons (pounds/2000)	Sugarcane Yield in Tons (sugar in tons*8.58)	EPIC Yield (tons/500 acres)
1745	405	589680	294.84	2529.73	84
1746	512	745472	372.74	3198.07	
1747	108	157248	78.62	674.59	
1748	548	797888	398.94	3422.94	7175
1749	529	770224	385.11	3304.26	
1750	530	771680	385.84	3310.51	
1751	449	653744	326.87	2804.56	25
1752	No data	No data	No data	No data	
1753	No data	No data	No data	No data	
1754	No data	No data	No data	No data	5490
1755	No data	No data	No data	No data	
1756	No data	No data	No data	No data	
1757	No data	No data	No data	No data	25
1758	No data	No data	No data	No data	
1759	No data	No data	No data	No data	
1760	187	272272	136.14	1168.05	5950
1761	519	755664	377.83	3241.80	
1762	592	861952	430.98	3697.77	
1763	271	394576	197.29	1692.73	75
1764	469	682864	341.43	2929.49	
1765	241	350896	175.45	1505.34	
1766	1252	1822912	911.46	7820.29	1285
1767	917	1335152	667.58	5727.80	
1768	752	1094912	547.46	4697.17	
1769	566	824096	412.05	3535.37	2665
1770	717	1043952	521.98	4478.55	
1771	325	473200	236.60	2030.03	
1772	283	412048	206.02	1767.69	2540
1773	317	461552	230.78	1980.06	
1774	975	1419600	709.80	6090.08	
1775	699	1017744	508.87	4366.12	2460
1776	398	579488	289.74	2486.00	
1777	395	575120	287.56	2467.26	
1778	333	484848	242.42	2080.00	2380
1779	179	260624	130.31	1118.08	
1780	No data	No data	No data	No data	
1781	No data	No data	No data	No data	3095
1782	577	840112	420.06	3604.08	

Appendix II. Recorded Sugar Sales, Sugarcane Yield, and EPIC Yield (continued)

Year	Recorded Hogsheads (hhds) of Sugar	Sugar in Pounds (hhds*1456)	Sugar in Tons (pounds/2000)	Sugarcane Yield in Tons (sugar in tons*8.58)	EPIC Yield (tons/500 acres)
1783	66	96096	48.05	412.25	
1784	948	1380288	690.14	5921.44	2900
1785	766	1115296	557.65	4784.62	
1786	641	933296	466.65	4003.84	
1787	1019	1483664	741.83	6364.92	2535
1788	791	1151696	575.85	4940.78	
1789	549	799344	399.67	3429.19	
1790	193	281008	140.50	1205.52	2780
1791	No data	No data	No data	No data	
1792	No data	No data	No data	No data	
1793	No data	No data	No data	No data	2630
1794	No data	No data	No data	No data	
1795	No data	No data	No data	No data	
1796	No data	No data	No data	No data	2410
1797	No data	No data	No data	No data	
1798	No data	No data	No data	No data	
1799	No data	No data	No data	No data	2600
1800	No data	No data	No data	No data	
1801	No data	No data	No data	No data	
1802	829	1207515	603.76	5180.24	2450
1803	693	1009147	504.57	4329.24	
1804	455	662480	331.24	2842.04	
1805	173	252373	126.19	1082.68	2885
1806	245	356720	178.36	1530.33	
1807	483	703248	351.62	3016.93	
1808	471	685180	342.59	2939.42	2730
1809	251	365222	182.61	1566.80	
1810	248	360374	180.19	1546.00	
1811	950	1383468	691.73	5935.08	3310
1812	505	735307	367.65	3154.47	
1813	357	519334	259.67	2227.94	
1814	20	29120	14.56	124.92	2565
1815	No data	No data	No data	No data	
1816	No data	No data	No data	No data	
1817	428	623168	311.58	2673.39	2765
1818	641	933296	466.65	4003.84	
1819	490	713440	356.72	3060.66	

Appendix II. Recorded Sugar Sales, Sugarcane Yield, and EPIC Yield (continued)

Year	Recorded Hogsheads (hhds) of Sugar	Sugar in Pounds (hhds*1456)	Sugar in Tons (pounds/2000)	Sugarcane Yield in Tons (sugar in tons*8.58)	EPIC Yield (tons/500 acres)
1820	270	393120	196.56	1686.48	2720
1821	253	368368	184.18	1580.30	
1822	100	145600	72.80	624.62	
1823	118	171808	85.90	737.06	3045
1824	99	144144	72.07	618.38	
1825	15	21840	10.92	93.69	
1826	145	211120	105.56	905.70	2810
1827	No data	No data	No data	No data	
1828	89	129584	64.79	555.92	

Appendix III. Six-Year Moving Averages for Recorded Sugar Yields and EPIC Yields

Years	Sugar Yield (tons)	EPIC Yield (tons/500 acres)
1707-1712	1078.52	960
1713-1718	2375.65	1865
1719-1724	2230.95	1610
1725-1730	2947.18	2447.5
1731-1736	2537.01	1990
1737-1742	2527.65	1415
1743-1748	2716.07	3629.5
1749-1754	1569.89	2757.5
1755-1760	No data	2987.5
1761-1766	3481.24	680
1767-1772	3706.1	2602.5
1773-1778	3244.92	2420
1779-1784	1842.64	2997.5
1785-1790	4121.48	2657.5
1791-1796	No data	2520
1797-1802	No data	2525
1803-1808	2623.44	2807.5
1809-1814	2425.87	2937.5
1815-1820	1904.06	2742.5
1821-1826	2222.62	2927.5

Appendix IV. Field Descriptions of Each Soil Sample

Auger Probe Number	Depth (cm)	Horizon	Diagnostic horizons, properties, and materials	Munsell color	Soil texture
BHAP1	0-20	A	Soft, loose, sandy clay; mottled;	2.5 Y 3/2 (very dark grayish brown)	Clay
BHAP1	20-40	B	Soft, compact clay; mottled	2.5 Y 6/2 (light brownish gray)	Clay
BHAP2	0-10	A1	Soft, loose, sandy silt; erosion from T2	2.5 Y 4/3 (olive brown)	Sandy clay loam
BHAP2	10-20	B1	Soft, loose, silty sand; erosion from T2	2.5 Y 5/3 (light olive brown)	Sandy clay loam
BHAP2	20-25	A2	Hard, compact, sandy clay; Buried A of T1	2.5 Y 3/2 (very dark grayish brown)	Sandy clay loam
BHAP2	25-30	B2	Hard, loose, sandy clay; transition between A and B horizons	2.5 Y 4/2 (dark grayish brown)	Sandy loam
BHAP2	30-35	B3	Hard, compact, sandy clay; B horizon of T1	2.5 Y 4/3 (olive brown)	Sandy clay loam
BHAP2	35-40	B4	Hard, loose, sandy silt, approaching sea	2.5 Y 5/3 (light olive brown)	Sandy clay loam
BHAP3	0-10	A1	Soft, loose, silty sand; T2 erosion	2.5 Y 3/3 (dark olive brown)	Sandy loam
BHAP3	10-20	B1	Soft, loose, sandy silt; lighter, more gravel	2.5 Y 4/3 (olive brown)	Sandy loam
BHAP3	20-30	A2	Hard, compact, sandy clay; transition, dark clay present	2.5 Y 3/1 (very dark gray)	Sandy clay
BHAP3	30-50	A3	Hard, compact, sandy clay; carbonate inclusions	2.5 Y 2.5/1 (black)	Clay
BHAP3	50-70	A4	Hard, loose sandy clay; transition, dark clay present	2.5 Y 2.5/1 (black)	Clay
BHAP3	70-90	A5	Hard, loose sandy clay; darker, black	10 YR 2/1 (black)	Clay
BHAP3	90-120	A6	Hard, loose, sandy clay	10 YR 2/1 (black)	Sandy clay loam
BHAP4	0-5	A	Hard, compact, dark, sandy clay	2.5 Y 2.5/1 (black)	Sandy clay loam
BHAP4	5-30	B	Hard, compact, dark, sandy clay; carbonate inclusions, darker	2.5 Y 2.5/1 (black)	Clay

Appendix IV. Field Descriptions of Each Soil Sample (continued)

Auger Probe Number	Depth (cm)	Horizon	Diagnostic horizons, properties, and materials	Munsell color	Soil texture
BHAP4	30-40	C	Weathered limestone, brown chert;	2.5 Y 2.5/1 (black)	Loam
BHAP5	0-10	A	Soft, loose, silty sand	2.5 Y 2.5/1 (black)	Sandy loam
BHAP5	10-40	B1	Hard, compact, sandy clay; dark black	10 YR 2/1 (black)	Sandy clay loam
BHAP5	40-60	B2	Hard, compact, sandy clay; carbonate inclusions	10 YR 2/1 (black)	Clay
BHAP5	60-80	B3	Hard, compact, sandy clay; carbon and carbonate inclusions, light gray	2.5 Y 4/2 (dark grayish brown)	Clay
BHAP5	80-120	B4	Hard, compact, sandy clay; lighter in color; mottled with carbon inclusions	2.5 Y 4/2 (dark grayish brown)	Clay
BHAP6	0-10	A	Soft, loose sandy silt; dark brown	10 YR 2/1 (black)	Sandy loam
BHAP6	10-20	AC1	Hard, loose, sandy clay; carbonate inclusions	2.5 Y 2.5/1 (black)	Sandy loam
BHAP6	20-30	AC2	Soft, loose, sandy silt	2.5 Y 4/3 (olive brown)	Sandy clay loam
BHAP6	30-40	C1	Soft, loose, light sandy silt	2.5 Y 4/3 (olive brown)	Sandy loam
BHAP6	40-60	C2	Soft, loose, light sandy silt	2.5 Y 4/3 (olive brown)	Sandy loam
BHAP7	0-10	A1	Soft, loose, sandy clay	2.5 Y 2.5/1 (black)	Clay
BHAP7	10-20	A2	Soft, loose, sandy clay; carbonate inclusions	2.5 Y 2.5/1 (black)	Clay
BHAP7	20-30	B1	Hard, compact, sandy clay; mottled, lighter in color	2.5 Y 5/2 (grayish brown)	Clay
BHAP7	30-60	B2	Hard, compact sandy clay; mottled; more black carbonate inclusions	2.5 Y 5/2 (grayish brown)	Clay
BHAP7	60-120	C	Hard, compact, sandy clay; light mottling	2.5 Y 5/2 (grayish brown)	Sandy clay

Appendix IV. Field Descriptions of Each Soil Sample (continued)

Auger Probe Number	Depth (cm)	Horizon	Diagnostic horizons, properties, and materials	Munsell color	Soil texture
BHAP8	0-10	A	Soft, loose, sandy clay	2.5 Y 3/2 (very dark grayish brown)	Sandy clay loam
BHAP8	10-20	B1	Soft, loose, sandy silt	2.5 Y 5/3 (light olive brown)	Sandy clay loam
BHAP8	20-30	B2	Soft, loose, sandy silt; lighter	2.5 Y 5/3 (light olive brown)	Clay
BHAP8	30-60	C1	Soft, loose, sandy silt; carbonate inclusions	2.5 Y 6/3 (light yellowish brown)	Clay
BHAP8	60-70	C2	Soft, loose, sandy silt; like C1, but darker in color	2.5 Y 6/3 (light yellowish brown)	Sandy clay loam
BHAP8	70-90	C3	Soft, loose, silty sand; carbonate inclusions	2.5 Y 5/4 (light olive brown)	Sandy clay
BHAP8	90-120	C4	Soft, loose, silty sand; like C3, but lighter in color	2.5 Y 6/3 (light yellowish brown)	Clay
BHAP8	120-150	C5	Soft, loose, silty sand; like C3, but more carbonate inclusions	2.5 Y 6/2 (light brownish gray)	Clay
BHAP8	150-170	C6	Soft, loose, sandy clay; weathered bedrock	2.5 Y 5/2 (grayish brown)	Clay
BHAP9	0-20	A	Hard, loose, sandy clay	2.5 Y 2.5/1 (black)	Clay
BHAP9	20-30	AB	Hard, loose, sandy clay	2.5 Y 2.5/1 (black)	Clay
BHAP9	30-60	B1	Hard, compact clay; mottled with carbon and carbonate inclusions	2.5 Y 5/2 (grayish brown)	Clay
BHAP9	60-90	B2	Hard, compact clay; mottled with carbon and carbonate inclusions	2.5 Y 5/2 (grayish brown)	Clay
BHAP9	90-110	C	Soft, loose, sandy silt; mottled with carbon, carbonate, and iron	2.5 Y 4/4 (olive brown)	Clay
BHAP10	0-20	A	Soft, loose, sandy clay	2.5 Y 2.5/1 (black)	Clay
BHAP10	20-30	AB	Hard, compact, sandy clay	2.5 Y 5/2 (grayish brown)	Clay
BHAP10	30-70	B	Hard, compact, sandy clay; mottled with carbon and carbonate inclusions	2.5 Y 5/2 (grayish brown)	Sandy loam

Appendix IV. Field Descriptions of Each Soil Sample (continued)

Auger Probe Number	Depth (cm)	Horizon	Diagnostic horizons, properties, and materials	Munsell color	Soil texture
BHAP10	70-90	C	Silty sand; carbonate inclusions, iron	2.5 Y 4/4 (olive brown)	Clay
BHAP11	0-10	A	Hard, compact, sandy clay; dark black	2.5 Y 2.5/1 (black)	Sandy loam
BHAP11	10-20	AB	Hard, compact, sandy clay; mottled	2.5 Y 3/3 (dark olive brown)	Sandy loam
BHAP11	20-30	B	Hard, compact, sandy clay; very sandy	2.5 Y 3/3 (dark olive brown)	Sandy loam
BHAP11	30-40	C1	Loose, silty sand; carbonate inclusions	2.5 Y 5/3 (light olive brown)	Sandy clay loam
BHAP11	40-50	C2	Loose, silty sand; like C1, but lighter and powdery	2.5 Y 6/3 (light yellowish brown)	Sandy clay loam
BHAP12	0-10	A	Soft, loose, sandy silt	2.5 Y 3/2 (very dark grayish brown)	Sandy clay loam
BHAP12	10-20	AC	Soft, loose, silty sand	2.5 Y 4/3 (olive brown)	Sandy clay loam
BHAP12	20-40	C	Soft, loose, silty sand	2.5 Y 7/3 (pale yellow)	Clay loam
BHAP13	0-10	A	Very sandy clay	2.5 Y 3/2 (very dark grayish brown)	Sandy clay loam
BHAP13	10-20	AC	Clayey sand	2.5 Y 4/2 (dark grayish brown)	Sandy clay loam
BHAP13	20-30	C	Silty sand; limestone inclusions	2.5 Y 6/3 (light yellowish brown)	Sandy clay loam
BHAP14	0-30	A	Sandy silt; dark black	2.5 Y 2.5/1 (black)	Sandy loam
BHAP14	30-40	AB	Hard, compact, sandy clay; mottled	2.5 Y 3/3 (dark olive brown)	Sandy clay loam
BHAP14	40-50	B	Hard, compact, sandy clay; mottled	2.5 Y 3/3 (dark olive brown)	Sandy clay loam
BHAP14	50-60	BC	Soft, loose, silty sand	2.5 Y 3/3 (dark olive brown)	Loamy sand
BHAP14	60-70	C1	Soft, loose, silty sand	2.5 Y 4/3 (olive brown)	Sandy clay loam
BHAP14	70-80	C2	Soft, loose, silty sand; like C1, but lighter with limestone inclusions	2.5 Y 4/3 (olive brown)	Sandy clay loam

Appendix IV. Field Descriptions of Each Soil Sample (continued)

Auger Probe Number	Depth (cm)	Horizon	Diagnostic horizons, properties, and materials	Munsell color	Soil texture
BHAP15	0-20	A	Hard, loose, sandy clay	2.5 Y 2.5/1 (black)	Sandy clay loam
BHAP15	20-30	AC	Soft, loose, sandy clay	2.5 Y 5/2 (grayish brown)	Sandy clay
BHAP15	30-50	C	Hard, loose, sandy silt; powdery with limestone inclusions	2.5 Y 6/3 (light yellowish brown)	Sandy loam
BHAP16	0-60	A	Hard, loose, sandy clay; mottled, carbonate inclusions	2.5 Y 2.5/1 (black)	Clay
BHAP16	60-80	B	Hard, compact, silty clay; mottled with A horizon	2.5 Y 5/2 (grayish brown)	Sandy clay loam
BHAP16	80-120	C	Hard, compact clay; mottled with carbon and carbonate inclusions, and iron oxide concretions	2.5 Y 7/4 (pale yellow)	Sandy clay loam
BHAP17	0-20	A	Soft, loose, silty sand; dark black	2.5 Y 2.5/1 (black)	Sandy loam
BHAP17	20-30	B	Hard, compact, sandy clay	2.5 Y 4/3 (olive brown)	Sandy clay loam
BHAP17	30-60	C1	Silt; beige; mottled with carbon and carbonate inclusions	2.5 Y 5/3 (light olive brown)	Sandy clay loam
BHAP17	60-90	C2	Silt; beige; mottled with carbon and carbonate inclusions	2.5 Y 5/3 (light olive brown)	Clay
BHAP17	90-120	C3	Sandy clay; mottled with carbon and carbonate inclusions, and iron oxide concretions	2.5 Y 5/3 (light olive brown)	Clay
BHAP17	120-170	C4	Sandy clay; mottled with carbon, carbonate inclusions, iron oxide concretions	2.5 Y 5/3 (light olive brown)	Clay
BHAP18	0-20	A1	Soft, loose, silty sand	2.5 Y 2.5/1 (black)	Sandy loam
BHAP18	20-40	A2	Soft, loose, silty sand; carbonate inclusions	2.5 Y 2.5/1 (black)	Sandy clay loam

Appendix IV. Field Descriptions of Each Soil Sample (continued)

Auger Probe Number	Depth (cm)	Horizon	Diagnostic horizons, properties, and materials	Munsell color	Soil texture
BHAP18	40-50	AB	Soft, loose, sandy silt	2.5 Y 3/2 (very dark grayish brown)	Sandy clay loam
BHAP18	50-90	B	Hard, loose, sandy clay	2.5 Y 3/3 (dark olive brown)	Sandy clay loam
BHAP18	90-100	BC	Hard, loose, sandy clay	2.5 Y 4/4 (olive brown)	Sandy loam
BHAP18	100-150	C	Soft, loose, sandy silt	2.5 Y 4/4 (olive brown)	Clay
BHAP19	0-20	A	Soft, loose, silty sand; organic, mottled anthrosol	2.5 Y 2.5/1 (black)	Sandy clay loam
BHAP19	20-25	B	Soft, loose, silty sand	2.5 Y 3/1 (very dark gray)	Sandy clay loam
BHAP19	25-45	C	Soft, loose, sandy silt; carbon, carbonate, and bedrock inclusions	2.5 Y 4/3 (olive brown)	Silt loam
BHAP20	0-20	A1	Soft, loose, silty sand; anthrosol	2.5 Y 2.5/1 (black)	Sandy loam
BHAP20	20-40	A2	Soft, loose, silty sand; anthrosol	2.5 Y 2.5/1 (black)	Loam
BHAP20	40-60	A3	Soft, loose, silty sand; anthrosol	2.5 Y 2.5/1 (black)	Clay loam
BHAP20	60-70	B	Hard, compact, sandy clay; upper/lower boundary transition abrupt; carbon and carbonate mottling	2.5 Y 3/2 (very dark grayish brown)	Sandy clay loam
BHAP20	70-120	C1	Hard, compact, sandy clay; mottled carbon and carbonate inclusions, and iron oxide concretions	2.5 Y 5/3 (light olive brown)	Clay loam
BHAP20	120-170	C2	Hard, compact, sandy clay; mottled carbon and carbonate inclusions, and iron oxide concretions	2.5 Y 5/3 (light olive brown)	Clay
BHAP20	170-230	C3	Hard, compact, sandy clay; mottled carbon/carbonate, and iron oxide concretions	2.5 Y 5/3 (light olive brown)	Sandy clay loam

Appendix V. Descriptive Statistics for Characteristics in Each Soil Profile

BHAP1

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	24875	351	1063	104	7	33	23	44	2	12
SD	970	33	409	19	0	7	4	11	1	4
COV	3.9%	9.4%	38.5%	18.2%	2.5%	21.6%	15.3%	23.7%	75.1%	32.4%
Min.	24057	323	719	84	7	27	20	33	1	9
Max.	25897	385	1494	120	8	40	27	53	3	16

BHAP2

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	27706	331	202	101	8	64	15	21	1	12
SD	2595	77	111	11	0	6	4	4	1	3
COV	9.4%	23.2%	55.3%	10.8%	4.1%	9.2%	30.0%	20.7%	67.0%	27.8%
Min.	24692	255	50	87	7	53	13	20	0	8
Max.	31209	469	382	122	8	67	27	33	3	15

BHAP3

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	25660	265	881	100	8	48	11	41	1	10
SD	1012	23	518	10	0	12	5	17	1	2
COV	3.9%	8.6%	58.8%	10.1%	100.0%	24.4%	46.0%	41.6%	80.7%	20.6%
Min.	23999	244	128	89	8	33	7	13	0	8
Max.	26958	305	1859	116	8	67	20	60	3	14

BHAP4

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	27846	229	414	98	8	31	21	47	0	8
SD	814	30	199	14	0	9	3	12	0	0
COV	2.9%	13.0%	48.2%	14.4%	0.2%	28.4%	13.7%	24.8%	36.5%	3.1%
Min.	27212	213	137	89	8	27	20	27	0	8
Max.	29081	281	701	122	8	47	27	53	0	8

BHAP5

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	29957	140	922	107	8	32	19	49	2	8
SD	1102	13	303	7	0	24	12	25	1	1
COV	3.7%	9.1%	32.8%	6.2%	0.7%	74.6%	64.4%	51.4%	38.8%	11.9%
Min.	28892	119	271	96	8	7	7	7	1	6
Max.	31601	155	1132	118	8	67	40	87	4	9

Appendix V. Descriptive Statistics for Characteristics in Each Soil Profile (continued)

BHAP6

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	23112	134	993	110	8	69	18	13	3	23
SD	7565	32	274	13	0	6	5	4	2	10
COV	32.7%	23.9%	27.6%	12.3%	2.2%	9.3%	27.9%	33.3%	74.0%	44.5%
Min.	15052	92	590	93	7	60	13	7	1	10
Max.	32230	172	1361	131	8	73	27	20	6	31

BHAP7

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	29038	121	785	97	8	38	14	48	1	13
SD	1376	28	686	11	0	12	6	16	2	0
COV	4.7%	23.0%	87.4%	11.1%	1.4%	31.6%	45.9%	33.4%	172.6%	3.4%
Min.	27212	99	138	84	8	13	7	33	0	12
Max.	31267	178	1918	108	8	47	20	73	4	14

BHAP8

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	15738	188	491	101	8	45	12	43	1	20
SD	4292	50	167	9	0	10	3	9	0	6
COV	27.3%	26.6%	34.1%	9.2%	1.0%	22.9%	26.6%	21.0%	48.2%	29.0%
Min.	9374	141	186	88	8	33	7	27	0	11
Max.	25535	256	665	119	8	67	20	53	1	29

BHAP9

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	28786	97	975	101	8	28	8	65	1	11
SD	1647	49	814	13	0	9	3	10	1	1
COV	5.7%	50.1%	83.5%	12.9%	1.8%	32.9%	32.3%	15.6%	97.3%	7.1%
Min.	26201	62	491	90	8	20	7	53	0	10
Max.	30691	198	2684	124	8	40	13	73	3	12

BHAP10

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	29532	141	267	108	8	42	12	46	1	13
SD	2800	56	220	11	0	27	3	29	1	1
COV	9.5%	39.7%	82.5%	10.5%	1.1%	62.4%	26.1%	62.3%	127.1%	9.3%
Min.	25921	106	115	99	8	13	7	13	0	12
Max.	33895	232	624	126	8	73	13	80	2	14

Appendix V. Descriptive Statistics for Characteristics in Each Soil Profile (continued)

BHAP11

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	CaCO 3 %
Mean	25170	116	615	91	8	67	12	22	7	13
SD	8795	59	366	12	0	4	7	5	8	4
COV	34.9%	50.4%	59.5%	12.8%	0.6%	6.3%	58.4%	24.0%	123.3%	27.4%
Min.	11611	59	134	76	8	60	7	13	1	10
Max.	33296	193	1045	106	8	73	20	27	22	20

BHAP12

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	CaCO 3 %
Mean	14688	132	198	89	8	50	19	30	6	30
SD	3193	23	93	15	0	11	7	6	7	10
COV	21.7%	17.7%	47.2%	16.5%	0.1%	22.1%	36.5%	19.4%	127.1%	33.8%
Min.	11370	110	109	78	8	40	13	20	1	17
Max.	17896	170	310	109	8	67	27	33	15	39

BHAP13

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	CaCO 3 %
Mean	13864	98	379	96	8	64	11	25	2	30
SD	5543	6	218	6	0	4	3	3	0	6
COV	40.0%	5.8%	57.5%	6.2%	1.3%	5.6%	28.5%	13.1%	11.9%	20.87$
Min.	7188	93	130	90	7	60	7	20	2	25
Max.	19353	105	601	102	8	67	13	27	2	39

BHAP14

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	CaCO 3 %
Mean	30434	95	580	105	8	68	14	18	3	17
SD	2496	35	187	29	0	9	2	7	2	5
COV	8.2%	36.9%	32.2%	27.8%	1.9%	12.6%	15.7%	40.8%	69.5%	28.2%
Min.	25990	50	288	70	8	53	13	7	0	8
Max.	33992	147	790	138	8	80	20	27	5	24

BHAP15

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	CaCO 3 %
Mean	18877	80	513	90	8	61	13	26	2	25
SD	10355	8	275	22	0	5	6	10	1	9
COV	54.9%	10.4%	53.7%	24.8%	0.6%	8.2%	49.4%	38.7%	35.3%	34.2%
Min.	8190	65	262	67	8	53	7	13	1	16
Max.	29484	88	800	111	8	67	20	33	2	34

Appendix V. Descriptive Statistics for Characteristics in Each Soil Profile (continued)

BHAP16

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	19382	173	550	93	8	35	22	43	1	18
SD	1975	47	117	17	0	23	5	18	0	4
COV	10.2%	27.0%	21.2%	18.6%	1.0%	66.6%	22.5%	42.5%	19.6%	25.1%
Min.	16807	116	381	71	8	13	13	20	0	14
Max.	21124	215	657	109	8	67	27	60	1	24

BHAP17

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	24041	229	593	103	8	30	18	52	5	6
SD	798	28	268	7	0	24	8	27	9	1
COV	3.3%	12.5%	45.1%	6.4%	1.1%	80.3%	47.1%	52.8%	183.3%	12.4%
Min.	22628	213	226	97	8	13	7	7	0	5
Max.	25587	297	959	122	8	67	27	80	24	7

BHAP18

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	21723	293	447	106	8	57	18	25	1	7
SD	804	32	177	21	0	13	3	11	1	2
COV	3.7%	10.8%	39.7%	20.1%	2.0%	22.5%	17.0%	42.6%	87.2%	32.7%
Min.	20816	261	209	88	8	40	13	13	0	5
Max.	23452	337	672	138	8	73	20	40	4	10

BHAP19

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	23970	319	472	126	8	50	31	19	2	11
SD	2468	68	137	15	0	14	25	10	1	2
COV	10.3%	21.4%	29.0%	11.9%	1.1%	29.0%	79.0%	55.3%	49.0%	15.0%
Min.	21767	226	318	109	8	33	7	7	1	9
Max.	26732	396	593	138	8	67	60	27	3	13

BHAP20

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C %	$CaCO_3$ %
Mean	21884	248	243	121	8	58	13	29	2	8
SD	1615	34	231	16	0	4	6	6	1	3
COV	7.4%	13.7%	95.2%	13.5%	1.7%	7.5%	48.7%	21.6%	56.6%	43.9%
Min.	19861	203	16	104	8	53	7	13	0	5
Max.	24251	324	684	138	8	67	20	33	5	16

Appendix VI. Soil Profile Analyses

VI.i. Auger Probe 12

Auger probe 12 was extracted from the crown of the hill slope on terrace three. Three horizons were identified: a shallow, dark grayish brown A horizon (from the ground surface to 10 cm below the surface), an olive brown AC horizon (from 10 to 20 cm below the surface), and a pale yellow C horizon (from 20 to 40 cm below the surface) (Figure VI.i.). No B horizon was present, and the three present horizons are very shallow, as is expected from the top of a slope where material is prone to erosion. The calcium carbonate percentage increases steadily down the profile while the organic carbon percentage decreases at approximately the same rate. The iron concentration is relatively low compared to concentrations in other profiles and decreases gradually as expected. The strontium concentration increases in the AC horizon then decreases slightly in the C horizon. The phosphate concentration decreases from the A to the AC and remains relatively constant in the C horizon. The manganese concentration is relatively low and decreases slightly down the soil profile. The pH level is nearly constant throughout the profile, though it decreases very slightly. Soil texture is not highly variable; the soil transitions from sandy clay loam in the A and AC horizons to clay loam in the C horizon. Given these patterns of mineral and particle distributions, auger probe 12 appears normal and does not show signs of anthropogenic disturbances. The horizons are shallow and mineral concentrations are low due to the erosion of sediment from the upper slope of the catena to the lower slopes.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.i.). Positive correlations are present between the iron and manganese concentrations, the manganese and phosphate concentrations, the

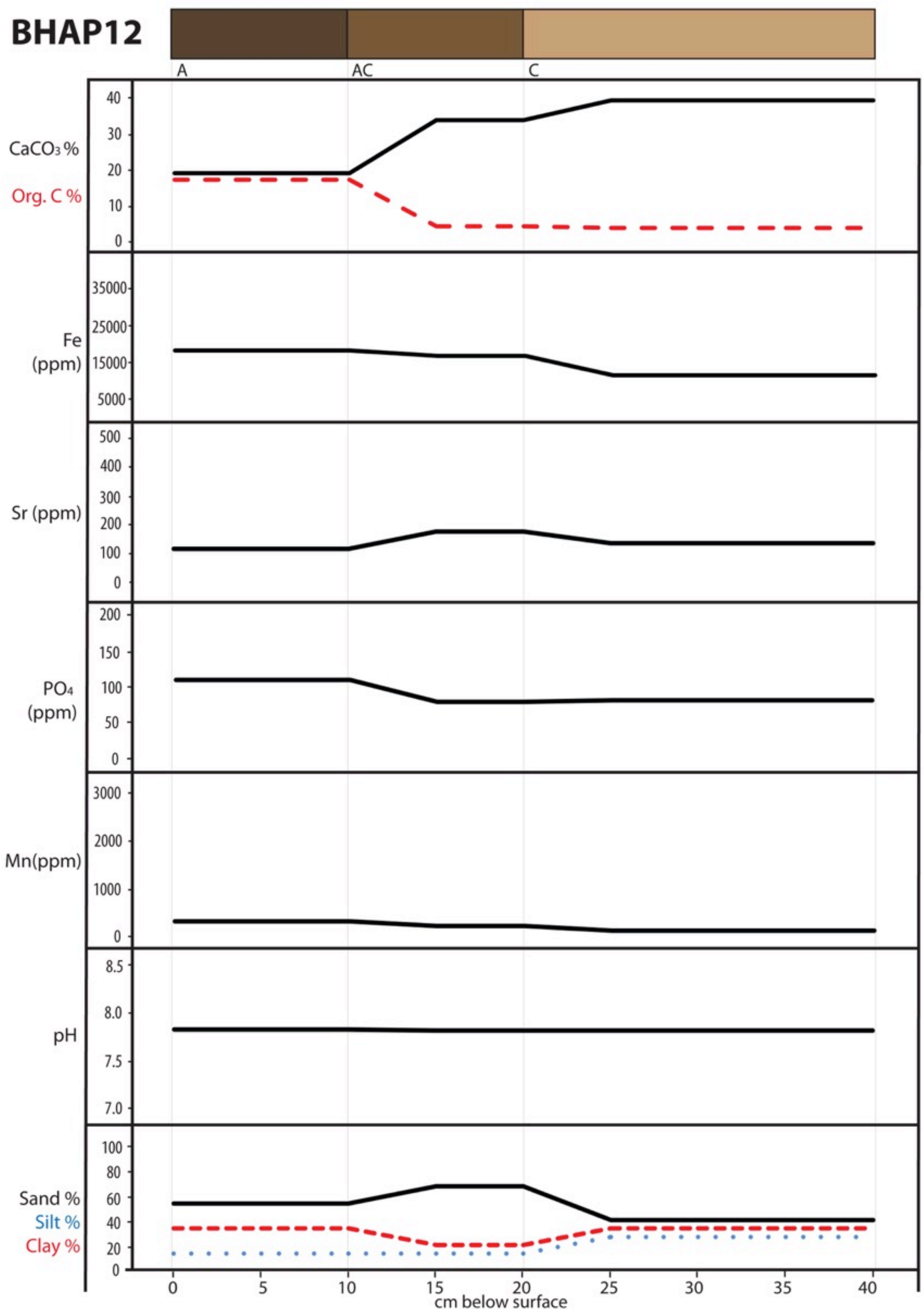


Figure VI.i. *BHAP12 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 12.*

Table VI.i. BHAP12 Correlations										
	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.049	1								
Mn (ppm)	.965**	-.309	1							
PO_4 (ppm)	.706*	-.742*	.867**	1						
pH	.753*	-.694*	.900**	.998**	1					
Sand %	.795*	.567	.608	.132	.200	1				
Silt %	-.986**	-.119	-.907**	-.577	-.632	-.885**	1			
Clay %	-.324	-.929**	-.064	.441	.378	-.832**	.478	1		
Organic Carbon %	.772*	-.673*	.912**	.995**	1.000**	.228	-.654	.351	1	
CaCO3 %	-.889**	.501	-.978**	-.952**	-.971**	-.428	.799**	-.146	-.977**	1

manganese concentration and the organic carbon percentage, the pH and the phosphate concentration, the pH and organic carbon percentage, and the calcium carbonate and silt percentages. Negative correlations are present between the iron concentration and the silt percentage, the iron concentration and the calcium carbonate percentage, the manganese concentration and the silt percentage, the manganese concentration and the calcium carbonate percentage, the pH and the calcium carbonate percentage, the sand and silt percentages, the sand and clay percentages, and the calcium carbonate and organic carbon percentages.

VI.ii. Auger Probe 11

Auger probe 11 was extracted near the top of the hill slopes on terrace three, south of auger probe 12. Five horizons were identified: a shallow black A horizon (from the ground surface to 10 cm below the surface), a dark olive brown AB horizon (from 10 to 20 cm below the surface), a dark olive brown B horizon (from 20 to 30 cm below the surface), a light olive brown C1 horizon (from 30 to 40 cm below the surface), and a light yellowish brown C2 horizon (from 30 to 40 cm below the surface) (Figure VI.ii). As with auger probe 12, the horizons in this profile are relatively thin due to soil erosion from the crown of the catena to lower slopes. The calcium carbonate percentage is variable; it decreases slightly from the A to the B, then increases in the C1 and decreases in the C2 horizon. The organic carbon percentage is constant across the A, AB, and B horizons, then increases in the C1 and C2 horizons. The dramatic increase in organic carbon in the C horizons is unexpected and may reflect erosion of organic material from the top horizons down the catena. The iron concentration is relatively constant in the A, AB, and B horizons, then decreases dramatically in the C1 and C3 horizons. The decrease is expected, but the sharp decline of the iron concentration may indicate mineral leaching. The strontium concentration increases gradually down the profile as expected. The phosphate concentration decreases slightly in the AB horizon, then gradually increases throughout the rest of the profile. The manganese concentration is variable; it decreases in the AB, then increases in the B and the C1 and decreases again in the C2 horizon. The pH value is relatively constant across all horizons with a slight increase in the C2 horizon. The soil texture is not highly variable; soil texture transitions from sandy loam in the A, AB, and B horizons to sandy clay loam in the C1 and C2 horizons. This profile is very similar to the profile from auger probe 12, but the increase of organic carbon and the dramatic decrease of iron in the C1 and C2 horizons represent deviations from a normal soil profile.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.ii). Positive correlations are present between the iron concentration and the sand percentage, the strontium concentration and the organic carbon percentage, the manganese concentration and the calcium carbonate percentage, and the

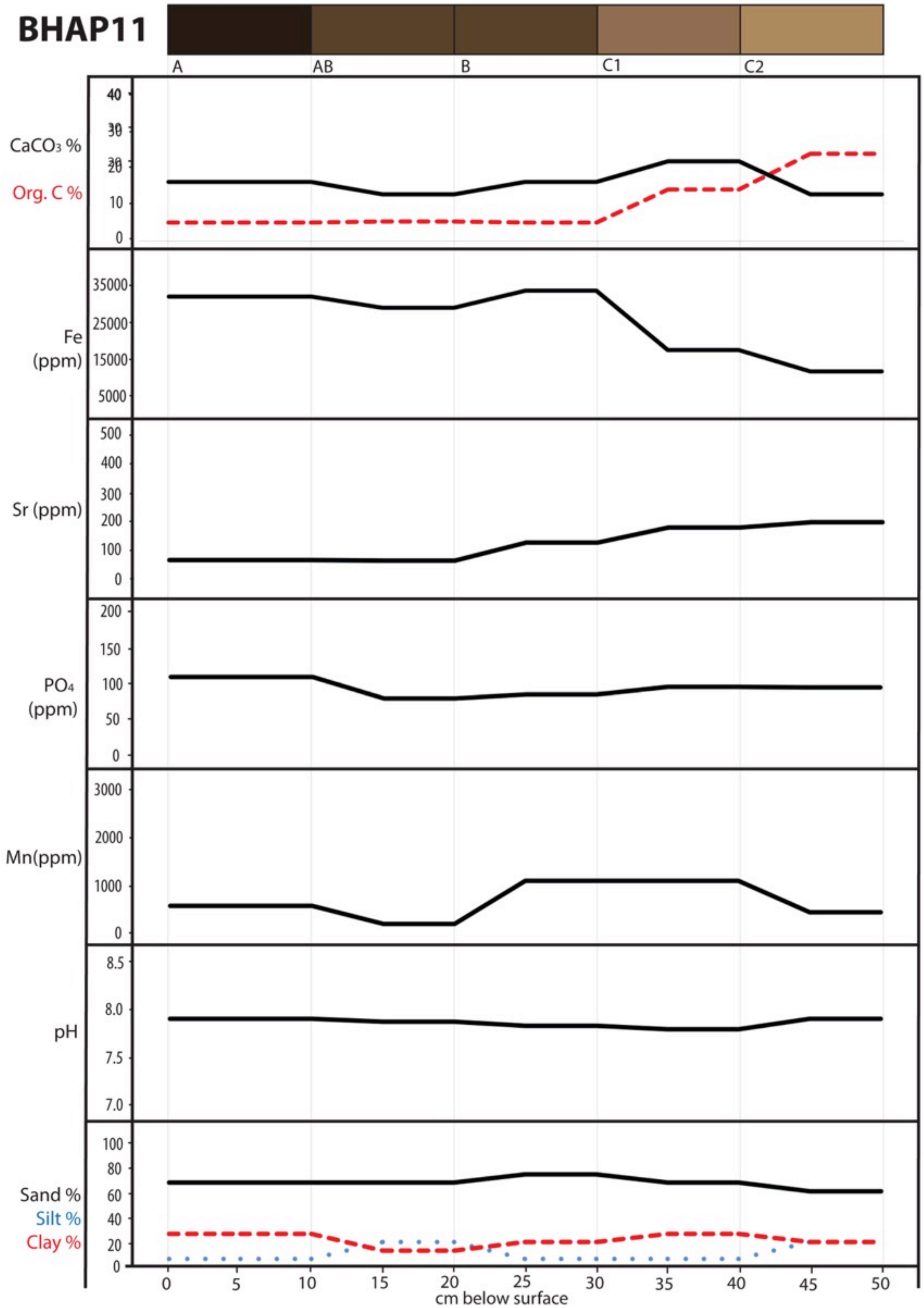


Figure VI.ii. *BHAP11 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 11.*

Table VI.ii. BHAP11 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.851**	1								
Mn (ppm)	.033	.430	1							
PO_4 (ppm)	.023	-.110	.062	1						
pH	.096	-.390	-.775**	.389	1					
Sand %	.780**	-.385	.568	-.260	-.498	1				
Silt %	-.454	.130	-.767**	-.507	.413	-.627*	1			
Clay %	-.044	.143	.528	.860**	-.130	.000	-.779**	1		
Organic Carbon %	-.966**	.871**	-.038	.026	.046	-.780**	.460	.037	1	
CaCO3 %	-.058	.265	.799**	.283	-.769**	.334	-.766**	.715*	-.076	1

phosphate concentration and the clay percentage. Negative correlations are present between the iron and strontium concentrations, the iron concentration and the organic carbon percentage, the manganese concentration and the pH, the manganese concentration and the silt percentage, the calcium carbonate percentage and the pH, the organic carbon and sand percentages, the silt and clay percentages, and the calcium carbonate and silt percentages.

VI.iii. Auger Probe 10

Auger probe 10 was extracted on the hill slope on terrace two. Four horizons were identified: a black A horizon (from the ground surface to 20 cm below the surface), a grayish brown AB horizon (from 20 to 30 cm below the surface), a thick grayish brown B horizon (from 30 to 70 cm below the surface), and an olive brown C horizon (from 70 to 90 cm below the surface) (Figure VI.iii). The calcium carbonate percentage increases slightly down the profile as expected, then declines slightly in the C horizon. The percentage of organic carbon is very low and follows the expected pattern of decrease down the profile. The iron concentration decreases

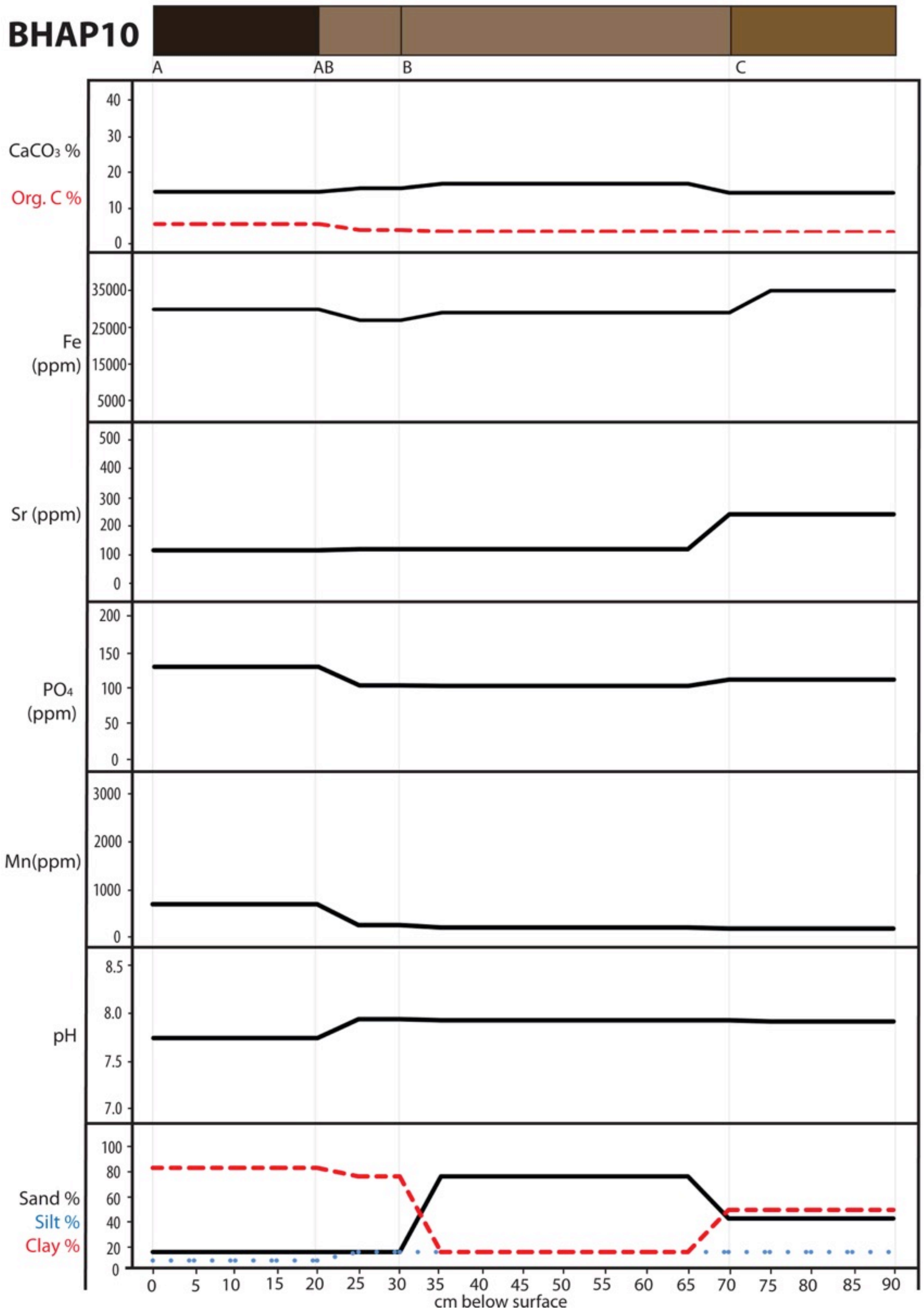


Figure VI.iii*. BHAP10 soil profile****.*** *Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 10.*

slightly in the AB horizon then increases in the C horizon, but remains relatively high and constant throughout the profile. The strontium concentration is constant through the A, AB, and B horizons, then increases in the C horizon as expected. The phosphate concentration decreases from the A to the B horizon, following the pattern, then increases very slightly in the C horizon. The manganese concentration decreases in the AB horizon and remains relatively low and constant throughout the remainder of the profile. The pH increases slightly in the AB horizon and then remains constant. The soil texture is variable; the A and AB horizons are clay, then the B horizon is sandy loam, and the C horizon is clay. The changes in mineral and other values throughout this profile are not dramatic or unexpected; the only drastic change is the increase in sand in the B horizon.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.iii). Positive correlations are present between the iron and strontium concentrations, the manganese and phosphate concentrations, the manganese concentration and the clay percentage, the manganese concentration and calcium carbonate percentage, the phosphate concentration and the clay percentage, the phosphate concentration and the organic carbon percentage, the pH and the sand percentage, the pH and the silt percentage, the sand and silt percentages, the sand and calcium carbonate percentages, and the clay and organic carbon percentages. Negative correlations are present between the iron concentration and calcium carbonate percentage, the strontium concentration and calcium carbonate percentage, the manganese concentration and the pH, the manganese concentration and the sand percentage, the manganese concentration and the silt percentage, the phosphate concentration and the pH, the phosphate concentration and the sand percentage, the phosphate

Table VI.iii. BHAP10 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	.950**	1								
Mn (ppm)	-.241	-.455	1							
PO_4 (ppm)	.167	-.062	.916**	1						
pH	.092	.332	-.987**	-.961**	1					
Sand %	-.058	-.032	-.687**	-.751**	.669**	1				
Silt %	.158	.389	-.995**	-.944**	.998**	.675**	1			
Clay %	.037	-.012	.741**	.795**	-.725**	-.997**	-.730**	1		
Organic Carbon %	-.321	-.512*	.994**	.880**	-.964**	-.707**	-.980**	.758**	1	
CaCO3 %	-.665**	-.599**	-.395	-.695**	.478*	.783**	.439	-.771**	-.357	1

concentration and the silt percentage, the phosphate concentration and the calcium carbonate percentage, the pH and the clay percentage, the sand and clay percentages, the sand and organic carbon percentages, the silt and clay percentages, the silt and organic carbon percentages, and the clay and calcium carbonate percentages.

VI.iv. Auger Probe 9

Auger probe 9 was extracted from a fallow field on the hill slopes of terrace two. Five horizons were identified: a black A horizon (from the ground surface to 20 cm below the surface), a black AB horizon (from 20 to 30 cm below the surface), a grayish brown B1 horizon (from 30 to 60 cm below the surface), a grayish brown B2 horizon (from 60 to 90 cm below the surface), and an olive brown C horizon (from 90 to 100 cm below the surface) (Figure VI.iv). The calcium carbonate percentage decreases slightly down the profile and increases again in the C horizon as expected, while the percentage of organic carbon declines gradually down the profile. The iron concentration is relatively high and constant but decreases slightly down the

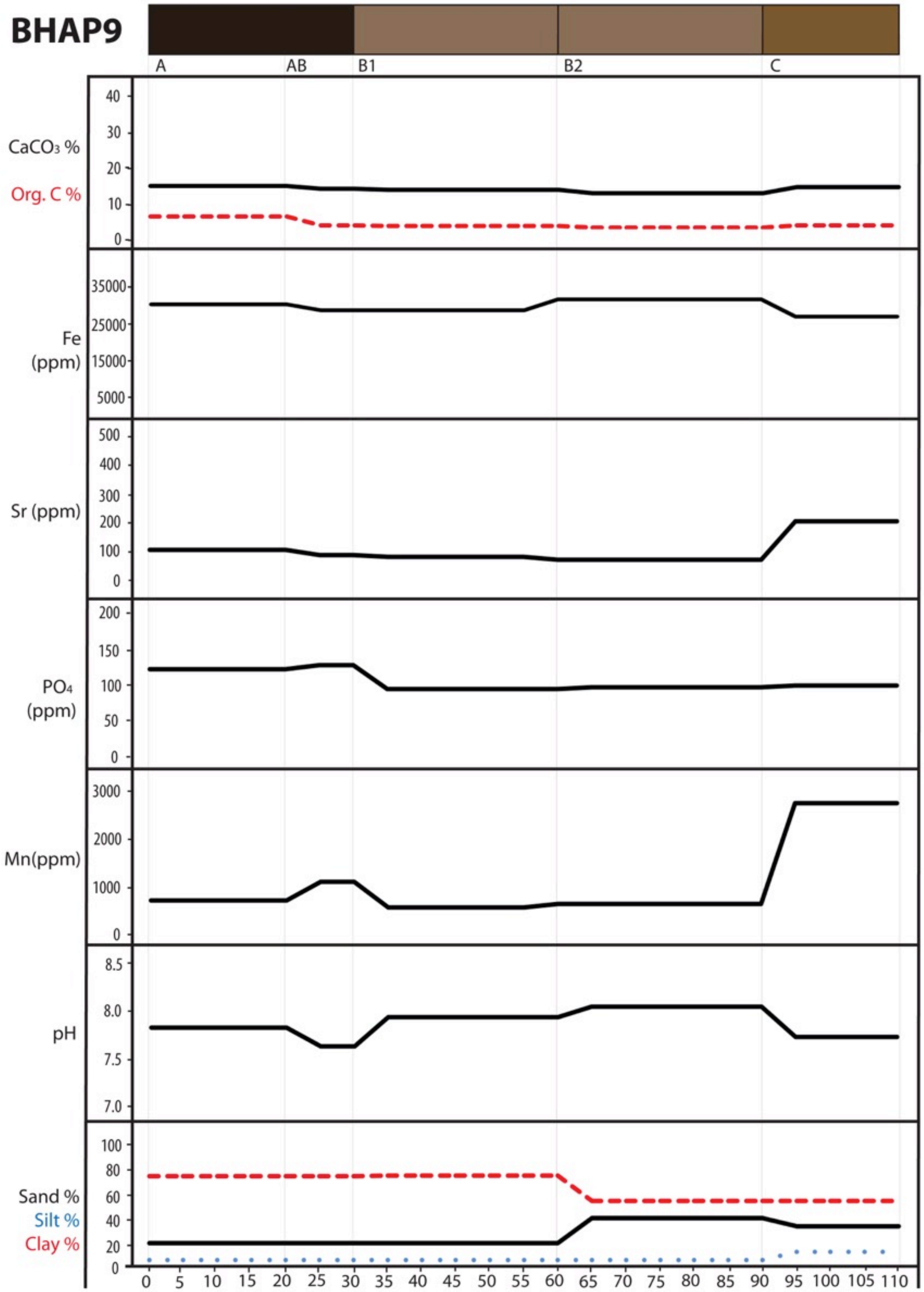


Figure VI.iv. *BHAP9 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 9.*

profile as expected. The strontium concentration decreases slightly down the soil profile, then increases in the C horizon. The phosphate concentration decreases in the B1 horizon and remains constant throughout the rest of the profile. The manganese concentration is constant in the A, B1, and B2 horizons, but is slightly elevated in the AB horizon and dramatically elevated in the C horizon. These anomalies in the expected pattern of decrease in the manganese concentration are mirrored by the pH levels, which are relatively consistent in the A, B1, and B2 horizons but decrease in the AB and C horizons. The soil texture is relatively constant throughout the profile; all horizons are clay. The location of this auger probe is a similar to auger probe 16; both were removed from fallow fields with thick and stable B horizons. This probe appears relatively normal except for the increase in manganese and decrease in pH in the AB and C horizons.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table **VI.iv**). Positive correlations are present between the iron concentration and the pH, the strontium and manganese concentrations, the strontium concentration and the silt percentage, the phosphate concentration and the organic carbon percentage, the phosphate concentration and the calcium carbonate percentage, the clay and organic carbon percentages, and the organic carbon and calcium carbonate percentages. Negative correlations are present between the iron and strontium concentrations, the iron and manganese concentrations, the iron concentration and the silt percentage, the iron concentration and the calcium carbonate percentage, the strontium concentration and the pH, the manganese concentration and the pH, the phosphate concentration and the pH, the pH and the silt percentage, the pH and the calcium carbonate percentage, the sand and clay percentages, the organic carbon and the sand percentages, and the calcium carbonate and sand percentages.

Table VI.iv. BHAP9 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.773**	1								
Mn (ppm)	-.749**	.963**	1							
PO_4 (ppm)	.022	.022	-.056	1						
pH	.717**	-.645**	-.627**	-.616**	1					
Sand %	.277	.120	.261	-.468*	.441*	1				
Silt %	-.734**	.977**	.984**	-.153	-.529**	.279	1			
Clay %	-.061	-.355	-.486*	.456*	-.257	-.970**	-.504*	1		
Organic Carbon %	.018	.126	-.097	.759**	-.381	-.570**	-.075	.534**	1	
CaCO3 %	-.585**	.569**	.395	.598**	-.792**	-.683**	.391	.516*	.769**	1

VI.v. Auger Probe 8

Auger probe 8 was extracted from an active farm field on terrace two. Nine horizons were identified: a very dark grayish brown A horizon (from the ground surface to 10 cm below the surface), a light olive brown B1 horizon (from 10 to 20 cm below the surface), a light olive brown B2 horizon (from 20 to 30 cm below the surface), a light yellowish brown C1 horizon (from 30 to 60 cm below the surface), a light yellowish brown C2 horizon (from 60 to 70 cm below the surface), a light olive brown C3 horizon (from 70 to 90 cm below the surface), a light yellowish brown C4 horizon (from 90 to 120 cm below the surface), a light brownish gray C5 horizon (from 120 to 150 cm below the surface), and a grayish brown C6 horizon (from 150 to 170 cm below the surface) (Figure VI.v). The probe was removed from a field that has been subjected to continuous cultivation, thus soil profile is highly variable. The calcium carbonate percentage increases steadily from the A1 horizon to the C1 horizon, then decreases to the C3 horizon, increases in the C4 and C5 horizons, and decreases in the C6 horizon. The phosphate,

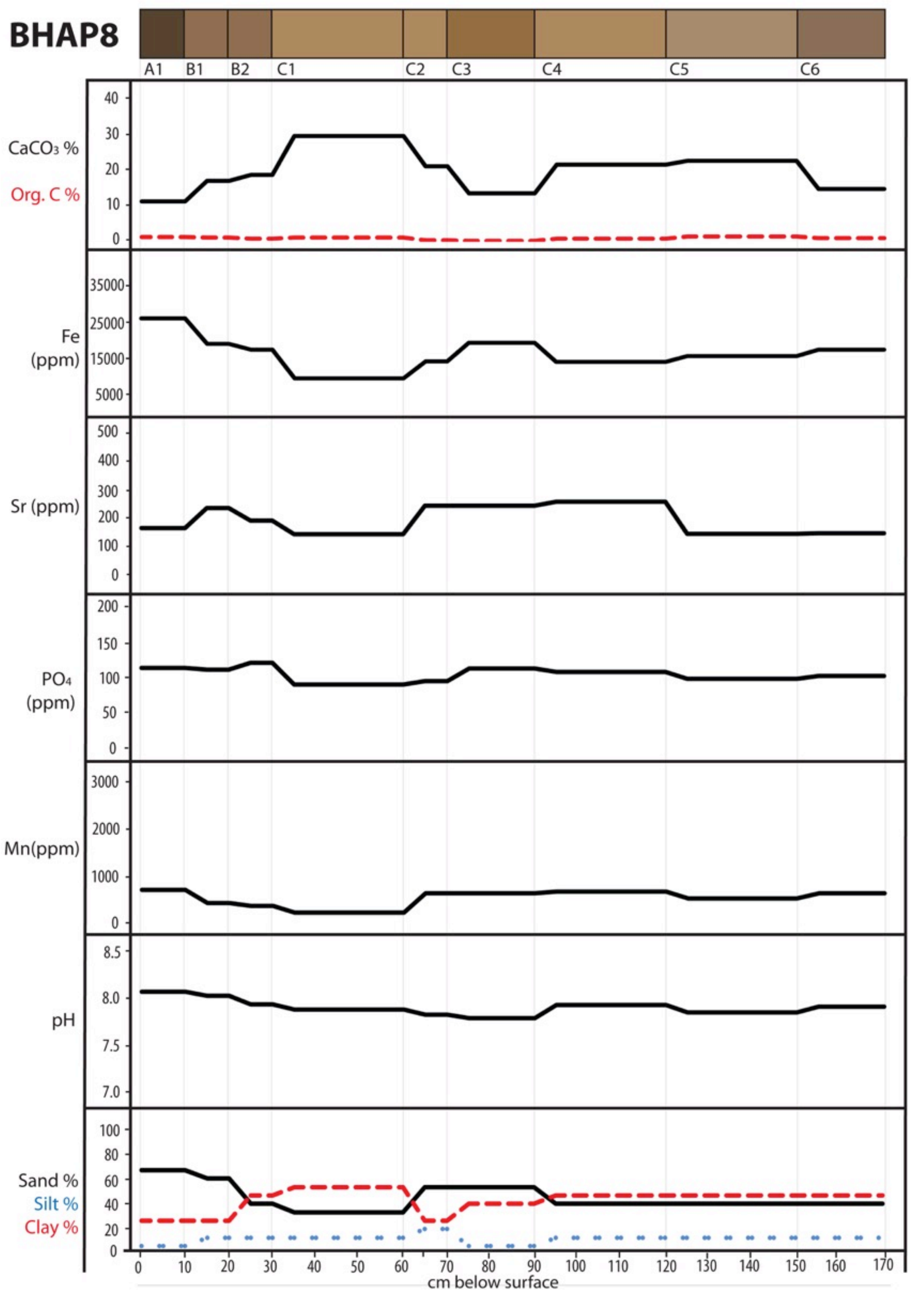


Figure VI.v. *BHAP8 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 8.*

manganese, and iron levels progressively drop from the A to the B1, B2, and C horizons, then increase in the C2 and C3 horizons, then decrease again in the C4 horizon and increase slightly in the C5 and C6 horizons. The strontium concentration increases from the A to the B1 horizon, then drops from the B1 to the C1 horizon, then increase across the C2 to the C4 horizon, then decreases in the C5 and C6 horizons. The pH levels fluctuate in tandem with the iron and strontium concentrations, decreasing steadily from the A to the C3 horizon, then increasing in the C4 horizon, decreasing in the C5, and increasing in the C6 horizon. Soil texture is also highly variable: the A and B1 horizons are sandy clay loam, the B2 and C1 horizons are clay, the C2 horizon is sandy clay loam, the C3 horizon is sandy clay, and the C4 through C6 horizons are clay. This soil profile displays a high level of disturbance to the expected mineral and particle patterns due to the continuous cultivation at this auger probe site. While all soil properties are highly variable, the fluctuations in iron, pH, calcium carbonate, and soil texture appear to vary in tandem with each other.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.v). Positive correlations are present between the iron and manganese concentrations, the iron and phosphate concentrations, the iron concentration and the pH, the iron concentration and the sand percentage, the strontium and manganese concentrations, the strontium and phosphate concentrations, the manganese and phosphate concentrations, the manganese concentration and the sand percentage, the phosphate concentration and the sand percentage, the pH and the organic carbon percentage, the calcium carbonate and silt percentages, and the calcium carbonate and clay percentages. Negative correlations are present between the iron concentration and the silt percentage, the iron concentration and the clay percentage, the iron concentration and the calcium carbonate

Table VI.v. BHAP8 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	.122	1								
Mn (ppm)	.643**	.488**	1							
PO_4 (ppm)	.755**	.524**	.543**	1						
pH	.468**	-.021	.126	.395*	1					
Sand %	.855**	.337*	.529**	.592**	.429*	1				
Silt %	-.632**	-.032	-.262	-.540**	-.153	-.490**	1			
Clay %	-.734**	-.368*	-.501**	-.471**	-.427*	-.948**	.188	1		
Organic Carbon %	-.079	-.674**	-.332	-.329	.471**	-.222	.155	.193	1	
CaCO3 %	-.925**	-.279	-.746**	-.782**	-.298	-.765**	.563**	.657**	.359*	1

percentage, the strontium concentration and the organic carbon percentage, the manganese concentration and the clay percentage, the manganese concentration and the calcium carbonate percentage, the phosphate concentration and the silt percentage, the phosphate concentration and the clay percentage, the phosphate concentration and the calcium carbonate percentage, the sand and silt percentages, the sand and clay percentages, and the calcium carbonate and sand percentages.

VI.vi. Auger Probe 15

Auger probe 15 was extracted near the drainage below the active field on terrace one. Three horizons were identified: a black A horizon (from the ground surface to 20 cm below the surface), a grayish brown AC horizon (from 20 to 30 cm below the surface), and a light yellowish brown C horizon (from 30 to 50 cm below the surface) (Figure VI.vi). No B horizon was present. The percentage of organic carbon slightly decreases down the profile while the percentage of calcium carbonate increases steadily. The iron concentration decreases

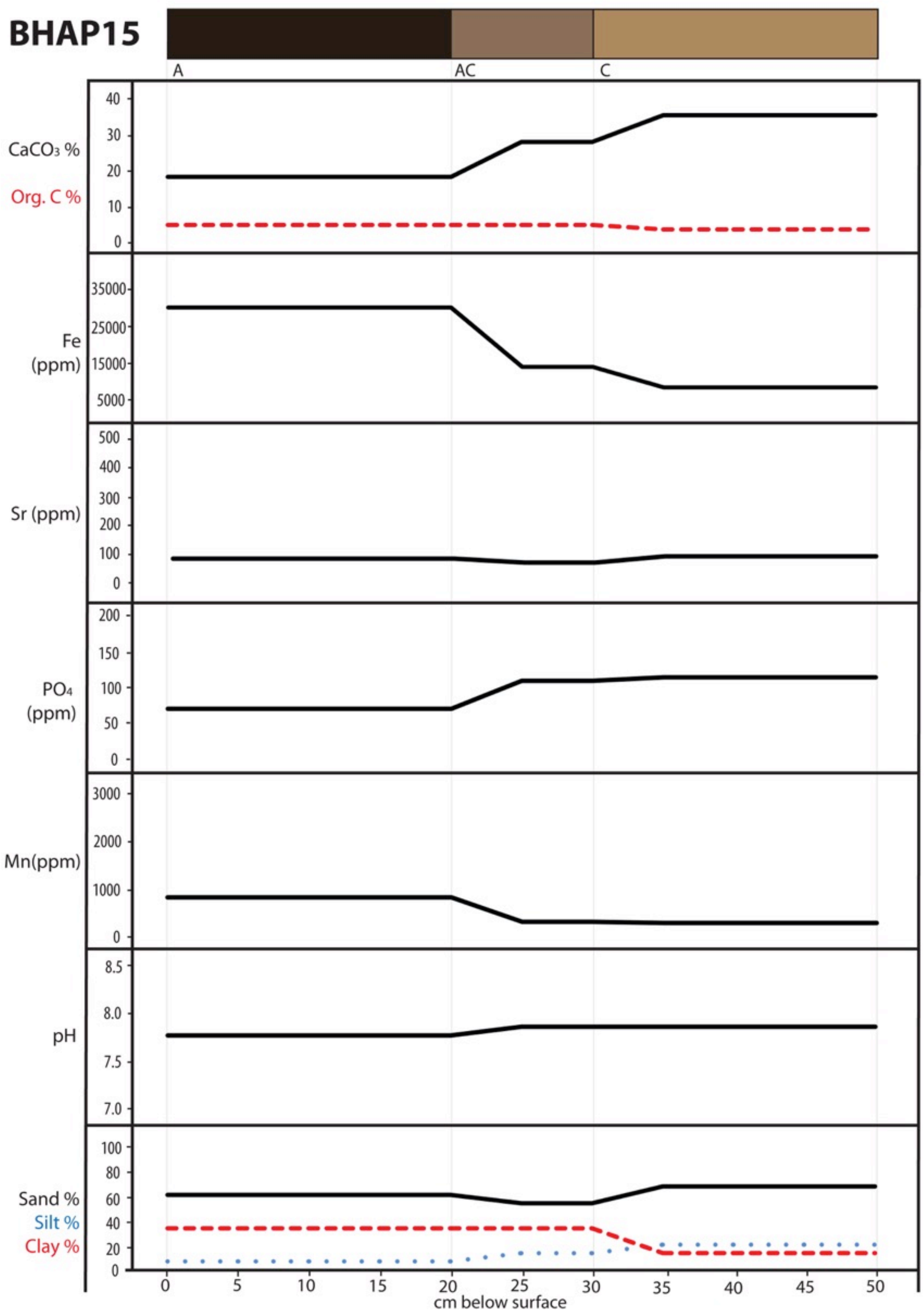


Figure VI.vi. *BHAP15 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 15.*

significantly but steadily down the profile. The change in iron concentration appears to be the inverse of the calcium carbonate percentage. The strontium concentration is consistent in the A and the C horizons, but decreases slightly in the AC horizon. The phosphate concentration increases down the profile as expected. The manganese concentration progressively decreases in the AC and the C horizons. As expected, the pH values increase very slightly down the profile. The soil texture is not highly variable, transitioning from sandy clay loam in the A horizon to sandy clay in the AC horizon to sandy loam in the C horizon. This soil profile appears normal and there are no major disturbances or unexpected values present in the profile.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.vi). Positive correlations are present between the iron and manganese concentrations, the iron concentration and the clay percentage, the iron concentration and the organic carbon percentage, the strontium concentration and the sand percentage, the phosphate concentration and the pH, the phosphate concentration and the silt percentage, the phosphate concentration and the calcium carbonate percentage, the pH and the silt percentage, the pH and the calcium carbonate percentage, the silt and calcium carbonate percentages, and the clay and organic carbon percentages. Negative correlations are present between the iron and phosphate concentrations, the iron concentration and the pH, the iron concentration and the silt percentage, the iron concentration and the calcium carbonate percentage, the strontium concentration and the clay percentage, the strontium concentration and the organic carbon percentage, the manganese and phosphate concentrations, the manganese concentration and the pH, the manganese concentration and the silt percentage, the manganese concentration and the calcium carbonate percentage, the phosphate concentration and the clay

Table VI.vi. BHAP15 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.247	1								
Mn (ppm)	.988**	-.097	1							
PO_4 (ppm)	-.993**	.135	-.999**	1						
pH	-.981**	.053	-.999**	.997**	1					
Sand %	-.418	.984**	-.275	.311	.232	1				
Silt %	-.980**	.435	-.938**	.951**	.922**	.590	1			
Clay %	.818**	-.759**	.722*	-.747**	-.690*	-.864**	-.916**	1		
Organic Carbon %	.791**	-.788**	.689*	-.716*	-.657*	-.886**	-.897**	.999**	1	
CaCO3 %	-.990**	.382	-.957**	.967**	.943**	.542	.998**	-.892**	-.870**	1

percentage, the sand and clay percentages, the sand and organic carbon percentages, the silt and clay percentages, the silt and organic carbon percentages, the clay and calcium carbonate percentages, and the organic carbon and calcium carbonate percentages.

VI.vii. Auger Probe 14

Auger probe 14 was extracted from the modern village on terrace one. Six horizons were identified: a black A horizon (from the ground surface to 30 cm below the surface), a dark olive brown AB horizon (from 30 to 40 cm below the surface), a dark olive brown B horizon (from 40 to 50 cm below the surface), a dark olive brown BC horizon (from 50 to 60 cm below the surface), an olive brown C1 horizon (from 60 to 70 cm below the surface), and an olive brown C2 horizon (from 70 to 80 cm below the surface) (Figure VI.vii). As expected, the organic carbon percentage decreases down the profile and the calcium carbonate percentage increases, though with a slight decrease in the B horizon. As expected, the organic carbon percentage decreases down the profile and the calcium carbonate percentage increases, though with a slight

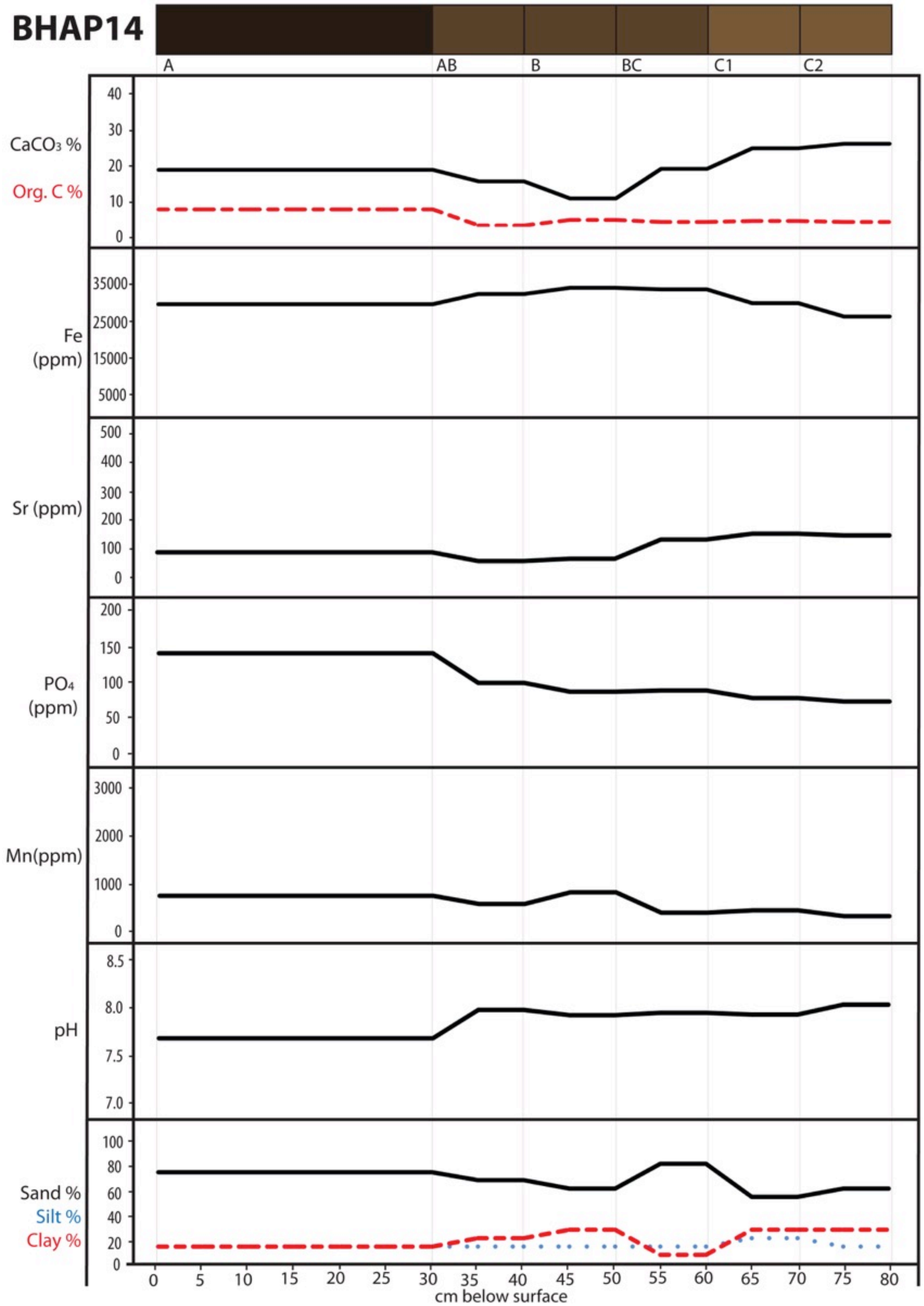


Figure VI.vii. *BHAP14 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 14.*

decrease in the B horizon. The iron concentration increases slightly in the B horizon and decreases from the BC to the C2 horizons. The strontium concentration decreases slightly in the AB horizon then gradually increases down the rest of the profile as expected. The phosphate and manganese concentrations decrease gradually down the profile. The pH also gradually increases down the profile, following the expected pattern. Soil texture is not highly variable, transitioning from sandy loam in the A horizon to sandy clay loam in the AB and B horizons to loamy sand in the BC horizon to sandy clay loam in the C1 and C2 horizons. Although this auger probe was located in a modern settlement, the soil profile appears relatively normal. The thickness of the A horizons and the high phosphate concentration in this horizon are indicators of human activity, but the rest of the profile appears normal.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.vii). Positive correlations are present between the strontium concentration and the calcium carbonate percentage, the manganese and phosphate concentrations, the manganese concentration and the organic carbon percentage, the phosphate concentration and the sand percentage, and the phosphate concentration and the organic carbon percentage. Negative correlations are present between the iron concentration and calcium carbonate percentage, the strontium and manganese concentrations, the manganese concentration and the pH, the manganese concentration and the calcium carbonate percentage, the phosphate concentration and the pH, the phosphate concentration and the clay percentage, the pH and the organic carbon percentage, the sand and silt percentages, and the sand and clay percentages.

Table VI.vii. BHAP14 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.442	1								
Mn (ppm)	.240	-.803**	1							
PO_4 (ppm)	-.162	-.513*	.732**	1						
pH	.192	.374	-.747**	-.959**	1					
Sand %	.189	-.276	.252	.643**	-.530*	1				
Silt %	-.097	.563*	-.338	-.392	.216	-.637**	1			
Clay %	-.190	.152	-.192	-.631**	.552*	-.973**	.441	1		
Organic Carbon %	-.330	-.262	.686**	.912**	-.975**	.488*	-.252	-.492*	1	
CaCO3 %	-.782**	.861**	-.701**	-.223	.154	-.239	.478	.134	-.051	1

VI.viii. Auger Probe 13

Auger probe 13 was extracted from an unoccupied field near the modern village of Pares on terrace two. Three horizons were identified: a very dark grayish brown A horizon (from the ground surface to 10 cm below the surface), a dark grayish brown AC horizon (from 10 to 20 cm below the surface), and a light yellowish brown C horizon (from 20 to 30 cm below the surface) (Figure VI.viii). No B horizon was present. The organic carbon percentage is low and constant down the profile while the calcium carbonate percentage gradually increases; both these trends follow the expected pattern. The iron concentration steadily decreases down the profile. The strontium concentration is relatively low and constant. The phosphate concentration increases very slightly. The manganese concentration, like the iron concentration, decreases steadily down the profile as expected. The pH value increases down the profile, following the expected pattern. The soil texture is consistently sandy clay loam across all three horizons. The soil profile from auger probe 13 is very similar to auger probe 14 and displays no unexpected patterns or indications of disturbance.

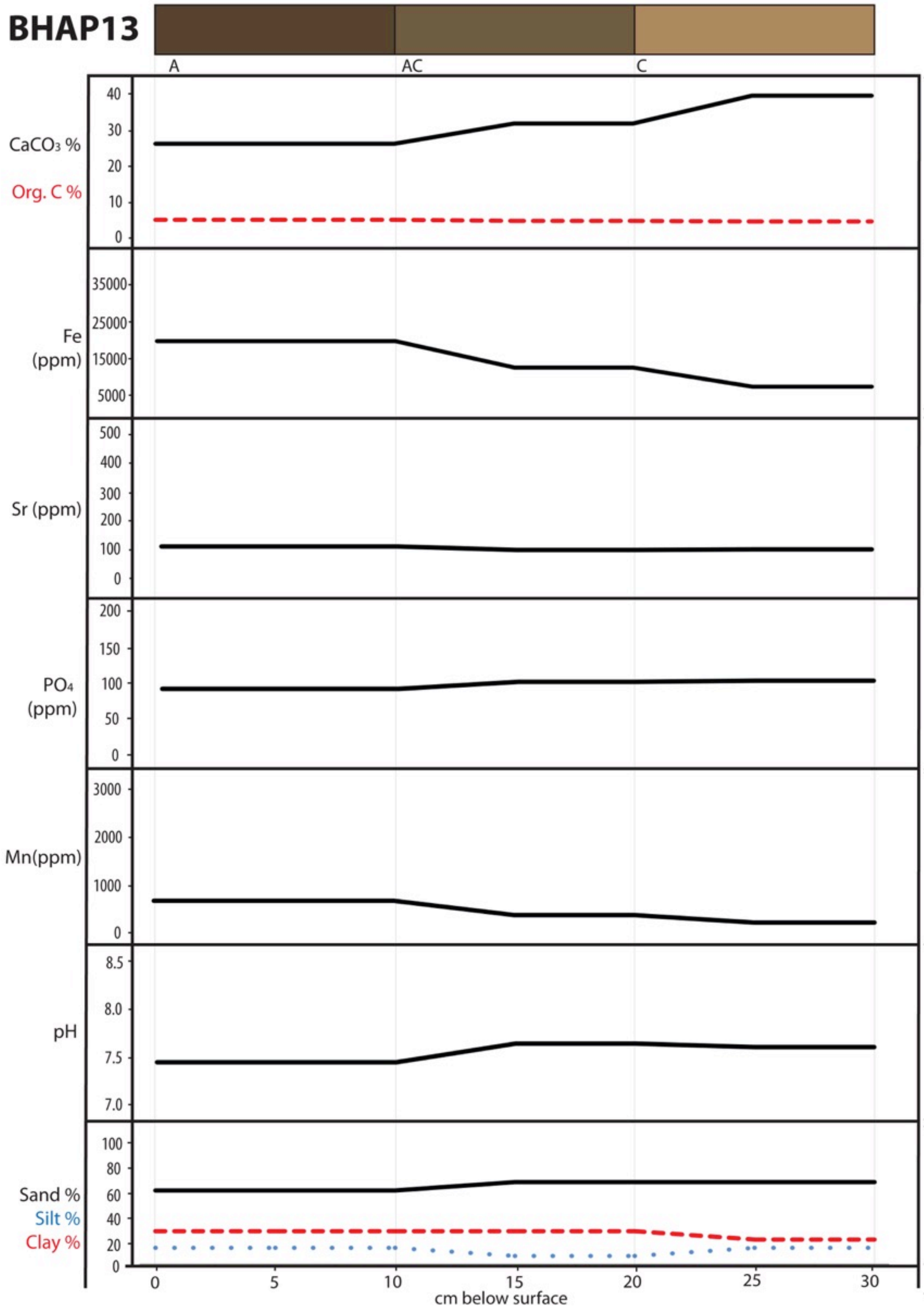


Figure VI.viii. *BHAP13 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 13.*

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.viii). Positive correlations are present between the iron and strontium concentrations, the iron and manganese concentrations, the iron concentration and the organic carbon the percentage, the strontium and manganese concentrations, the manganese concentration and the organic carbon percentage, the phosphate concentration and the pH, the phosphate concentration and the sand percentage, the phosphate concentration and the calcium carbonate percentage, the pH and the sand percentage, and the organic carbon and clay percentages. Negative correlations are present between the iron and phosphate concentrations, the iron concentration and the sand percentage, the iron concentration and the calcium carbonate percentage, the strontium and phosphate concentrations, the strontium concentration and the pH, the strontium concentration and the sand percentage, the manganese and phosphate concentrations, the manganese concentration and the pH, the manganese concentration and the sand percentage, the manganese concentration and the calcium carbonate percentage, the phosphate concentration and the organic carbon percentage, the calcium carbonate and clay percentages, and the organic carbon and calcium carbonate percentages.

Table VI.viii. BHAP13 Correlations

	Fe (ppm)	**Sr (ppm)**	**Mn (ppm)**	**PO_4 (ppm)**	**pH**	**Sand %**	**Silt %**	**Clay %**	**Org. C. %**	**CaCO3 %**
Fe (ppm)	1									
Sr (ppm)	.894**	1								
Mn (ppm)	.998**	.922**	1							
PO_4 (ppm)	-.969**	-.977**	-.984**	1						
pH	-.850*	-.996**	-.884**	.954**	1					
Sand %	-.926**	-.997**	-.950**	.990**	.986**	1				
Silt %	.192	.611	.258	-.427	-.680	-.548	1			
Clay %	.823*	.481	.782*	-.658	-.400	-.548	-.400	1		
Organic Carbon %	.993**	.833*	.982**	-.932**	-.780*	-.874*	.072	.885**	1	
CaCO3 %	-.985**	-.805*	-.972**	.913**	.748	.849*	-.022	-.907**	-.999**	1

VI.ix. Auger Probe 7

Auger probe 7 was extracted from a field on terrace two. Five horizons were identified: a black A1 horizon (from the ground surface to 10 cm below the surface), a black A2 horizon (from 10 to 20 cm below the surface), a grayish brown B1 horizon (from 20 to 30 cm below the surface), a grayish brown B2 horizon (from 30 to 60 cm below the surface), and a grayish brown C horizon (from 60 to 120 cm below the surface) (Figure VI.ix). The organic carbon percentage decreases down the profile while the calcium carbonate percentage remains relatively constant throughout the profile. The iron concentration is relatively high and constant throughout the profile, but displays a slight decline in the B2 horizon. The strontium concentration decreases steadily down the profile as expected. The phosphate concentration increases in the B1 horizon, decreases in the B2, and increases in the C horizon, but is relatively constant across the entire profile. The manganese concentration increases from the A1 to the B1 horizons, then steadily decreases through the C horizon. The pH value is variable from the A1 through the B1 horizon, and then increases in the B2 and C horizons. The soil texture is slightly more variable than other profiles, but the A through B2 horizons are clay and the C horizon is sandy clay. The decline of major elements down the profile indicates that erosion has occurred. The variable manganese and pH levels in the A1, A2, B1, and B2 horizons suggests some recent disturbance to the upper soil horizons, but the C horizon is thick and stable, suggesting that it has been impervious to erosional events or that disturbances to the profile have been more recent.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.ix). Positive correlations are present between the iron and strontium concentrations, the iron concentration and the organic carbon percentage,

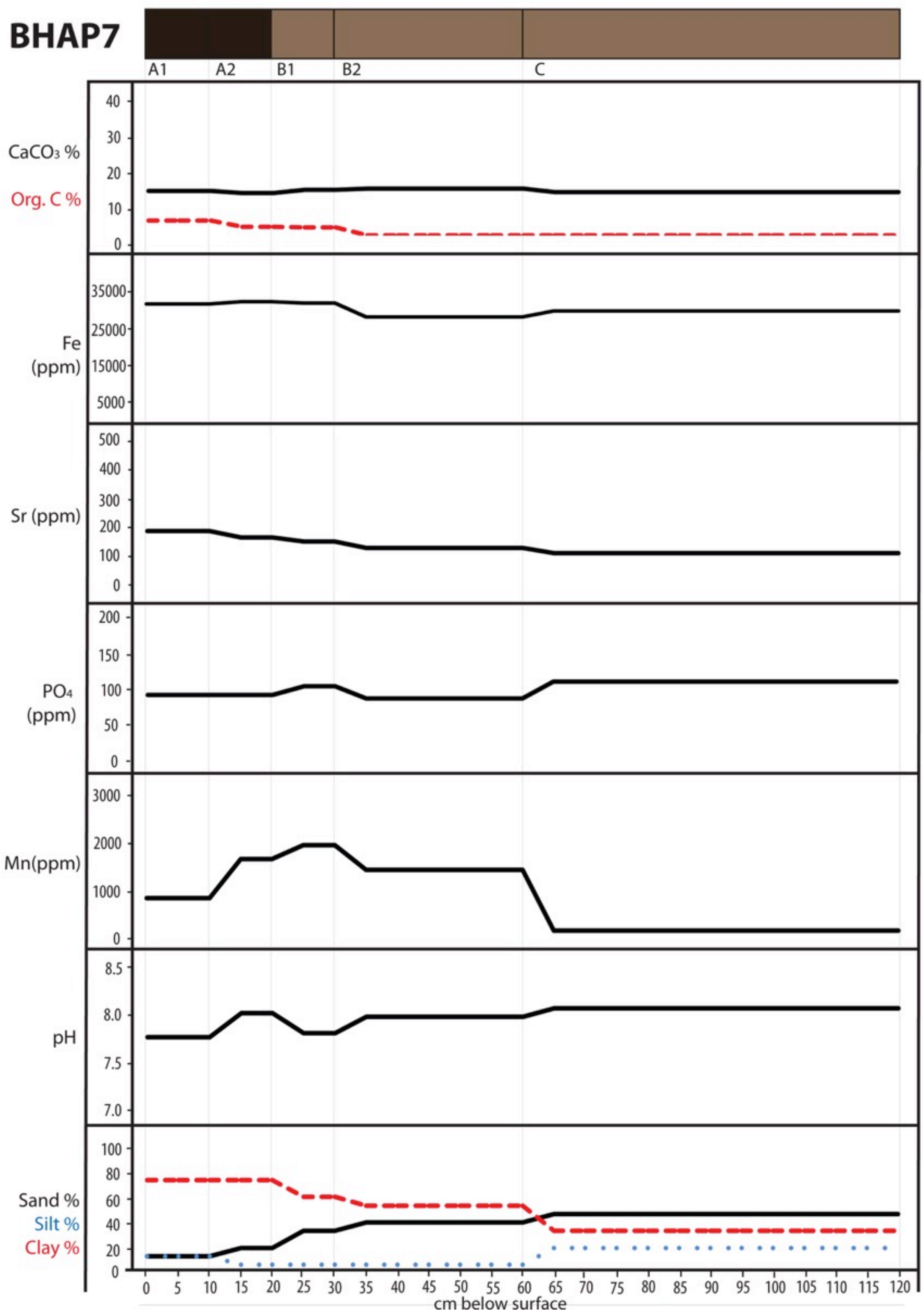


Figure VI.ix. *BHAP7 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 7.*

Table VI.ix. BHAP7 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	.641**	1								
Mn (ppm)	.127	.581**	1							
PO_4 (ppm)	.173	-.602**	-.779**	1						
pH	-.465*	-.864**	-.575**	.521**	1					
Sand %	-.653**	-.991**	-.525**	.587**	.795**	1				
Silt %	.016	-.549**	-.982**	.873**	.527**	.502*	1			
Clay %	.478*	.952**	.776**	-.780**	-.798**	-.940**	-.767**	1		
Organic Carbon %	.796**	.960**	.390	-.357	-.839**	-.954**	-.324	.836**	1	
CaCO3 %	-.519**	.173	.627**	-.712**	-.464*	-.083	-.698**	.337	-.035	1

the strontium and manganese concentrations, the strontium concentration and the clay percentage, the strontium concentration and the organic carbon percentage, the manganese concentration and the clay percentage, the manganese concentration and the calcium carbonate percentage, the phosphate concentration and the pH, the phosphate concentration and the sand percentage, the phosphate concentration and the silt percentage, the pH and the sand percentage, the pH and the silt percentage, and the organic carbon and clay percentages. Negative correlations are present between the iron concentration and the sand percentage, the iron concentration and the calcium carbonate percentage, the strontium and phosphate concentrations, the strontium concentration and the pH, the strontium concentration and the sand percentage, the strontium concentration and the silt percentage, the manganese and phosphate concentrations, the manganese concentration and the pH, the manganese concentration and the sand percentage, the manganese concentration and the silt percentage, the phosphate concentration and the clay percentage, the phosphate concentration and the calcium carbonate percentage, the pH and the clay percentage, the pH and the organic carbon percentage, the sand and clay percentages, the organic carbon and sand percentages, the silt and clay percentages, and the calcium carbonate and silt percentages.

VI.x. Auger Probe 6

Auger probe 6 was extracted from an empty field on terrace two. Five horizons were identified: a black A horizon (from the ground surface to 10 cm below the surface), a black AC1 horizon (from 10 to 20 cm below the surface), an olive brown AC2 horizon (from 20 to 30 cm below the surface), an olive brown C1 horizon (from 30 to 40 cm below the surface), and an olive brown C2 horizon (from 40 to 60 cm below the surface) (Figure VI.x). No B horizon was present. As expected, the organic carbon percentage declines gradually down the profile while the calcium carbonate percentage increases gradually from the A to the AC1 and increases sharply in the AC2 and remains constant down the rest of the profile. The pattern of calcium carbonate change reflects the decline in iron concentration. The iron concentration is constant in the A and AC1 horizons, then decreases down the profile. The strontium concentration increases slightly but steadily down the profile, following the expected pattern. The phosphate concentration decreases from the A to the AC1 horizons, then increases very slightly down the rest of the profile. The manganese concentration declines in the AC2 horizon, then increases slightly in the C1 and C2 horizons. As expected, the pH values increase steadily down the profile. Soil texture is relatively constant: the A and AC1 are sandy loams, the AC2 is sandy clay loam, and the C1 and C2 are sandy loams. The location of auger probe 6 was formerly party of the active cultivation area of Betty's Hope. The thick A horizon is the result of sediment eroding from the upper slopes, contributing to an A horizon high in mineral concentrations. The dramatic changes in iron concentration and calcium carbonate percentage in the AC2 horizon may be

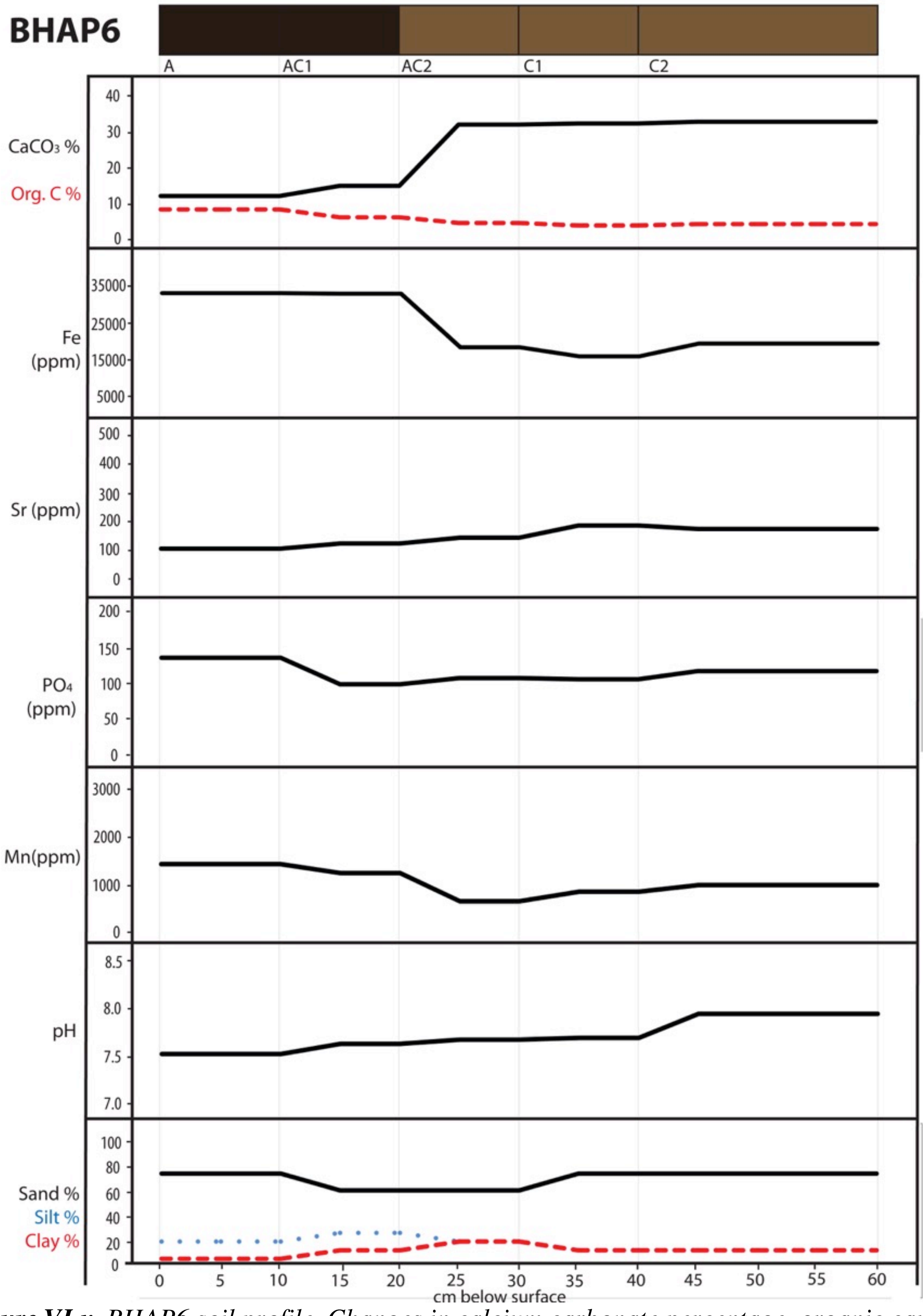


Figure VI.x. *BHAP6 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 6.*

indicative of a recent disturbance. The A and AC1 horizons may be composed sediment eroded from the upper slopes to inundate the surface of a formerly cultivated field.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.x). Positive correlations are present between the iron concentration and the pH, the strontium and manganese concentrations, the strontium and phosphate concentrations, the strontium concentration and the sand percentage, the strontium concentration and the organic carbon percentage, the manganese and phosphate concentrations, the manganese concentration and sand percentage, the manganese concentration and organic carbon percentage, the phosphate concentration and silt percentage, the pH and the clay percentage, and the organic carbon and sand percentages. Negative correlations are present between the iron concentration and the calcium carbonate percentage, the strontium concentration and the pH, the strontium concentration and the clay percentage, the manganese concentration and the pH, the manganese concentration and the clay percentage, the pH and the sand percentage, the sand and clay percentages, and the organic carbon and clay percentages.

Table VI.x. BHAP6 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.180	1								
Mn (ppm)	-.316	.880**	1							
PO_4 (ppm)	.143	.534**	.744**	1						
pH	.691**	-.773**	-.682**	-.157	1					
Sand %	-.388	.736**	.620**	-.011	-.763**	1				
Silt %	.378	.104	.426*	.751**	.359	-.160	1			
Clay %	.183	-.753**	-.801**	-.361	.550**	-.873**	-.341	1		
Organic Carbon %	-.337	.535**	.621**	.087	-.479*	.868**	.221	-.936**	1	
CaCO3 %	-.769**	-.455*	-.222	-.420*	-.073	-.120	-.283	.254	.035	1

VI.VI. Auger Probe 5

Auger probe 5 was extracted from an empty field on terrace two. Five horizons were identified: a black A horizon (from the ground surface to 10 cm below the surface), a black B1 horizon (from 10 to 40 cm below the surface), a black B2 horizon (from 40 to 60 cm below the surface), a dark grayish brown B3 horizon (from 60 to 80 cm below the surface), and a dark grayish brown B4 horizon (from 80 to 120 cm below the surface) (Figure VI.xi). The organic carbon percentage decreases very slightly and the calcium carbonate percentage increases very slightly, but both are relatively constant throughout the profile. The iron concentration is also relatively constant and quite high compared to other soil profiles. The high concentration of iron may be due to iron-rich sediment eroding from upper slopes. The strontium concentration is also quite constant, with a slight decrease in the B2 horizon and an overall slight decline throughout the profile. The phosphate concentration decreases slightly from the A to the B2 horizons, increases in the B3 horizon, and decreases in the B4 horizon. The manganese concentration declines gradually down the profile, but displays a dramatic decrease in the B2 horizon. The pH level is relatively constant throughout and does not exhibit the expected gradual decline down the profile. There is a slight increase in pH in the B2 horizon. The soil texture is variable: the A horizon is sandy loam, the B1 is sandy clay loam, and the B2 through B4 horizons are clay. Interestingly, the decline in manganese in the B2 horizon is matched by a spike in the percentage of clay. Like BHAP6, the location of BHAP5 was formerly part of the active cultivation area of Betty’s Hope. The thick, stable A and B horizons indicate no recent cultivation activity, but rather represent an accumulation of sediment eroded from the upper slopes of the catena. However, the changes in the B2 horizon may indicate that it is a buried A horizon, in which a past cultivated surface has now been covered by erosion from upper slopes.

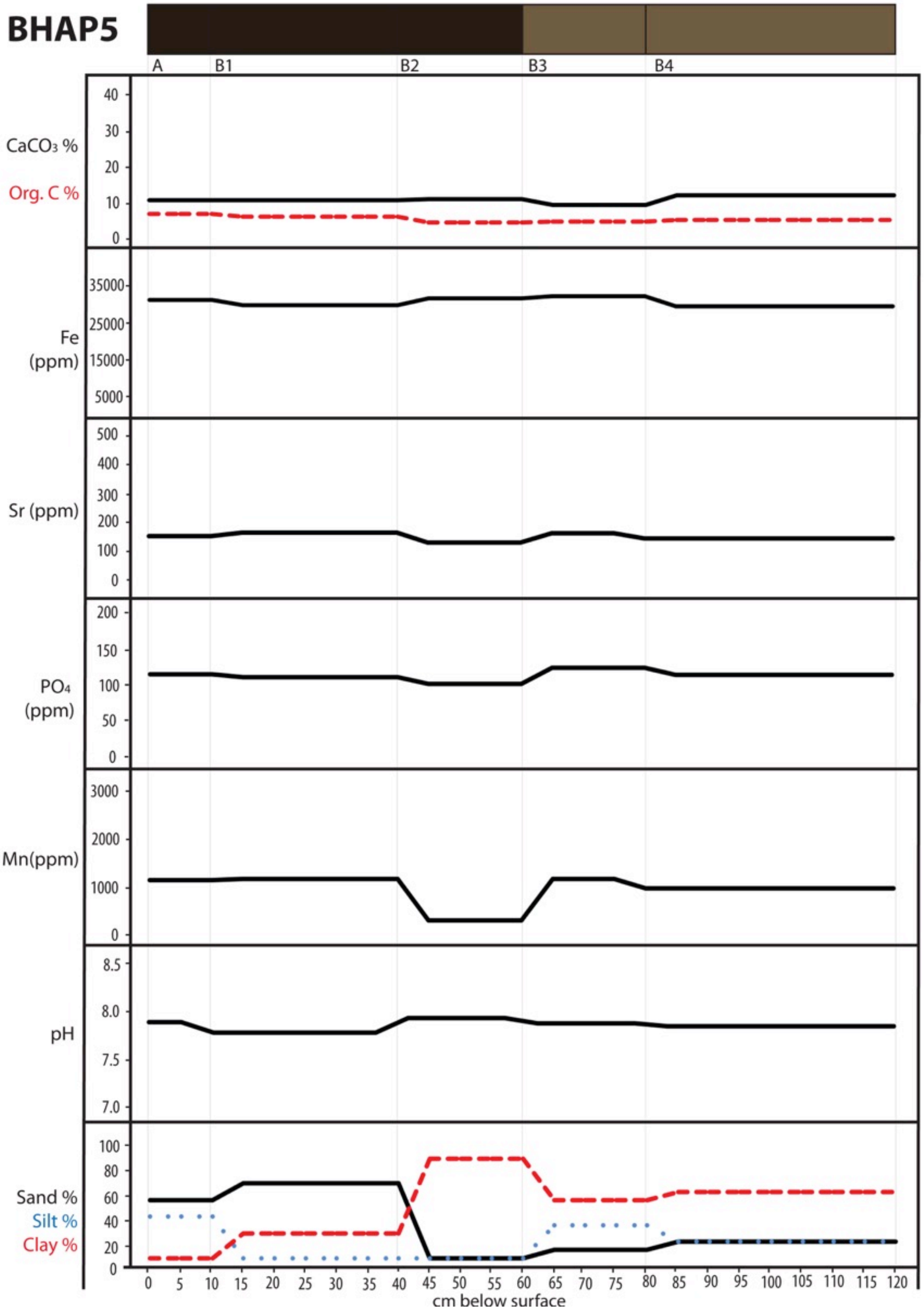


Figure VI.vi. *BHAP5 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 5.*

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.xi). Positive correlations are present between the iron concentration and the pH, the strontium and manganese concentrations, the strontium and phosphate concentrations, the strontium concentration and the sand percentage, the strontium concentration and the organic carbon percentage, the manganese and phosphate concentrations, the manganese concentration and the sand percentage, the manganese concentration and the organic carbon percentage, the phosphate concentration and the silt percentage, the pH and the clay percentage, and the sand and organic carbon percentages. Negative correlations are present between the iron concentration and calcium carbonate percentage, the strontium concentration and the pH, the strontium concentration and the clay percentage, the manganese concentration and the pH, the manganese concentration and the clay percentage, the pH and the sand percentage, the sand and clay percentages, and the organic carbon and clay percentages.

Table VI.VI. BHAP5 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.180	1								
Mn (ppm)	-.316	.880**	1							
PO_4 (ppm)	.143	.534**	.744**	1						
pH	.691**	-.773**	-.682**	-.157	1					
Sand %	-.388	.736**	.620**	-.011	-.763**	1				
Silt %	.378	.104	.426*	.751**	.359	-.160	1			
Clay %	.183	-.753**	-.801**	-.361	.550**	-.873**	-.341	1		
Organic Carbon %	-.337	.535**	.621**	.087	-.479*	.868**	.221	-.936**	1	
CaCO3 %	-.769**	-.455*	-.222	-.420*	-.073	-.120	-.283	.254	.035	1

VI.xii. Auger Probe 4

Auger probe 4 was extracted from terrace two. Three horizons were identified: a shallow black A horizon (from the ground surface to 5 cm below the surface), a black B horizon (from 5 to 30 cm below the surface), and a black C horizon (from 30 to 40 cm below the surface) (Figure VI.xii). The soil profile is quite shallow and concentrations of major elements remain relatively constant throughout. The organic carbon and calcium carbonate percentages are relatively low compared to other soil profile and do not vary down the profile. The iron concentration declines very slightly in the B horizon and increases slightly in the C horizon, but is high and constant throughout all three horizons. The strontium concentration increases slightly in the C horizon as expected. The phosphate concentration declines in the B horizon and remains constant throughout the rest of the profile. The manganese concentration steadily declines down the profile. The pH is constant throughout all three horizons. The soil texture is also mostly consistent, transitioning from sandy clay loam in the A and B horizons to loam in the C horizon. The three horizons present in this profile represent sediment eroded from the upper slopes of the catena, indicated by the high concentrations of iron and phosphates and the relative uniformity of all horizons.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.xii). Positive correlations are present between the iron and phosphate concentrations, the strontium concentration and the pH, the strontium concentration and the sand percentage, the strontium concentration and the silt percentage, the strontium concentration and the organic carbon percentage, the strontium concentration and the calcium carbonate percentage, the pH and the sand percentage, the pH and

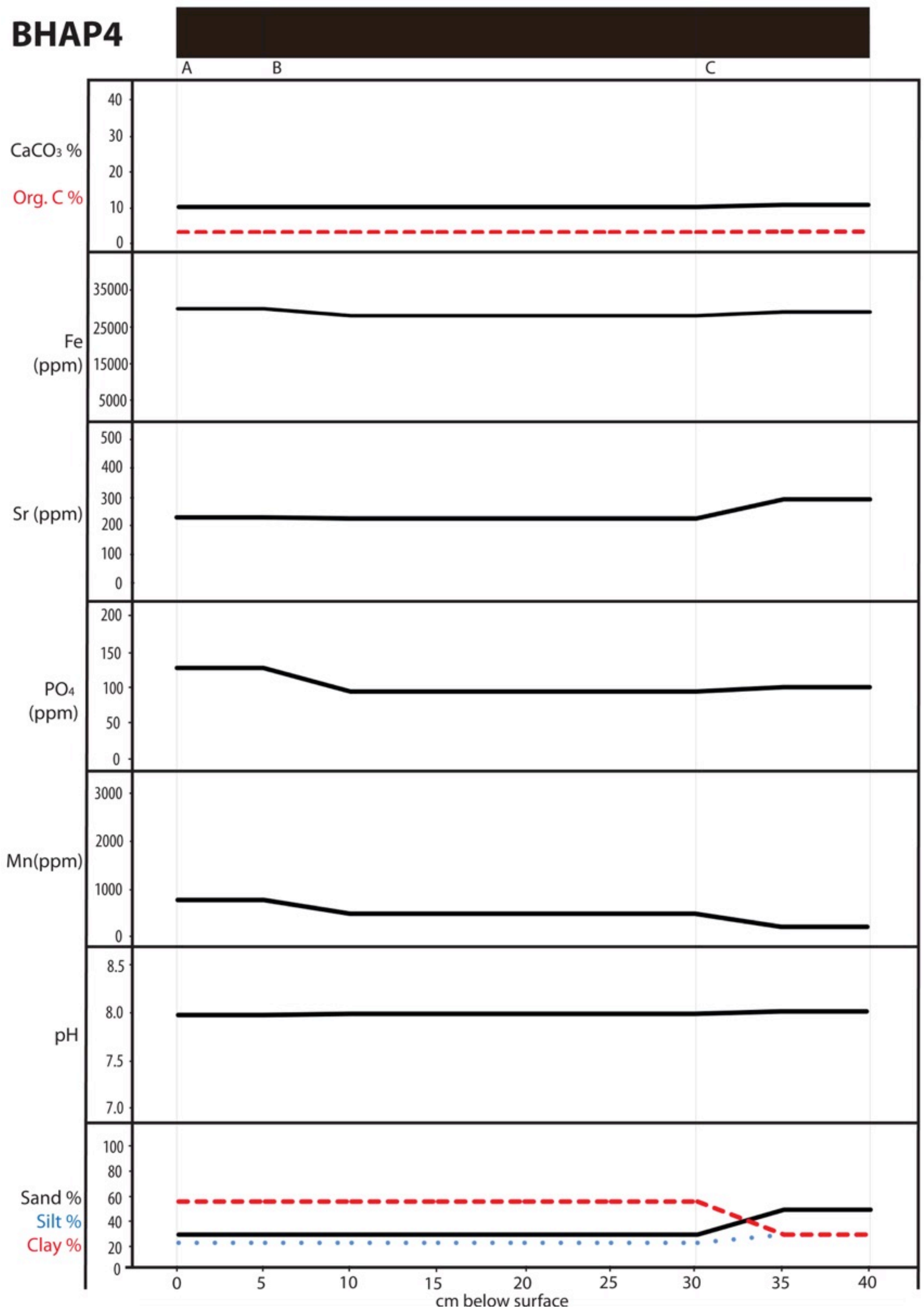


Figure VI.xii. *BHAP4 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 4.*

Table VI.xii. BHAP4 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	.316	1								
Mn (ppm)	.405	-.740*	1							
PO_4 (ppm)	.938**	-.033	.697*	1						
pH	-.037	.936**	-.929**	-.382	1					
Sand %	.244	.997**	-.788*	-.108	.960**	1				
Silt %	.244	.997**	-.788*	-.108	.960**	1.000**	1			
Clay %	-.244	-.997**	.788*	.108	-.960**	-1.000**	-1.000**	1		
Organic Carbon %	.244	.997**	-.788*	-.108	.960**	1.000**	1.000**	-1.000**	1	
CaCO3 %	.244	.997**	-.788*	-.108	.960**	1.000**	1.000**	-1.000**	1.000**	1

the silt percentage, the pH and the organic carbon percentage, the pH and the calcium carbonate percentage, the sand and silt percentages, the sand and organic carbon percentages, the sand and calcium carbonate percentages, the silt and organic carbon percentages, the silt and calcium carbonate percentages, and the organic carbon and calcium carbonate percentages. Negative correlations are present between the strontium concentration and the clay percentage, the manganese concentration and the pH, the pH and the clay percentage, the sand and clay percentages, the silt and clay percentages, the organic carbon and clay percentages, and the calcium carbonate and clay percentages.

VI.xiii. Auger Probe 3

Auger probe 3 was extracted from terrace one. Seven horizons were identified: a dark olive brown A horizon (from the ground surface to 10 cm below the surface), an olive brown B1 horizon (from 10 to 20 cm below the surface), a very dark gray A2 horizon (from 20 to 30 cm below the surface), a black A3 horizon (from 30 to 50 cm below the surface), a black A4 horizon (from 50 to 70 cm below the surface), a black A5 horizon (from 70 to 90 cm below the surface), and a black A6 horizon (from 90 to 120 cm below the surface) (Figure VI.xiii). The organic carbon and calcium carbonate percentages are relatively constant: the calcium carbonate percentage declines in the A2 horizon then increases gradually down the rest of the profile while the organic carbon percentage declines steadily and gradually down the profile as expected. The iron concentration is also relatively constant but increases slightly from the A1 to the A2 horizons and again in the A4 horizon. The strontium concentration is also relatively constant, but displays slight increases in the B1 and A4 horizons. The phosphate concentration is relatively constant throughout the profile, with slight increases in the B1 and A4 horizons matching the increases in the strontium concentration. The manganese concentration increases down the profile then declines in the A6 horizon; this general trend of increase does not follow the expected pattern. The pH values are not highly variable, though there is a slight increase in the A2 and the A4 horizons. The soil texture changes from sandy loam in the A1 and B1 horizons to sandy clay in percentage of clay increases in the A2 horizon, matching slight changes in the pH, iron, phosphate, and manganese concentrations. This soil profile exhibits a buried A horizon that is indicative of a past cultivation surface that is now covered by sediment that has eroded from the upper slopes of the catena.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.xiii). Positive correlations are present between the iron concentration and the pH, the strontium and phosphate concentrations, the manganese concentration and the clay percentage, the pH and the clay percentage, the sand and silt percentages, the sand and organic carbon percentages, the sand and calcium carbonate

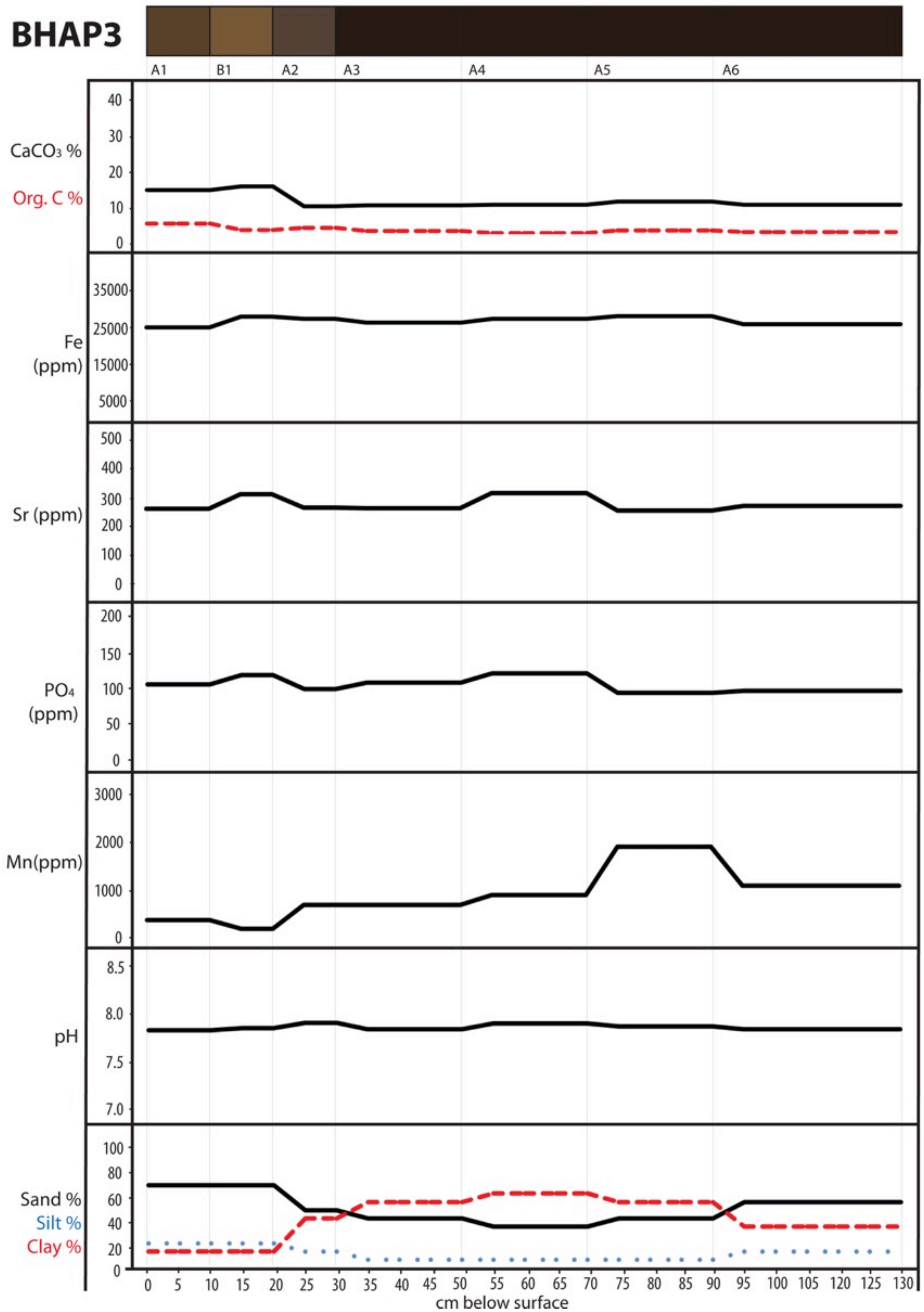


Figure VI.xiii. *BHAP3 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 3.*

Table VI.xiii. BHAP3 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	.333	1								
Mn (ppm)	.433*	-.358	1							
PO_4 (ppm)	.182	.848**	-.604**	1						
pH	.700**	.441*	.216	.300	1					
Sand %	-.515**	-.143	-.518**	-.138	-.619**	1				
Silt %	-.470*	.002	-.608**	-.014	-.439*	.971**	1			
Clay %	.504*	.099	.549**	.100	.567**	-.997**	-.986**	1		
Organic Carbon %	-.392	-.430*	-.411*	-.124	-.263	.616**	.631**	-.625**	1	
CaCO3 %	-.095	.119	-.465*	.253	-.371	.763**	.748**	-.763**	.632**	1

percentages, the silt and organic carbon percentages, the silt and calcium carbonate percentages, and the organic carbon and calcium carbonate percentages. Negative correlations are present between the iron concentration and the sand percentage, the manganese and phosphate concentrations, the manganese concentration and the sand percentage, the manganese concentration and the silt percentage, the pH and the sand percentage, the pH and the silt percentage, the sand and clay percentages, the silt and clay percentages, the organic carbon and clay percentages, and the calcium carbonate and clay percentages.

VI.xiv. Auger Probe 2

Auger probe 2 was extracted from the north side of the drainage channel between the two catenas on terrace one. Six thin horizons were identified: an olive brown A1 horizon (from the ground surface to 10 cm below the surface), a light olive brown B1 horizon (from 10 to 20 cm below the surface), a very dark grayish brown A2 horizon (from 20 to 25 cm below the surface), a dark grayish brown B2 horizon (from 25 to 30 cm below the surface), an olive brown B3 horizon (from 30 to 35 cm below the surface), and a light olive brown B4 horizon (from 35 to 40 cm below the surface) (Figure VI.xiv). The calcium carbonate percentage declines down the profile; this does not follow the expected pattern. The organic carbon percentage gradually decreases down the profile as expected. The iron concentration is not highly variable, but decreases slightly in the B1 horizon, then increases in the A2, B2, and B3 horizons until a slight decline in the B4 horizon. The strontium concentration increases in the B3 and B4 horizons as expected. The phosphate concentration, like the iron concentration, is largely constant throughout the profile, but declines slightly in the B1 horizon and then increases throughout the rest of the profile. Such an increase does not follow the expected pattern. The manganese concentration decreases in the B2, B3, and B4 horizons, following the expected pattern. The pH increases sharply from the A1 to the B1 horizons, then decreases slightly down the rest of the profile. The soil texture is consistently sandy clay loam, except for the B2 horizon, which is sandy loam.

A correlation matrix produced in SPSS reveals a small number of correlations between soil characteristics at the .01 confidence level (Table VI.xiv). No positive correlations are present, but negative correlations are present between the iron concentration and the calcium carbonate percentage, and the pH and organic carbon percentage.

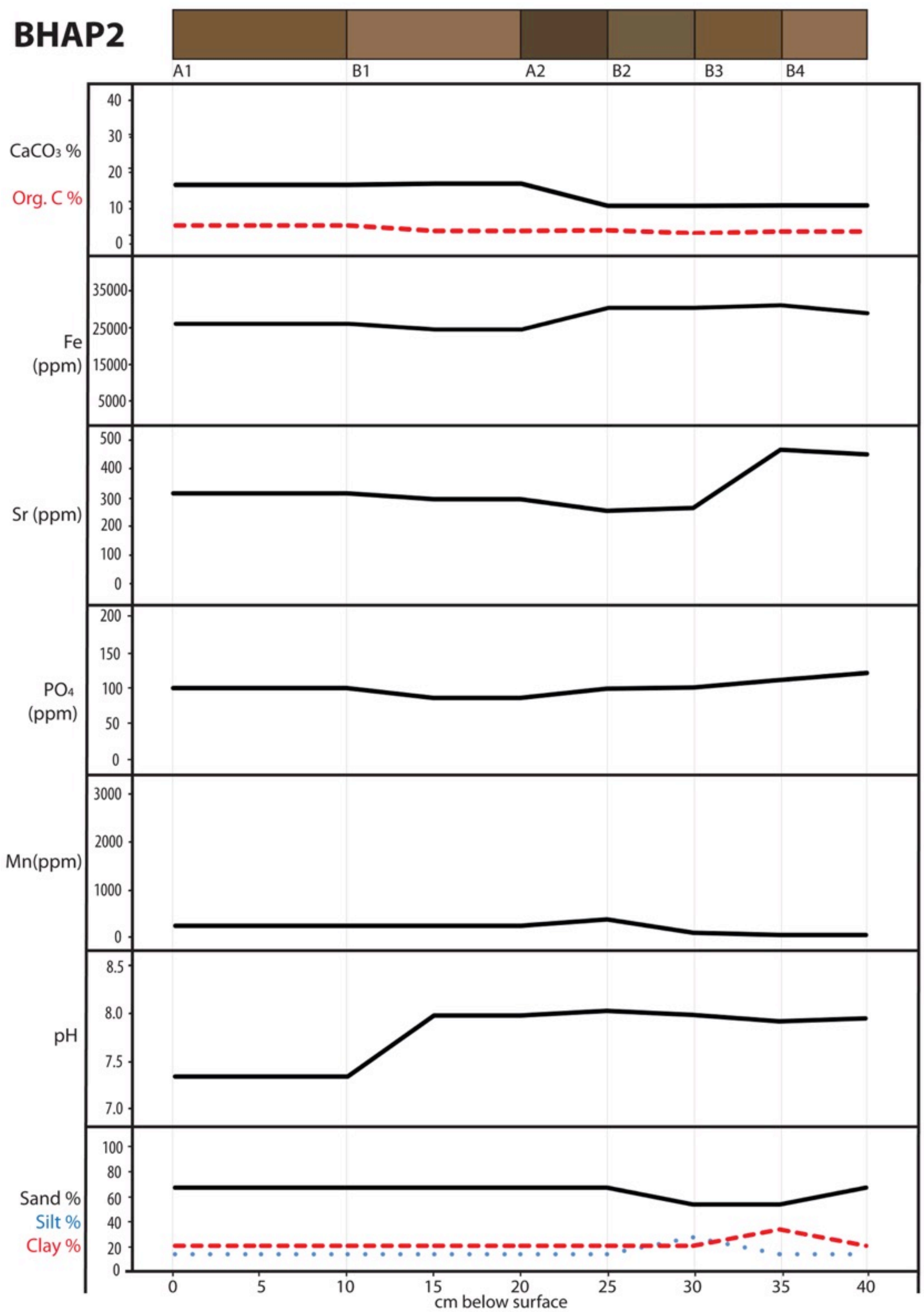


Figure VI.xiv. *BHAP2 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 2.*

Table VI.xiv. BHAP2 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	.329	1								
Mn (ppm)	-.426	-.750*	1							
PO_4 (ppm)	.658	.759*	-.651	1						
pH	.407	.066	-.231	-.021	1					
Sand %	-.686*	-.262	.649	-.278	-.341	1				
Silt %	.401	-.326	-.349	.004	.267	-.661	1			
Clay %	.506	.673*	-.510	.364	.184	-.661	-.125	1		
Organic Carbon %	-.489	-.171	.482	-.106	-.952**	.550	-.465	-.263	1	
CaCO3 %	-.959**	-.346	.471	-.664	-.586	.598	-.406	-.385	.651	1

VI.xv. Auger Probe 1

Auger probe 1 was extracted from the south side of the drainage channel between the two catenas on terrace zero. Two horizons were identified: a very dark grayish brown A horizon (from the ground surface to 20 cm below the surface), and a light brownish gray B horizon (from 20 to 40 cm below the surface) (Figure VI.xv). The calcium carbonate percentage increases down the profile as expected. The organic carbon percentage increases slightly down the profile; this does not follow the expected pattern. The iron concentration is relatively constant, though increases slightly in the B horizon, which does not follow the expected pattern. The strontium concentration is quite high compared to other soil profiles and increases down the profile as expected. The phosphate decreases gradually down the profile. The manganese concentration increases down the profile, defying the expectation that the concentration should decline. The pH level increases down the profile, matching the increase in the manganese concentration. This is unexpected since in most other profiles, the manganese concentration and pH are the inverse of each other. The soil texture is not variable; both horizons are clay. This soil profile, like auger

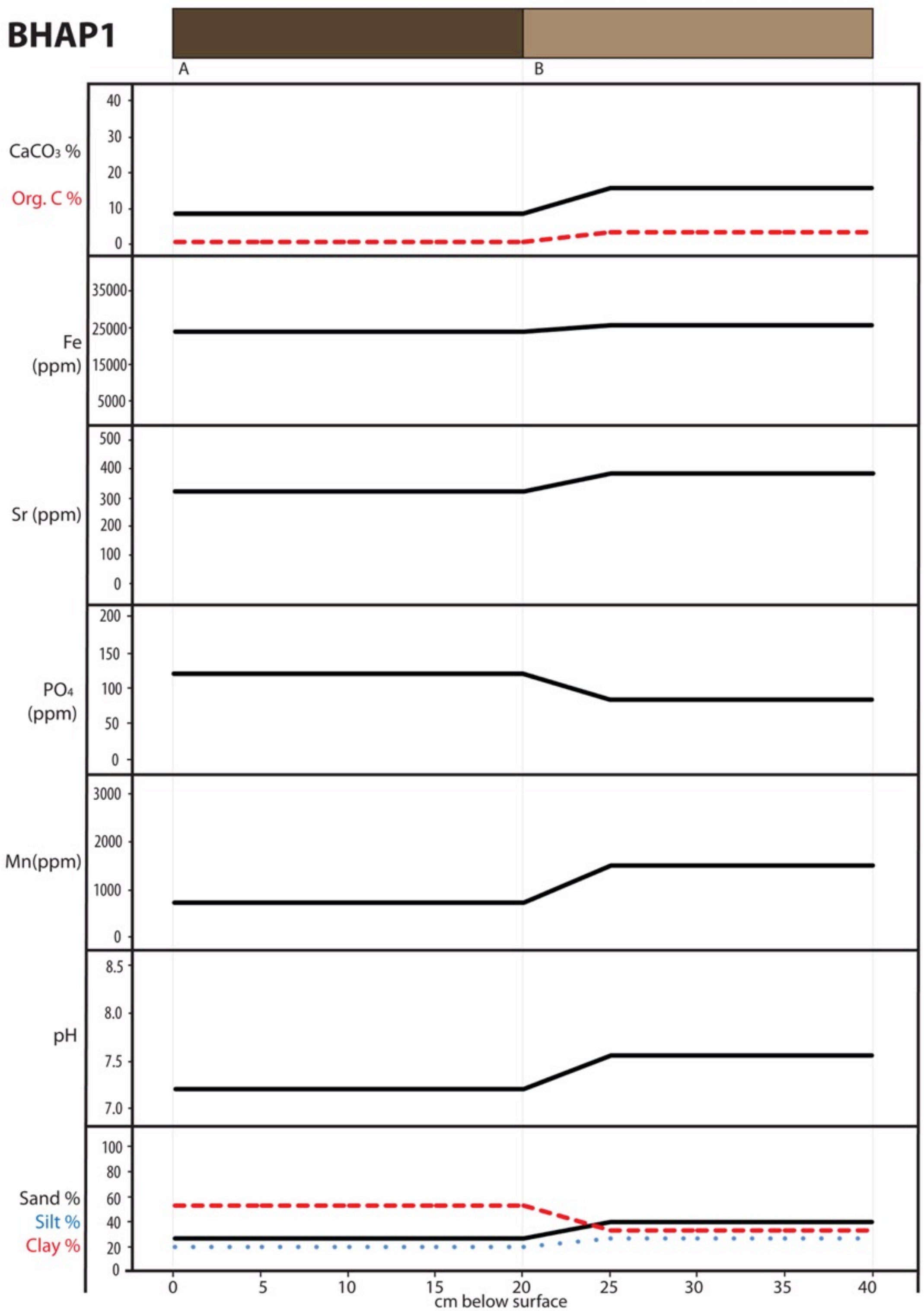


Figure VI.xv. *BHAP1 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 1.*

probe 2, is composed of alluvial sediments deposited by water. The A and B horizons are shallow but stable. The higher concentrations of heavy metals in the B horizon is unexpected, and the relatively high concentration of strontium may indicate different formation processes at the location of this auger probe.

A correlation matrix produced in SPSS reveals strong correlations between all soil characteristics at the .01 confidence level (Table VI.xv). This is perhaps expected because this soil profile only has two horizons. The iron concentration is correlated positively with the strontium concentration, the manganese concentration, the pH, the sand percentage, the silt percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the phosphate concentration and the clay percentage. The strontium

Table VI.xv. BHAP1 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	1.000**	1								
Mn (ppm)	1.000**	1.000**	1							
PO_4 (ppm)	-1.000**	-1.000**	-1.000**	1						
pH	1.000**	1.000**	1.000**	-1.000**	1					
Sand %	1.000**	1.000**	1.000**	-1.000**	1.000**	1				
Silt %	1.000**	1.000**	1.000**	-1.000**	1.000**	1.000**	1			
Clay %	-1.000**	-1.000**	-1.000**	1.000**	-1.000**	-1.000**	-1.000**	1		
Organic Carbon %	1.000**	1.000**	1.000**	-1.000**	1.000**	1.000**	1.000**	-1.000**	1	
CaCO3 %	1.000**	1.000**	1.000**	-1.000**	1.000**	1.000**	1.000**	-1.000**	1.000**	1

concentration is correlated positively with the iron concentration, the manganese concentration, the pH, the sand percentage, the silt percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the phosphate concentration and the clay percentage. The manganese concentration is correlated positively with the iron concentration, the strontium concentration, the pH, the sand percentage, the silt percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the phosphate concentration and the clay percentage. The phosphate concentration is correlated positively with the clay percentage and correlated negatively with the iron concentration, the strontium concentration, the manganese concentration, the pH, the sand percentage, the silt percentage, the organic carbon percentage, and the calcium carbonate percentage. The pH is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the sand percentage, the silt percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the phosphate concentration and the clay percentage. The sand percentage is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the pH, the silt percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the phosphate concentration and the clay percentage. The silt percentage is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the pH, the sand percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the phosphate concentration and the clay percentage. The clay percentage is correlated positively with the phosphate concentration and correlated negatively with the iron concentration, the strontium concentration, the manganese concentration, the pH, the sand percentage, the silt percentage, the organic carbon percentage, and the calcium carbonate percentage. The organic carbon percentage is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the pH, the sand percentage, the silt percentage, and the calcium carbonate percentage and correlated negatively with the phosphate concentration and the clay percentage. The calcium carbonate percentage is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the pH, the sand percentage, the silt percentage, and the organic carbon percentage and correlated negatively with the phosphate concentration and the clay percentage.

VI.xvi. Auger Probe 16

Auger probe 16 was extracted from a fallow field on the hill slope of terrace one. Three horizons were identified: an unusually thick black A horizon (from the ground surface to 60 cm below the surface), a grayish brown B horizon (from 60 to 80 cm below the surface), and a pale yellow C horizon (from 80 to 120 cm below the surface) (Figure VI.xvi). The organic carbon percentage declines slightly down the profile while the calcium carbonate percentage increases. As expected, the phosphate, iron, and manganese concentrations decline gradually down the profile. The strontium concentration also declines; this change down the profile does not follow the expected pattern. The pH values increase down the profile as expected. The soil texture varies slightly, from clay in the A horizon to sandy clay loam in the B and C horizons. This soil profile represents a typical soil profile, with the exception of the unexpected decline of the strontium concentration. The auger probe location was a fallow field on the slope below the site of Betty's Hope and represents a soil profile suitable for cultivation. The A horizon is thick and rich with minerals, which gradually leach out of the B and C horizons. The profile does not

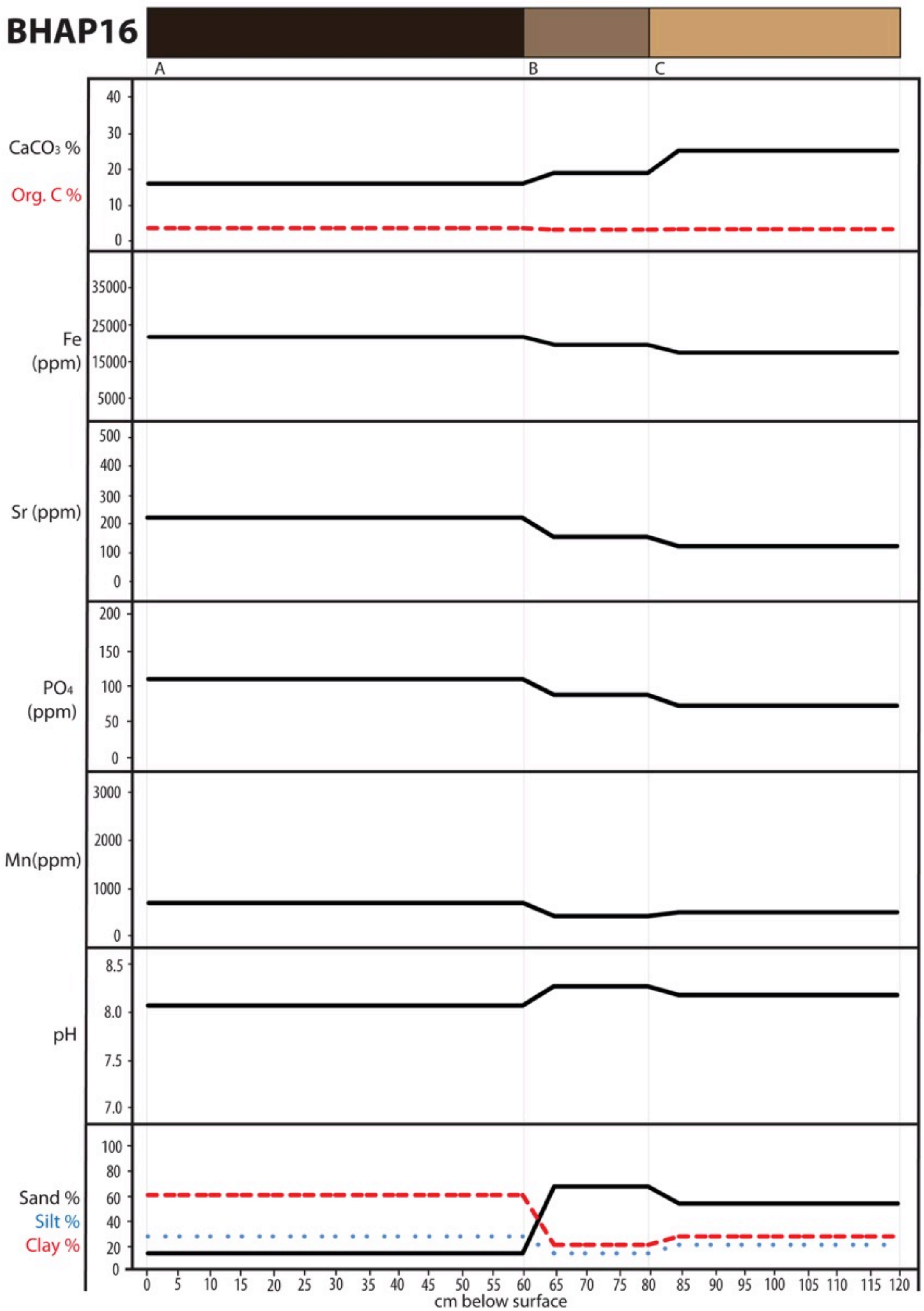


Figure VI.xvi. *BHAP16 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 16.*

display any unexpected patterns, all changes in mineral concentrations and particle percentages occur at steady increments.

A correlation matrix produced in SPSS reveals a large number of correlations between soil characteristics at the .01 confidence level (Table VI.xvi). The iron concentration is correlated positively with the strontium concentration, the manganese concentration, the phosphate concentration, the pH, the silt percentage, the clay percentage the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the sand percentage. The strontium concentration is correlated positively with the iron concentration, the manganese concentration, the phosphate concentration, the silt percentage, the clay percentage the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the pH and the sand percentage. The manganese concentration is correlated positively with the iron concentration, the strontium concentration, the phosphate concentration, the silt percentage, the clay percentage, and the organic carbon percentage and correlated negatively with the pH, the

Table VI.xvi. BHAP16 Correlations

	Fe (ppm)	**Sr (ppm)**	**Mn (ppm)**	**PO_4 (ppm)**	**pH**	**Sand %**	**Silt %**	**Clay %**	**Org. C. %**	**CaCO3 %**
Fe (ppm)	1									
Sr (ppm)	.992**	1								
Mn (ppm)	.831**	.895**	1							
PO_4 (ppm)	.998**	.998**	.864**	1						
pH	-.729**	-.811**	-.987**	-.771**	1					
Sand %	-.853**	-.913**	-.999**	-.884**	.979**	1				
Silt %	.688**	.775**	.975**	.732**	-.998**	-.966**	1			
Clay %	.888**	.940**	.994**	.915**	-.962**	-.997**	.945**	1	.920**	
Organic Carbon %	.637**	.731**	.958**	.685**	-.992**	-.946**	.998**	.920**	1	
CaCO3 %	-.987**	-.958**	-.730**	-.975**	.609**	.757**	-.562**	-.802**	-.504*	1

sand percentage, and the calcium carbonate percentage. The phosphate concentration is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the silt percentage, the clay percentage, and the organic carbon percentage and correlated negatively with the pH, the sand percentage, and the calcium carbonate percentage. The pH is correlated positively with the sand percentage and the calcium carbonate percentage and correlated negatively with the iron concentration, the strontium concentration, the manganese concentration, the phosphate concentration, the silt percentage, the clay percentage, and the organic carbon percentage. The sand percentage is correlated positively with the pH and the calcium carbonate percentage and correlated negatively with the iron concentration, the strontium concentration, the manganese concentration, the phosphate concentration, the silt percentage, the clay percentage, and the organic carbon percentage. The silt percentage is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the phosphate concentration the clay percentage, and the organic carbon percentage and correlated negatively with the pH, the sand percentage, and the calcium carbonate percentage. The clay percentage is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the phosphate concentration the silt percentage, and the organic carbon percentage and correlated negatively with the pH, the sand percentage, and the calcium carbonate percentage. The organic carbon percentage is correlated positively with the iron concentration, the strontium concentration, the manganese concentration, the phosphate concentration, the silt percentage, and the clay percentage and correlated negatively with the pH and the sand percentage. The calcium carbonate percentage is correlated positively with the pH and the sand percentage and correlated negatively with the iron concentration, the strontium concentration, the manganese concentration, the phosphate concentration, the silt percentage, and the clay percentage.

VI.xvii. Auger Probe 17

Auger probe 17 was extracted from the hill slope of terraces one and two at the site of the historic slave village associated with Betty's Hope prior to emancipation in 1833. Six horizons were identified: a black A horizon (from the ground surface to 20 cm below the surface), an olive brown B horizon (from 20 to 30 cm below the surface), a light olive brown C1 horizon (from 30 to 60 cm below the surface), a light olive brown C2 horizon (from 60 to 90 cm below the surface), a light olive brown C3 horizon (from 90 to 120 cm below the surface), and a light olive brown C4 horizon (from 120 to 170 cm below the surface) (Figure VI.xvii). The calcium carbonate percentage is relatively constant throughout the profile, displaying only very slight decline. The organic carbon percentage increases dramatically in the B and C1 horizons, then remains relatively low and constant throughout the remainder of the profile. The iron concentration increases in the B horizon then declines steadily down the remainder of the profile. Unexpectedly, the strontium concentration declines down the profile; in a normal profile the concentration should increase. The phosphate concentration declines steadily down the profile as expected, although there is a spike in the concentration in the B horizon. The manganese concentration generally increases down the profile, defying the expected pattern of decrease, though the concentration declines in the B and C3 horizons. The pH value increases sharply in the B horizon, then declines slightly and increases gradually throughout the rest of the profile. The soil texture is variable, transitioning from a sandy loam in the A horizon, to sandy clay loam

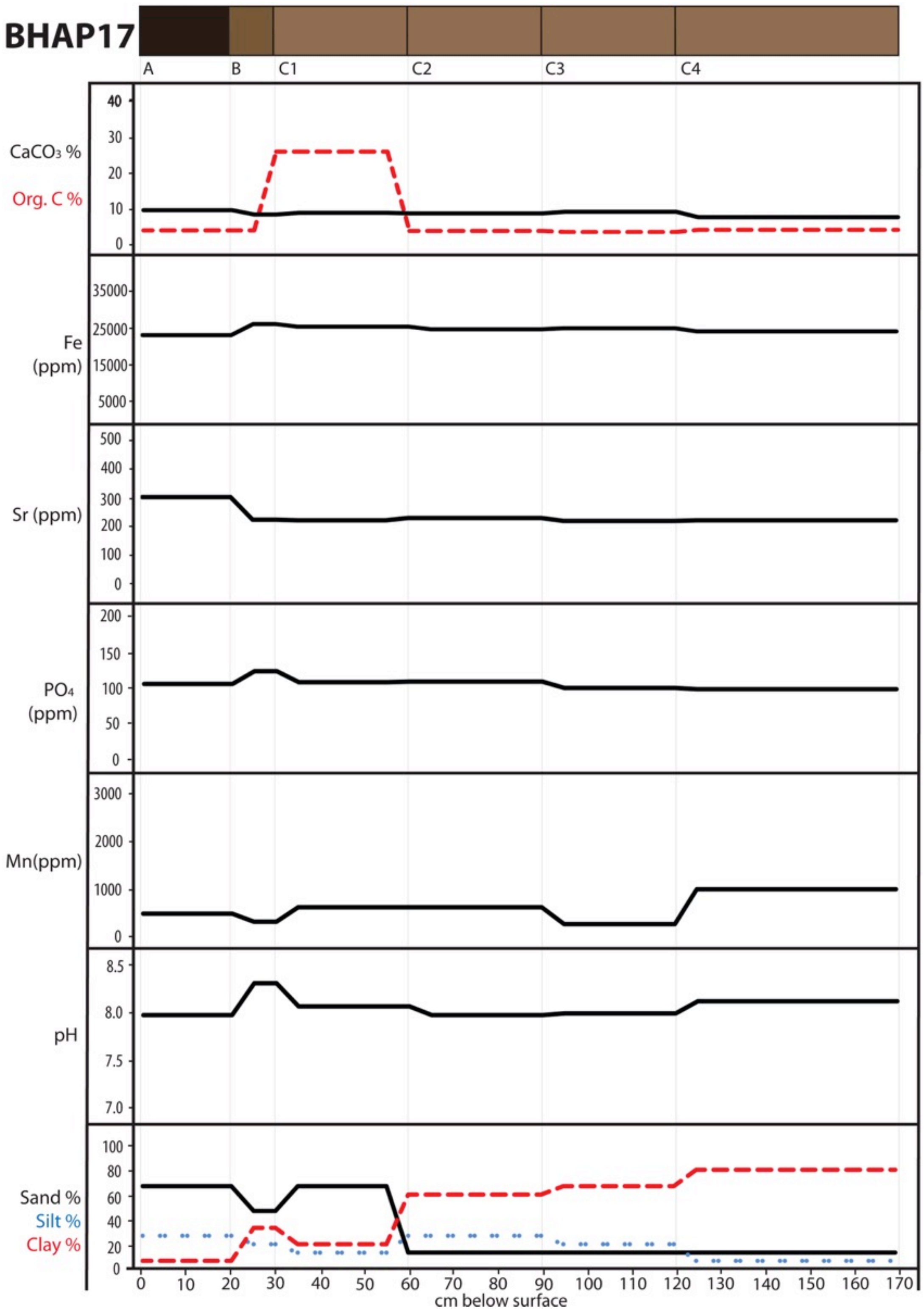


Figure VI.xvii. *BHAP17 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 17.*

in the B and C1 horizons, and to clay in the C2, C3, and C4 horizons. The historic anthropogenic disturbance to the soil profile is very clear in the B horizon (and, to a lesser extent the C1 horizon). The increase in pH, phosphate and iron concentration, and organic carbon percentage are indicative of human occupation: the historic slave village. The ground surface which was occupied during the period when people lived at this location has now been covered by the A horizon due to sediment eroding from the upper slopes of the catena.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.xvii). Positive correlations are present between the iron and phosphate concentrations, the iron concentration and the organic carbon percentage, the strontium concentration and the sand percentage, the strontium concentration and the silt percentage, the strontium concentration and the calcium carbonate percentage, the manganese concentration and the clay percentage, the phosphate concentration and the sand percentage, the phosphate concentration and the silt percentage, the sand and organic carbon percentages, the sand and calcium carbonate percentages, and the silt and calcium carbonate

Table VI.xvii. BHAP17 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.721**	1								
Mn (ppm)	-.352*	-.210	1							
PO_4 (ppm)	.482**	.142	-.449**	1						
pH	.356*	-.394*	.349*	.206	1					
Sand %	-.060	.598**	-.271	.450**	-.006	1				
Silt %	-.065	.538**	-.713**	.537**	-.632**	.216	1			
Clay %	.073	-.694**	.456**	-.562**	.196	-.956**	-.493**	1		
Organic Carbon %	.560**	-.194	-.082	.419*	.285	.621**	-.191	-.495**	1	
CaCO3 %	-.040	.590**	-.851**	.356*	-.657**	.521**	.830**	-.714**	.075	1

percentages. Negative correlations are present between the iron and strontium concentrations, the strontium concentration and the clay percentage, the manganese and phosphate concentrations, the manganese concentration and the silt percentage, the manganese concentration and the calcium carbonate percentage, the phosphate concentration and the clay percentage, the pH and the silt percentage, the pH and the calcium carbonate percentage, the sand and clay percentages, the silt and clay percentages, the organic carbon and clay percentages, and the calcium carbonate and clay percentages.

VI.xviii. Auger Probe 18

Auger probe 18 was extracted from the hill slope of terrace one at the site of the historic slave village associated with Betty's Hope prior to emancipation in 1833. Six horizons were identified: a black A1 horizon (from the ground surface to 20 cm below the surface), a black A2 horizon (from 20 to 40 cm below the surface), a very dark grayish brown AB horizon (from 40 to 50 cm below the surface), a dark olive brown B horizon (from 50 to 90 cm below the surface), an olive brown BC horizon (from 90 to 100 cm below the surface), and an olive brown C horizon (from 100 to 150 cm below the surface) (Figure VI.xviii). The organic carbon percentage gradually decreases down the profile while the calcium carbonate percentage decreases. The decrease in calcium carbonate does not follow the expected pattern. The iron concentration is relatively constant, but does decline slightly down the profile. The strontium concentration increases gradually down the profile as expected. The phosphate concentration declines steadily down the profile as expected. The manganese concentration decreases in the B horizon, increases in the BC horizon, and declines again in the C horizon. This does not follow the expected pattern of gradual decrease down the profile. The pH value increases steadily from the A1 to the B as

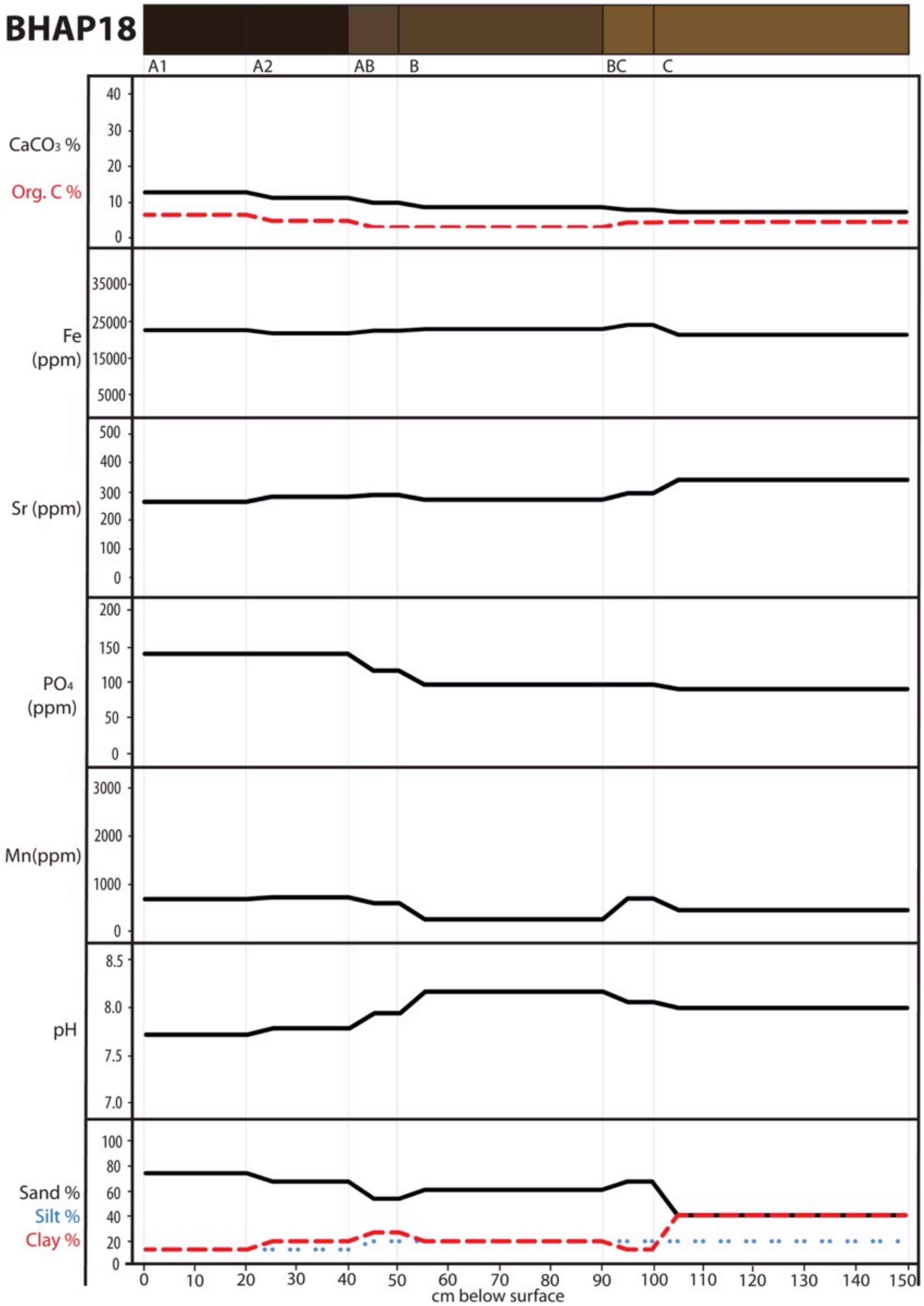


Figure VI.xviii. *BHAP18 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 18.*

expected, then declines down the remainder of the profile. The soil texture is variable, transitioning from sandy loam in the A1 horizon to sandy clay loam in the A2, AB, and B horizons, to sandy loam in the BC horizon, to clay in the C horizon. This soil profile displays anthropogenic disturbance with high phosphate concentrations in the A1 and A2 horizons, though the disturbance is less acute than that visible in the profile from auger probe 17.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table 6.20). Positive correlations are present between the iron concentration and the sand percentage, the strontium concentration and the silt percentage, the strontium concentration and the clay percentage, the manganese and phosphate concentrations, the manganese concentration and the organic carbon percentage, the manganese concentration and the calcium carbonate percentage, the phosphate concentration and the sand percentage, the phosphate concentration and the organic carbon percentage, the phosphate concentration and the calcium carbonate percentage, the pH and the silt percentage, the sand and calcium carbonate percentages, the silt and clay percentages, and the organic carbon and calcium

Table VI.xviii. BHAP18 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.737**	1								
Mn (ppm)	-.069	-.120	1							
PO_4 (ppm)	.102	-.625**	.750**	1						
pH	.281	.164	-.875**	-.852**	1					
Sand %	.681**	-.925**	.432*	.772**	-.416*	1				
Silt %	.030	.504**	-.736**	-.957**	.887**	-.704**	1			
Clay %	-.812**	.948**	-.300	-.639**	.238	-.979**	.546**	1		
Organic Carbon %	-.249	-.038	.732**	.640**	-.889**	.333	-.772**	-.174	1	
CaCO3 %	.232	-.740**	.620**	.967**	-.777**	.836**	-.912**	-.727**	.616**	1

carbonate percentages. Negative correlations are present between the iron and strontium concentrations, the iron concentration and the clay percentage, the strontium and phosphate concentrations, the strontium concentration and the sand percentage, the strontium concentration and the calcium carbonate percentage, the manganese concentration and the pH, the manganese concentration and the silt percentage, the phosphate concentration and the pH, the phosphate concentration and the silt percentage, the phosphate concentration and the clay percentage, the pH and the organic carbon percentage, the pH and the calcium carbonate percentage, the sand and silt percentages, the sand and clay percentages, the silt and organic carbon percentages, the silt and calcium carbonate percentages, and the clay and calcium carbonate percentages.

VI.xix. Auger Probe 19

Auger probe 19 was extracted from the hill slope of terrace two. Three horizons were identified: a black A horizon (from the ground surface to 20 cm below the surface), a thin very dark gray B horizon (from 20 to 25 cm below the surface), and an olive brown C horizon (from 25 to 45 cm below the surface) (Figure VI.xix). The organic carbon percentage declines steadily as expected; the calcium carbonate percentage also declines, defying the expected pattern. The iron concentration increases slightly; again, this does not follow the expectation o a normal soil profile. The strontium concentration increases slightly down the profile as expected. The phosphate and manganese concentrations both decline gradually down the profile. The pH values also increase gradually, following the expected pattern. The soil texture transitions from sandy clay loam in A and B horizons to silt loam in the C horizon. The horizons in this profile are

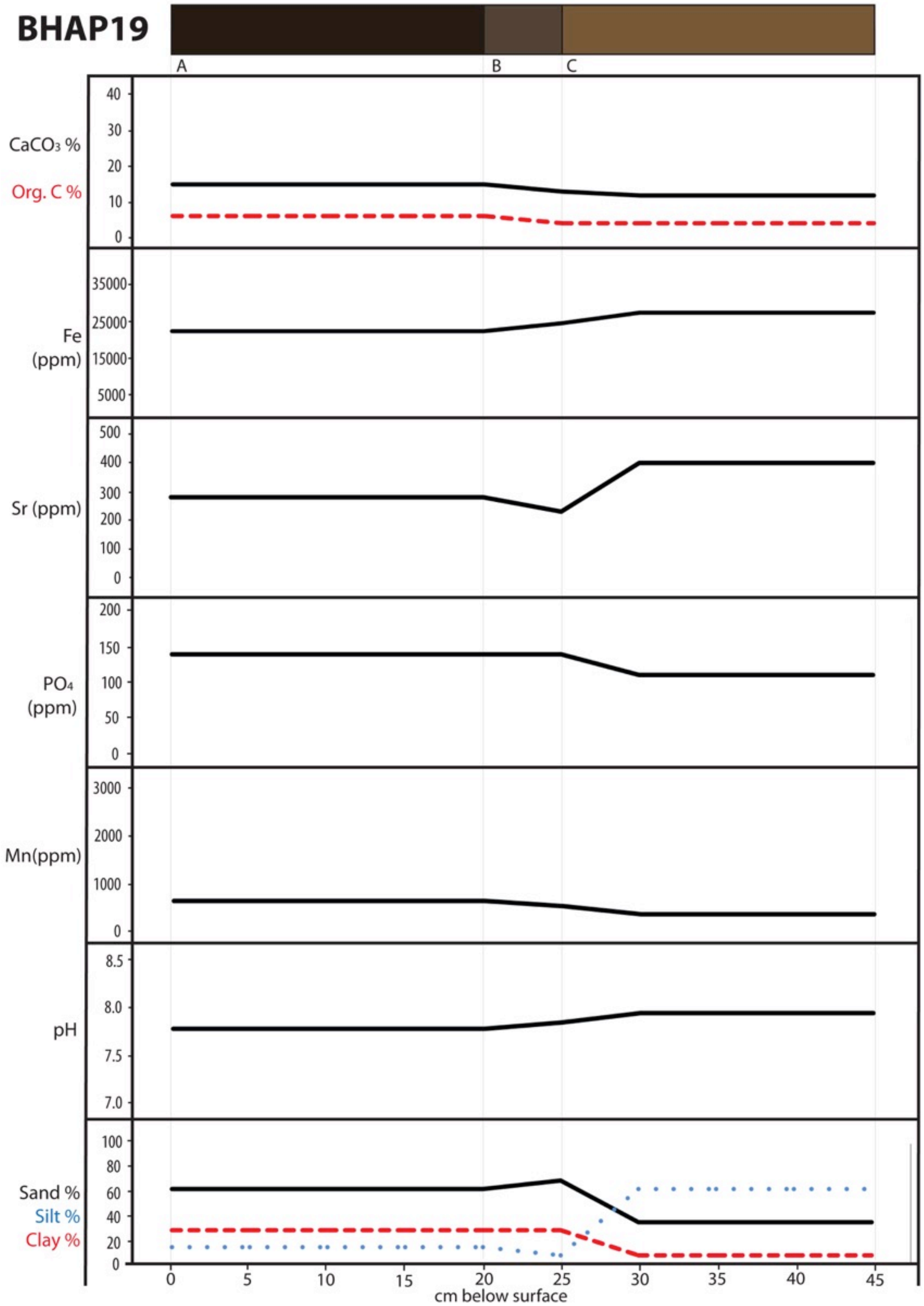


Figure VI.xix. *BHAP19 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 19.*

shallow due to the ager probe site's location on a slope near the top of the catena. The auger probe site is near the location of the Betty's Hope Great House, thus this area has been subjected to historic occupation and anthropogenic disturbance. The increase in iron concentration down the profile can be explained by the fact that sediment erodes from the upper slopes to the lower, depleting the iron in the A horizon.

A correlation matrix produced in SPSS reveals a large number correlations between soil characteristics at the .01 confidence level (Table VI.xix). The iron concentration is correlated positively with the strontium concentration, the pH, and the silt percentage and correlated negatively with the manganese concentration, the phosphate concentration, the sand percentage, the clay percentage, the organic carbon percentage, and the calcium carbonate percentage. The strontium concentration is correlated positively with the iron concentration, the pH, and the silt percentage and correlated negatively with the manganese concentration, the phosphate concentration, the sand percentage, the clay percentage, the organic carbon percentage, and the

Table VI.xix. BHAP19 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	.880**	1								
Mn (ppm)	-.999**	-.899**	1							
PO_4 (ppm)	-.964**	-.975**	.974**	1						
pH	1.000**	.888**	-1.000**	-.968**	1					
Sand %	-.917**	-.997**	.932**	.990**	-.923**	1				
Silt %	.938**	.990**	-.952**	-.997**	.944**	-.998**	1			
Clay %	-.964**	-.975**	.974**	1.000**	-.968**	.990**	-.997**	1		
Organic Carbon %	-.939**	-.664*	.925**	.813**	-.934**	.724*	-.763*	.813**	1	
CaCO3 %	-.992**	-.813**	.986**	.922**	-.990**	.858**	-.887**	.922**	.975**	1

calcium carbonate percentage. The manganese concentration is correlated positively with the phosphate concentration, the sand percentage, the lay percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the iron concentration, the strontium concentration, the pH, and the silt percentage. The phosphate concentration is correlated positively with the manganese concentration, the sand percentage, the clay percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the iron concentration, the strontium concentration, the pH, and the silt percentage. The pH is correlated positively with the iron concentration, the strontium concentration, and the silt percentage and correlated negatively with the manganese concentration, the phosphate concentration, the sand percentage, the clay percentage, and the calcium carbonate percentage. The sand percentage is correlated positively with the manganese concentration, the phosphate concentration, the clay percentage, and the calcium carbonate percentage and correlated negatively with the iron concentration, the strontium concentration, the pH, and the silt percentage. The silt percentage is correlated positively with the iron concentration, the strontium concentration, and the pH and correlated negatively with the manganese concentration, the phosphate concentration, the sand percentage, the clay percentage, the organic carbon percentage, and the calcium carbonate percentage. The clay percentage is correlated positively with the manganese concentration, the phosphate concentration, the sand percentage, the organic carbon percentage, and the calcium carbonate percentage and correlated negatively with the iron concentration, the strontium concentration, the pH, and the silt percentage. The organic carbon percentage is correlated positively with the manganese concentration, the phosphate concentration, the sand percentage, the clay percentage, and the calcium carbonate percentage and correlated negatively with the iron concentration, the strontium concentration, the pH, and the silt percentage. The calcium carbonate percentage is correlated positively with the manganese concentration, the phosphate concentration, the sand percentage, the clay percentage, and the organic carbon percentage and correlated negatively with the iron concentration, the strontium concentration, the pH, and the silt percentage.

VI.xx. Auger Probe 20

Auger probe 20 was extracted from the crown of the hill slope of terrace two. Seven horizons were identified: a black A1 horizon (from the ground surface to 30 cm below the surface), a black A2 horizon (from 30 to 50 cm below the surface), a black A3 horizon (from 50 to 70 cm below the surface), a very dark grayish brown B horizon (from 70 to 80 cm below the surface), a light olive brown C3 horizon (from 80 to 130 cm below the surface), a light olive brown C2 horizon (from 130 to 180 cm below the surface), and a light olive brow C3 horizon (from 180 to 230 cm below the surface) (Figure VI.xx). The organic carbon percentage declines from the A1 to the A3 horizon, then increases sharply in the B and C1 horizons before decreasing in the C2 and C3 horizons. The calcium carbonate percentage decreases from the A1 to the C1 horizon, then increases slightly in the C2 and C3 horizons. The iron concentration increases gradually down the profile, except for a decline in the C3 horizon. The strontium concentration increases in the A3 horizon, then decreases through the C2 horizon, and increases in the C3 horizon. The phosphate concentration is variable across the profile: the concentration is constant across the A1, A2, and A3, and B horizons, then decreases in the C1 horizon, increases in the C2 horizon, and decreases again in the C3 horizon. The manganese concentration increases in the A1, A2, and A3 horizons, the decreases in the B, C1, and C2 horizons, then increases again in the C3 horizon. The pH value increases from the A1 to the C1 horizon, and then

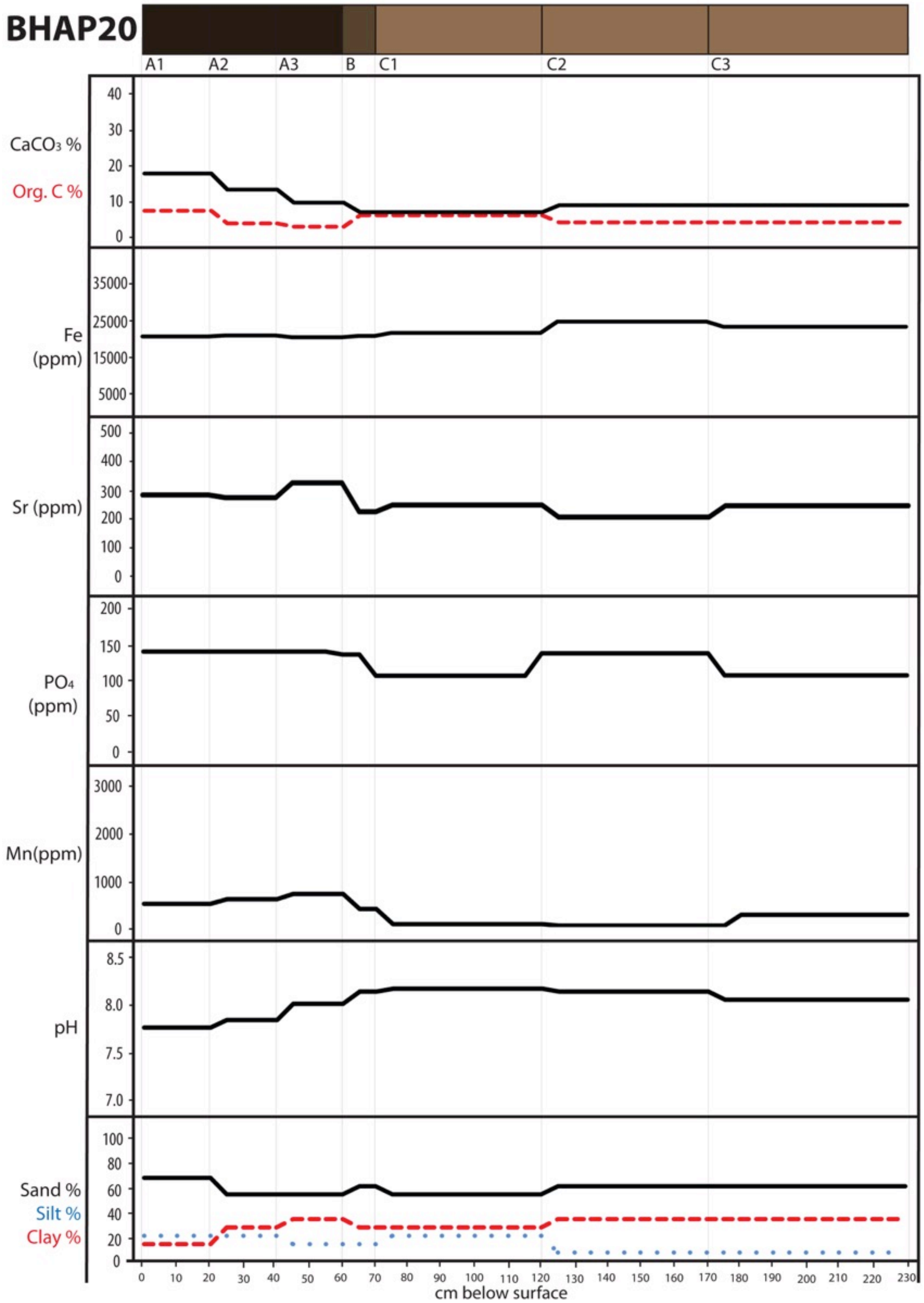


Figure VI.xx. *BHAP20 soil profile. Changes in calcium carbonate percentage, organic carbon percentage, iron concentration, strontium concentration, phosphate concentration, manganese concentration, pH, and soil texture down the soil profile of auger probe 20.*

decreases gradually in the C2 and C3 horizons. The soil texture is variable: the A1 horizon is sandy loam, the A2 horizon in loam, the A3 horizon is clay loam, the B horizon is sandy clay loam, the C1 horizon is clay loam, the C2 horizon is clay, and the C3 horizon is sandy clay loam. Auger probe 20 was extracted from the top of the catena, near the site of Betty's Hope. As such, the area has been subject to centuries of anthropogenic disturbance and the fluctuations of mineral concentrations reflect this. The increase in organic carbon percentage in the C1 reflects the anthropogenic addition of organic material due to past human occupation.

A correlation matrix produced in SPSS reveals several correlations between soil characteristics at the .01 confidence level (Table VI.xx). Positive correlations are present between the iron concentration and the pH, the iron concentration and the clay percentage, the strontium and manganese concentrations, the strontium concentration and the silt percentage, the strontium concentration and the calcium carbonate percentage, the manganese and phosphate concentrations, the phosphate concentration and the calcium carbonate percentage, the pH and the clay percentage, the sand and calcium carbonate percentages, and the silt and organic carbon percentages Negative correlations are present between the iron and strontium concentrations, the iron and manganese concentrations, the iron concentration and the silt percentage, the iron concentration and the organic carbon percentage, the iron concentration and the calcium carbonate percentage, the strontium concentration and the pH, the manganese concentration and the pH, the phosphate concentration and the pH, the pH and the sand percentage, the pH and the calcium carbonate percentage, the silt and clay percentages, the clay and organic carbon percentages, and the clay and calcium carbonate percentages.

Table VI.xx. BHAP20 Correlations

	Fe (ppm)	Sr (ppm)	Mn (ppm)	PO_4 (ppm)	pH	Sand %	Silt %	Clay %	Org. C. %	CaCO3 %
Fe (ppm)	1									
Sr (ppm)	-.826**	1								
Mn (ppm)	-.700**	.850**	1							
PO_4 (ppm)	-.085	.161	.393**	1						
pH	.505**	-.608**	-.764**	-.446**	1					
Sand %	.270	-.210	.004	.200	-.419**	1				
Silt %	-.828**	.504**	.304*	.097	-.341*	-.349*	1			
Clay %	.643**	-.360*	-.307*	-.236	.632**	-.341*	-.762**	1		
Organic Carbon %	-.422**	.008	-.155	-.137	-.157	.283	.646**	-.844**	1	
CaCO3 %	-.374**	.446**	.598**	.560**	-.951**	.570**	.318*	-.714**	.280	1

Appendix VII. pH Measurements

Auger probe number	Horizon	Depth (cm)	pH	Temperature (°C)
BHAP1	A	0-20	7.2	20.0
BHAP1	B	20-40	7.6	19.8
BHAP2	A1	0-10	7.3	19.7
BHAP2	B1	10-20	8.0	19.4
BHAP2	A2	20-25	8.0	19.5
BHAP2	B2	25-30	8.0	19.3
BHAP2	B3	30-35	7.9	19.5
BHAP2	B4	35-40	8.0	19.3
BHAP3	A1	0-10	7.8	19.1
BHAP3	B1	10-20	7.8	19.5
BHAP3	A2	20-30	7.9	19.4
BHAP3	A3	30-50	7.8	19.8
BHAP3	A4	50-70	7.9	19.5
BHAP3	A5	70-90	7.8	19.5
BHAP3	A6	90-120	7.8	19.5
BHAP4	A	0-5	8.0	19.6
BHAP4	B	5-30	8.0	19.5
BHAP4	C	30-40	8.0	19.3
BHAP5	A	0-10	7.9	19.1
BHAP5	B1	10-40	7.8	19.8
BHAP5	B2	40-60	7.9	19.8
BHAP5	B3	60-80	7.9	19.6
BHAP5	B4	80-120	7.8	19.8
BHAP6	A	0-10	7.5	19.7
BHAP6	AC1	10-20	7.6	19.7
BHAP6	AC2	20-30	7.6	19.7
BHAP6	C1	30-40	7.7	19.7
BHAP6	C2	40-60	7.9	19.7
BHAP7	A1	0-10	7.8	19.8
BHAP7	A2	10-20	8.0	19.9
BHAP7	B1	20-30	7.8	20.2
BHAP7	B2	30-60	8.0	20.0
BHAP7	C	60-120	8.1	20.0
BHAP8	A	0-10	8.1	20.1
BHAP8	B1	10-20	8.0	20.0
BHAP8	B2	20-30	7.9	20.4
BHAP8	C1	30-60	7.9	20.3
BHAP8	C2	60-70	7.8	20.4
BHAP8	C3	70-90	7.8	20.5
BHAP8	C4	90-120	7.9	20.2

Appendix VII. pH Measurements (continued)

Auger probe number	Horizon	Depth (cm)	pH	Temperature (°C)
BHAP8	C5	120-150	7.8	19.8
BHAP8	C6	150-170	7.9	20.1
BHAP9	A	0-20	7.8	20.1
BHAP9	AB	20-30	7.6	20.0
BHAP9	B1	30-60	7.9	20.0
BHAP9	B2	60-90	8.0	20.2
BHAP9	C	90-110	7.7	20.5
BHAP10	A	0-20	7.7	20.5
BHAP10	AB	20-30	7.9	20.0
BHAP10	B	30-70	7.9	20.1
BHAP10	C	70-90	7.9	20.1
BHAP11	A	0-10	7.9	20.1
BHAP11	AB	10-20	7.9	20.4
BHAP11	B	20-30	7.8	20.3
BHAP11	C1	30-40	7.8	20.5
BHAP11	C2	40-50	7.9	20.5
BHAP12	A	0-10	7.8	20.4
BHAP12	AC	10-20	7.8	20.5
BHAP12	C	20-40	7.8	20.5
BHAP13	A	0-10	7.4	20.6
BHAP13	AC	10-20	7.6	20.2
BHAP13	C	20-30	7.6	19.8
BHAP14	A	0-30	7.7	19.9
BHAP14	AB	30-40	8.0	20.0
BHAP14	B	40-50	7.9	20.1
BHAP14	BC	50-60	7.9	20.0
BHAP14	C1	60-70	7.9	20.2
BHAP14	C2	70-80	8.0	20.0
BHAP15	A	0-20	7.8	20.0
BHAP15	AC	20-30	7.8	20.0
BHAP15	C	30-50	7.8	19.9
BHAP16	A	0-60	8.1	20.0
BHAP16	B	60-80	8.3	20.0
BHAP16	C	80-120	8.2	20.0
BHAP17	A	0-20	8.0	19.9
BHAP17	B	20-30	8.3	19.8
BHAP17	C1	30-60	8.0	19.8
BHAP17	C2	60-90	8.0	19.6
BHAP17	C3	90-120	8.0	19.7
BHAP17	C4	120-170	8.1	19.4
BHAP18	A1	0-20	7.7	19.2

Appendix VII. pH Measurements (continued)				
Auger probe number	**Horizon**	**Depth (cm)**	**pH**	**Temperature (°C)**
BHAP18	A2	20-40	7.8	18.9
BHAP18	AB	40-50	7.9	18.8
BHAP18	B	50-90	8.2	19.3
BHAP18	BC	90-100	8.0	19.2
BHAP18	C	100-150	8.0	19.4
BHAP19	A	0-20	7.8	18.9
BHAP19	B	20-25	7.8	18.9
BHAP19	C	25-45	7.9	18.9
BHAP20	A1	0-20	7.8	19.6
BHAP20	A2	20-40	7.8	19.3
BHAP20	A3	40-60	8.0	19.2
BHAP20	B	60-70	8.1	19.5
BHAP20	C1	70-120	8.2	19.3
BHAP20	C2	120-170	8.1	19.2
BHAP20	C3	170-230	8.0	18.9

Appendix VIII. Phosphate Concentrations

Auger probe number	Horizon	Depth (cm)	PO_4	P	P_2O_5	PO_4 calib.	P calib.	P_2O_5 calib.
BHAP1	A	0-20	2.4	0.8	1.8	120.0	39.0	89.5
BHAP1	B	20-40	1.7	0.6	1.3	84.0	27.5	63.0
BHAP2	A1	0-10	2.0	0.7	1.5	101.0	33.0	75.5
BHAP2	B1	10-20	1.7	0.6	1.3	87.0	28.5	65.0
BHAP2	A2	20-25	2.0	0.7	1.5	100.0	32.5	75.0
BHAP2	B2	25-30	2.0	0.7	1.5	101.5	33.0	76.0
BHAP2	B3	30-35	2.2	0.7	1.7	112.0	36.5	83.5
BHAP2	B4	35-40	2.4	0.8	1.8	122.0	40.0	91.5
BHAP3	A1	0-10	2.0	0.7	1.5	100.5	33.0	75.0
BHAP3	B1	10-20	2.3	0.7	1.7	114.0	37.0	85.0
BHAP3	A2	20-30	1.9	0.6	1.4	94.5	31.0	70.5
BHAP3	A3	30-50	2.1	0.7	1.5	103.0	33.5	77.0
BHAP3	A4	50-70	2.3	0.8	1.7	116.0	38.0	86.5
BHAP3	A5	70-90	1.8	0.6	1.3	89.0	29.0	66.5
BHAP3	A6	90-120	1.8	0.6	1.4	91.5	30.0	68.5
BHAP4	A	0-5	2.4	0.8	1.8	122.0	40.0	91.5
BHAP4	B	5-30	1.8	0.6	1.3	89.0	29.0	66.5
BHAP4	C	30-40	1.9	0.6	1.4	95.0	31.0	71.0
BHAP5	A	0-10	2.2	0.7	1.6	109.0	35.5	81.5
BHAP5	B1	10-40	2.1	0.7	1.6	105.0	34.5	78.5
BHAP5	B2	40-60	1.9	0.6	1.4	95.5	31.0	71.5
BHAP5	B3	60-80	2.4	0.8	1.8	118.0	38.5	88.5
BHAP5	B4	80-120	2.2	0.7	1.6	108.0	35.0	80.5
BHAP6	A	0-10	2.6	0.9	2.0	130.5	42.5	97.5
BHAP6	AC1	10-20	1.9	0.6	1.4	93.0	30.5	69.5
BHAP6	AC2	20-30	2.0	0.7	1.5	101.5	33.0	76.0
BHAP6	C1	30-40	2.0	0.7	1.5	100.0	32.5	74.5
BHAP6	C2	40-60	2.2	0.7	1.7	111.0	36.0	83.0
BHAP7	A1	0-10	1.8	0.6	1.3	88.5	29.0	66.0
BHAP7	A2	10-20	1.8	0.6	1.3	89.0	29.0	66.5
BHAP7	B1	20-30	2.0	0.7	1.5	100.5	32.5	75.0
BHAP7	B2	30-60	1.7	0.6	1.3	83.5	27.5	62.5
BHAP7	C	60-120	2.2	0.7	1.6	107.5	35.0	80.5
BHAP8	A	0-10	2.2	0.7	1.7	111.5	36.5	83.0
BHAP8	B1	10-20	2.2	0.7	1.6	109.0	35.5	81.5
BHAP8	B2	20-30	2.4	0.8	1.8	118.5	38.5	88.5
BHAP8	C1	30-60	1.8	0.6	1.3	87.5	28.5	65.5
BHAP8	C2	60-70	1.9	0.6	1.4	92.5	30.0	69.5
BHAP8	C3	70-90	2.2	0.7	1.7	110.5	36.0	82.5
BHAP8	C4	90-120	2.1	0.7	1.6	105.5	34.5	79.0
BHAP8	C5	120-150	1.9	0.6	1.4	96.0	31.5	71.5
BHAP8	C6	150-170	2.0	0.7	1.5	100.0	32.5	74.5
BHAP9	A	0-20	2.4	0.8	1.8	118.0	38.5	88.5

Appendix VIII. Phosphate Concentrations (continued)								
Auger probe number	**Horizon**	**Depth (cm)**	**PO_4**	**P**	**P_2O_5**	**PO_4 calib.**	**P calib.**	**P_2O_5 calib.**
BHAP9	AB	20-30	2.5	0.8	1.9	123.5	40.5	92.5
BHAP9	B1	30-60	1.8	0.6	1.4	90.0	29.5	67.5
BHAP9	B2	60-90	1.9	0.6	1.4	93.0	30.5	69.5
BHAP9	C	90-110	1.9	0.6	1.4	95.5	31.0	71.5
BHAP10	A	0-20	2.5	0.8	1.9	125.5	41.0	94.0
BHAP10	AB	20-30	2.0	0.7	1.5	99.0	32.5	74.0
BHAP10	B	30-70	2.0	0.6	1.5	98.5	32.0	73.5
BHAP10	C	70-90	2.2	0.7	1.6	107.5	35.0	80.5
BHAP11	A	0-10	2.1	0.7	1.6	106.0	34.5	79.0
BHAP11	AB	10-20	1.5	0.5	1.1	75.5	24.5	56.5
BHAP11	B	20-30	1.6	0.5	1.2	81.5	26.5	61.0
BHAP11	C1	30-40	1.8	0.6	1.4	91.5	30.0	68.5
BHAP11	C2	40-50	1.8	0.6	1.4	91.0	29.5	68.0
BHAP12	A	0-10	2.2	0.7	1.6	108.5	35.5	81.0
BHAP12	AC	10-20	1.6	0.5	1.2	77.5	25.5	58.0
BHAP12	C	20-40	1.6	0.5	1.2	80.0	26.0	60.0
BHAP13	A	0-10	1.8	0.6	1.3	90.0	29.5	67.0
BHAP13	AB	10-20	2.0	0.7	1.5	100.0	32.5	75.0
BHAP13	C	20-30	2.0	0.7	1.5	102.0	33.5	76.0
BHAP14	A	0-30	2.8	0.9	2.1	137.5	45.0	103.0
BHAP14	AB	30-40	1.9	0.6	1.4	96.0	31.5	71.5
BHAP14	B	40-50	1.7	0.6	1.3	83.5	27.5	62.5
BHAP14	BC	50-60	1.7	0.6	1.3	85.5	28.0	63.5
BHAP14	C1	60-70	1.5	0.5	1.1	74.5	24.5	55.5
BHAP14	C2	70-80	1.4	0.5	1.1	70.0	23.0	52.5
BHAP15	A	0-20	1.3	0.4	1.0	66.5	21.5	49.5
BHAP15	AC	20-30	2.1	0.7	1.6	105.5	34.5	79.0
BHAP15	C	30-50	2.2	0.7	1.7	110.5	36.0	82.5
BHAP16	A	0-60	2.2	0.7	1.6	108.5	35.5	81.0
BHAP16	B	60-80	1.7	0.6	1.3	86.0	28.0	64.5
BHAP16	C	80-120	1.4	0.5	1.1	71.0	23.0	53.0
BHAP17	A	0-20	2.1	0.7	1.6	104.0	34.0	77.5
BHAP17	B	20-30	2.4	0.8	1.8	122.0	40.0	91.0
BHAP17	C1	30-60	2.1	0.7	1.6	106.5	35.0	79.5
BHAP17	C2	60-90	2.2	0.7	1.6	107.5	35.0	80.5
BHAP17	C3	90-120	2.0	0.6	1.5	98.5	32.0	74.0
BHAP17	C4	120-170	1.9	0.6	1.3	96.5	28.0	64.5
BHAP17	C4	120-170	1.9	0.6	1.3	96.5	28.0	64.5
BHAP18	A1	0-20	2.8	0.9	2.1	137.5	45.0	103.0
BHAP18	A2	20-40	2.8	0.9	2.1	137.5	45.0	103.0
BHAP18	AB	40-50	2.3	0.7	1.7	114.0	37.0	85.0
BHAP18	B	50-90	1.9	0.6	1.4	94.5	31.0	71.0

Appendix VIII. Phosphate Concentrations (continued)

Auger probe number	Horizon	Depth (cm)	PO_4	P	P_2O_5	PO_4 calib.	P calib.	P_2O_5 calib.
BHAP18	BC	90-100	1.9	0.6	1.4	94.5	31.0	71.0
BHAP18	C	100-150	1.8	0.6	1.3	88.0	28.5	65.5
BHAP19	A	0-20	2.8	0.9	2.1	137.5	45.0	103.0
BHAP19	B	20-25	2.8	0.9	2.1	137.5	45.0	103.0
BHAP19	C	25-45	2.2	0.7	1.6	108.5	35.5	81.0
BHAP20	A1	0-20	2.8	0.9	2.1	137.5	45.0	103.0
BHAP20	A2	20-40	2.8	0.9	2.1	137.5	45.0	103.0
BHAP20	A3	40-60	2.8	0.9	2.1	137.5	45.0	103.0
BHAP20	B	60-70	2.7	0.9	2.0	133.5	43.5	100.0
BHAP20	C1	70-120	2.1	0.7	1.6	103.5	33.5	77.5
BHAP20	C2	120-170	2.7	0.9	2.0	135.0	44.0	101.0
BHAP20	C3	170-230	2.1	0.7	1.6	104.0	34.0	78.0

Appendix IX. Calcium Carbonate Percentage and Organic Carbon Percentage

Auger probe number	Horizon	Depth (cm)	Crucible weight (g)	Sample weight (g)	Crucible + sample weight (g)	Dry crucible + sample weight (g)	Dry sample weight (g)	Ashed crucible + sample weight (g)	Ashed sample weight (g)	Proportion organic carbon	Weight without CaCo3 (g)	CaCO3 weight (g)	Proportion CaCO3 (g)
BHAP1	A	0-20	22.5	5.0	27.5	26.9	4.4	26.8	4.3	0.0	26.5	4.0	0.1
BHAP1	B	20-40	19.1	5.0	24.1	23.6	4.5	23.4	4.3	0.0	22.7	3.6	0.2
BHAP2	A1	0-10	22.7	5.0	27.7	27.1	4.4	27.0	4.3	0.0	26.3	3.6	0.2
BHAP2	B1	10-20	18.8	5.0	23.8	23.2	4.4	23.1	4.4	0.0	22.5	3.7	0.2
BHAP2	A2	20-25	21.9	5.0	26.9	26.3	4.4	26.3	4.4	0.0	25.9	4.0	0.1
BHAP2	B2	25-30	20.9	5.0	25.9	25.2	4.4	25.2	4.4	0.0	24.9	4.0	0.1
BHAP2	B3	30-35	20.0	5.0	25.0	24.1	4.1	24.1	4.1	0.0	23.7	3.7	0.1
BHAP2	B4	35-40	20.5	5.0	25.5	24.7	4.2	24.7	4.2	0.0	24.3	3.8	0.1
BHAP3	A1	0-10	21.9	5.0	26.9	26.2	4.3	26.1	4.2	0.0	25.5	3.7	0.1
BHAP3	B1	10-20	19.5	5.0	24.5	23.8	4.4	23.8	4.3	0.0	23.2	3.7	0.1
BHAP3	A2	20-30	20.9	5.0	25.9	25.3	4.3	25.2	4.3	0.0	24.8	3.9	0.1
BHAP3	A3	30-50	22.1	5.0	27.1	26.5	4.5	26.5	4.4	0.0	26.1	4.1	0.1
BHAP3	A4	50-70	19.5	5.0	24.5	23.7	4.3	23.7	4.2	0.0	23.3	3.9	0.1
BHAP3	A5	70-90	20.9	5.0	25.9	24.9	4.1	24.9	4.0	0.0	24.5	3.6	0.1
BHAP3	A6	90-120	20.6	5.0	25.7	24.8	4.1	24.8	4.1	0.0	24.4	3.8	0.1
BHAP4	A	0-5	20.2	5.0	25.3	24.6	4.3	24.5	4.3	0.0	24.1	3.9	0.1
BHAP4	B	5-30	20.0	5.0	25.0	24.2	4.3	24.2	4.3	0.0	23.9	3.9	0.1
BHAP4	C	30-40	18.6	5.0	23.6	22.9	4.3	22.8	4.2	0.0	22.5	3.9	0.1
BHAP5	A	0-10	20.3	5.0	25.3	24.6	4.3	24.4	4.1	0.0	24.1	3.8	0.1
BHAP5	B1	10-40	20.0	5.0	25.0	24.3	4.3	24.1	4.1	0.0	23.8	3.8	0.1
BHAP5	B2	40-60	19.5	5.0	24.5	23.8	4.3	23.7	4.2	0.0	23.4	3.9	0.1
BHAP5	B3	60-80	18.9	5.0	23.9	23.2	4.3	23.1	4.2	0.0	22.8	4.0	0.1
BHAP5	B4	80-120	19.5	5.0	24.5	23.6	4.1	23.5	4.0	0.0	23.2	3.7	0.1
BHAP6	A	0-10	19.1	5.0	24.1	23.2	4.1	23.0	3.9	0.1	22.6	3.5	0.1
BHAP6	AC1	10-20	22.7	5.0	27.7	26.9	4.2	26.8	4.1	0.0	26.3	3.6	0.1
BHAP6	AC2	20-30	20.6	5.0	25.7	25.2	4.6	25.2	4.5	0.0	23.8	3.1	0.3
BHAP6	C1	30-40	20.3	5.0	25.3	25.0	4.7	24.9	4.7	0.0	23.5	3.2	0.3
BHAP6	C2	40-60	20.9	5.0	25.9	25.6	4.7	25.5	4.6	0.0	24.1	3.2	0.3
BHAP7	A1	0-10	20.4	5.0	25.5	24.7	4.3	24.5	4.1	0.0	24.0	3.6	0.1
BHAP7	A2	10-20	22.1	5.0	27.1	26.4	4.3	26.3	4.2	0.0	25.8	3.7	0.1
BHAP7	B1	20-30	20.0	5.0	25.0	24.4	4.4	24.3	4.3	0.0	23.7	3.7	0.1
BHAP7	B2	30-60	18.7	5.0	23.7	23.0	4.4	23.0	4.4	0.0	22.4	3.8	0.1
BHAP7	C	60-120	20.0	5.0	25.0	24.2	4.2	24.2	4.2	0.0	23.7	3.7	0.1
BHAP8	A	0-10	21.9	5.0	27.0	26.4	4.4	26.3	4.4	0.0	25.8	3.9	0.1
BHAP8	B1	10-20	22.6	5.0	27.6	26.8	4.2	26.8	4.2	0.0	26.1	3.5	0.2
BHAP8	B2	20-30	20.5	5.0	25.5	24.8	4.3	24.8	4.3	0.0	24.0	3.5	0.2
BHAP8	C1	30-60	21.9	5.0	26.9	26.0	4.2	26.0	4.1	0.0	24.8	2.9	0.3
BHAP8	C2	60-70	20.9	5.0	25.9	25.2	4.3	25.2	4.3	0.0	24.3	3.4	0.2

Appendix IX. Calcium Carbonate Percentage and Organic Carbon Percentage (continued)

Auger probe number	Horizon	Depth (cm)	Crucible weight (g)	Sample weight (g)	Crucible + sample weight (g)	Dry crucible + sample weight (g)	Dry sample weight (g)	Ashed crucible + sample weight (g)	Ashed sample weight (g)	Proportion organic carbon	Weight without CaCo3 (g)	CaCO3 weight (g)	Proportion CaCO3 (g)
BHAP8	C3	70-90	20.9	5.0	26.0	25.5	4.5	25.5	4.5	0.0	24.9	3.9	0.1
BHAP8	C4	90-120	20.0	5.0	25.0	24.3	4.3	24.3	4.3	0.0	23.4	3.4	0.2
BHAP8	C5	120-150	27.9	5.0	32.9	32.1	4.1	32.0	4.1	0.0	31.1	3.2	0.2
BHAP8	C6	150-170	26.7	5.0	31.7	30.8	4.1	30.8	4.1	0.0	30.2	3.5	0.1
BHAP9	A	0-20	27.1	5.0	32.1	31.4	4.3	31.3	4.2	0.0	30.8	3.7	0.1
BHAP9	AB	20-30	27.0	5.0	32.1	31.3	4.2	31.2	4.2	0.0	30.7	3.7	0.1
BHAP9	B1	30-60	26.6	5.0	31.6	30.6	4.1	30.6	4.0	0.0	30.2	3.6	0.1
BHAP9	B2	60-90	27.5	5.0	32.6	31.6	4.1	31.6	4.1	0.0	31.2	3.7	0.1
BHAP9	C	90-110	26.6	5.0	31.6	30.9	4.3	30.9	4.3	0.0	30.3	3.8	0.1
BHAP10	A	0-20	26.8	5.0	31.8	31.0	4.2	30.9	4.1	0.0	30.4	3.6	0.1
BHAP10	AB	20-30	25.9	5.0	30.9	30.2	4.3	30.1	4.3	0.0	29.6	3.7	0.1
BHAP10	B	30-70	25.6	5.0	30.6	29.9	4.3	29.9	4.3	0.0	29.3	3.7	0.1
BHAP10	C	70-90	26.4	5.0	31.4	30.8	4.4	30.8	4.4	0.0	30.3	3.9	0.1
BHAP11	A	0-10	26.8	5.0	31.9	30.9	4.1	30.9	4.0	0.0	30.3	3.5	0.1
BHAP11	AB	10-20	26.6	5.0	31.6	30.7	4.0	30.6	4.0	0.0	30.2	3.6	0.1
BHAP11	B	20-30	25.3	5.0	30.3	29.5	4.2	29.5	4.2	0.0	28.9	3.6	0.1
BHAP11	C1	30-40	25.9	5.0	30.9	30.3	4.4	29.8	3.9	0.1	29.0	3.2	0.2
BHAP11	C2	40-50	25.2	5.0	30.2	29.9	4.6	28.9	3.6	0.2	28.5	3.3	0.1
BHAP12	A	0-10	27.2	5.0	32.2	31.3	4.2	30.7	3.5	0.2	27.6	0.4	0.2
BHAP12	AC	10-20	26.0	5.0	31.0	30.2	4.2	30.1	4.1	0.0	28.8	2.8	0.3
BHAP12	C	20-40	29.0	5.0	34.1	33.4	4.3	33.3	4.3	0.0	31.7	2.6	0.4
BHAP13	A	0-10	28.0	5.0	33.1	32.3	4.2	32.2	4.1	0.0	31.2	3.1	0.3
BHAP13	AB	10-20	24.5	5.0	29.6	28.8	4.2	28.7	4.1	0.0	27.4	2.9	0.3
BHAP13	C	20-30	27.5	5.0	32.5	31.8	4.3	31.7	4.2	0.0	30.1	2.6	0.4
BHAP14	A	0-30	27.5	5.0	32.5	31.7	4.2	31.5	4.0	0.1	30.8	3.3	0.2
BHAP14	AB	30-40	25.8	5.0	30.8	29.7	3.9	29.7	3.9	0.0	29.2	3.4	0.1
BHAP14	B	40-50	18.6	5.0	23.6	22.7	4.1	22.7	4.0	0.0	22.3	3.7	0.1
BHAP14	BC	50-60	20.9	5.0	25.9	25.3	4.4	25.2	4.4	0.0	24.5	3.6	0.2
BHAP14	C1	60-70	20.2	5.0	25.2	24.9	4.6	24.8	4.6	0.0	23.7	3.5	0.2
BHAP14	C2	70-80	19.1	5.0	24.1	23.7	4.6	23.7	4.6	0.0	22.5	3.5	0.2
BHAP15	A	0-20	21.9	5.0	26.9	26.1	4.2	26.0	4.1	0.0	25.4	3.5	0.2
BHAP15	AC	20-30	20.7	5.0	25.6	25.2	4.5	25.0	4.4	0.0	23.9	3.2	0.3
BHAP15	C	30-50	20.5	5.0	25.5	25.2	4.7	25.2	4.7	0.0	23.6	3.1	0.3
BHAP16	A	0-60	22.5	5.0	27.5	27.0	4.5	27.0	4.5	0.0	26.3	3.8	0.1
BHAP16	B	60-80	19.5	5.0	24.5	23.6	4.1	23.6	4.1	0.0	22.9	3.4	0.2
BHAP16	C	80-120	20.3	5.0	25.3	24.5	4.2	24.5	4.2	0.0	23.5	3.2	0.2
BHAP17	A	0-20	20.0	5.0	25.0	24.4	4.4	24.3	4.3	0.0	24.0	4.0	0.1

Appendix IX. Calcium Carbonate Percentage and Organic Carbon Percentage (continued)

Auger probe number	Horizon	Depth (cm)	Crucible weight (g)	Sample weight (g)	Crucible + sample weight (g)	Dry crucible + sample weight (g)	Dry sample weight (g)	Ashed crucible + sample weight (g)	Ashed sample weight (g)	Proportion organic carbon	Weight without CaCo3 (g)	CaCO3 weight (g)	Proportion CaCO3 (g)
BHAP17	B	20-30	22.7	5.0	27.7	26.9	4.2	26.9	4.2	0.0	26.7	4.0	0.1
BHAP17	C1	30-60	20.9	5.0	25.9	25.0	4.1	24.0	3.1	0.2	24.8	3.8	0.1
BHAP17	C2	60-90	20.0	5.0	25.1	24.2	4.2	24.2	4.1	0.0	23.9	3.9	0.1
BHAP17	C3	90-120	19.4	5.0	24.4	23.6	4.2	23.6	4.2	0.0	23.3	3.9	0.1
BHAP17	C4	120-170	18.8	5.0	23.8	23.0	4.2	22.9	4.1	0.0	22.7	3.9	0.1
BHAP18	A1	0-20	21.9	5.0	26.9	26.2	4.3	26.0	4.1	0.0	25.6	3.7	0.1
BHAP18	A2	20-40	20.8	5.0	25.8	26.3	5.5	26.2	5.4	0.0	25.7	4.9	0.1
BHAP18	AB	40-50	20.8	5.0	25.8	25.2	4.4	25.2	4.4	0.0	24.9	4.0	0.1
BHAP18	B	50-90	19.9	5.0	24.9	24.3	4.3	24.3	4.3	0.0	24.0	4.1	0.1
BHAP18	BC	90-100	25.9	5.0	30.9	30.2	4.3	30.2	4.3	0.0	29.9	4.1	0.1
BHAP18	C	100-150	27.2	5.0	32.2	31.7	4.5	31.6	4.4	0.0	31.4	4.2	0.1
BHAP19	A	0-20	25.2	5.0	30.2	29.4	4.2	29.2	4.0	0.0	28.7	3.5	0.1
BHAP19	B	20-25	25.0	5.0	30.0	29.2	4.1	29.1	4.1	0.0	28.7	3.6	0.1
BHAP19	C	25-45	26.9	5.0	31.8	30.9	4.0	30.9	4.0	0.0	30.5	3.7	0.1
BHAP20	A1	0-20	28.6	5.0	33.6	33.0	4.4	32.7	4.1	0.1	32.1	3.5	0.2
BHAP20	A2	20-40	27.4	5.0	32.4	31.8	4.4	31.7	4.3	0.0	31.3	3.9	0.1
BHAP20	A3	40-60	25.7	5.0	30.6	29.9	4.2	29.9	4.2	0.0	29.4	3.7	0.1
BHAP20	B	60-70	26.6	5.0	31.6	30.9	4.3	30.8	4.3	0.0	30.5	4.0	0.1
BHAP20	C1	70-120	25.2	5.0	30.2	29.4	4.2	29.2	4.0	0.0	29.1	3.8	0.1
BHAP20	C2	120-170	27.7	5.0	32.7	31.9	4.2	31.8	4.1	0.0	31.6	3.9	0.1
BHAP20	C3	170-230	24.3	5.0	29.3	28.4	4.1	28.3	4.0	0.0	28.0	3.7	0.1

Appendix X. Soil Texture

Auger probe number	Horizon	Depth (cm)	Sand fill line	Silt fill line	Clay fill line	% Sand	% Silt	% Clay	USDA Soil Type
BHAP1	A	0-20	4	3	8	27	20	53	clay
BHAP1	B	20-40	6	4	5	40	27	33	clay
BHAP2	A1	0-10	10	2	3	67	13	20	sandy clay loam
BHAP2	B1	10-20	10	2	3	67	13	20	sandy clay loam
BHAP2	A2	20-25	10	2	3	67	13	20	sandy clay loam
BHAP2	B2	25-30	8	4	3	53	27	20	sandy loam
BHAP2	B3	30-35	8	2	5	53	13	33	sandy clay loam
BHAP2	B4	35-40	10	2	3	67	13	20	sandy clay loam
BHAP3	A1	0-10	10	3	2	67	20	13	sandy loam
BHAP3	B1	10-20	10	3	2	67	20	13	sandy loam
BHAP3	A2	20-30	7	2	6	47	13	40	sandy clay
BHAP3	A3	30-50	6	1	8	40	7	53	clay
BHAP3	A4	50-70	5	1	9	33	7	60	clay
BHAP3	A5	70-90	6	1	8	40	7	53	clay
BHAP3	A6	90-120	8	2	5	53	13	33	sandy clay loam
BHAP4	A	0-5	11	1	3	73	7	20	sandy clay loam
BHAP4	B	5-30	4	3	8	27	20	53	clay
BHAP4	C	30-40	7	4	4	47	27	27	loam
BHAP5	A	0-10	8	6	1	53	40	7	sandy loam
BHAP5	B1	10-40	10	1	4	67	7	27	sandy clay loam
BHAP5	B2	40-60	1	1	13	7	7	87	clay
BHAP5	B3	60-80	2	5	8	13	33	53	clay
BHAP5	B4	80-120	3	3	9	20	20	60	clay
BHAP6	A	0-10	11	3	1	73	20	7	sandy loam
BHAP6	AC1	10-20	9	4	2	60	27	13	sandy loam
BHAP6	AC2	20-30	9	3	3	60	20	20	sandy clay loam
BHAP6	C1	30-40	11	2	2	73	13	13	sandy loam
BHAP6	C2	40-60	11	2	2	73	13	13	sandy loam
BHAP7	A1	0-10	2	2	11	13	13	73	clay
BHAP7	A2	10-20	3	1	11	20	7	73	clay
BHAP7	B1	20-30	5	1	9	33	7	60	clay
BHAP7	B2	30-60	6	1	8	40	7	53	clay
BHAP7	C	60-120	7	3	5	47	20	33	sandy clay
BHAP8	A	0-10	10	1	4	67	7	27	sandy clay loam
BHAP8	B1	10-20	9	2	4	60	13	27	sandy clay loam
BHAP8	B2	20-30	6	2	7	40	13	47	clay
BHAP8	C1	30-60	5	2	8	33	13	53	clay
BHAP8	C2	60-70	8	3	4	53	20	27	sandy clay loam
BHAP8	C3	70-90	8	1	6	53	7	40	sandy clay
BHAP8	C4	90-120	6	2	7	40	13	47	clay

Appendix X. Soil Texture (continued)

Auger probe number	Horizon	Depth (cm)	Sand fill line	Silt fill line	Clay fill line	% Sand	% Silt	% Clay	USDA Soil Type
BHAP8	C5	120-150	6	2	7	40	13	47	clay
BHAP8	C6	150-170	6	2	7	40	13	47	clay
BHAP9	A	0-20	1	1	13	20	7	73	clay
BHAP9	AB	20-30	13	1	1	20	7	73	clay
BHAP9	B1	30-60	3	1	11	20	7	73	clay
BHAP9	B2	60-90	6	1	8	40	7	53	clay
BHAP9	C	90-110	5	2	8	33	13	53	clay
BHAP10	A	0-20	2	1	12	13	7	80	clay
BHAP10	AB	20-30	2	2	11	13	13	73	clay
BHAP10	B	30-70	11	2	2	73	13	13	sandy loam
BHAP10	C	70-90	6	2	7	40	13	47	clay
BHAP11	A	0-10	10	1	4	67	7	27	sandy loam
BHAP11	AB	10-20	10	3	2	67	20	13	sandy loam
BHAP11	B	20-30	11	1	3	73	7	20	sandy loam
BHAP11	C1	30-40	10	1	4	67	7	27	sandy clay loam
BHAP11	C2	40-50	9	3	3	60	20	20	sandy clay loam
BHAP12	A	0-10	8	2	5	53	13	33	sandy clay loam
BHAP12	AC	10-20	10	2	3	67	13	20	sandy clay loam
BHAP12	C	20-40	6	4	5	40	27	33	clay loam
BHAP13	A	0-10	9	2	4	60	13	27	sandy clay loam
BHAP13	AC	10-20	10	1	4	67	7	27	sandy clay loam
BHAP13	C	20-30	10	2	3	67	13	20	sandy clay loam
BHAP14	A	0-30	11	2	2	73	13	13	sandy loam
BHAP14	AB	30-40	10	2	3	67	13	20	sandy clay loam
BHAP14	B	40-50	9	2	4	60	13	27	sandy clay loam
BHAP14	BC	50-60	12	2	1	80	13	7	loamy sand
BHAP14	C1	60-70	8	3	4	53	20	27	sandy clay loam
BHAP14	C2	70-80	9	2	4	60	13	27	sandy clay loam
BHAP15	A	0-20	9	1	5	60	7	33	sandy clay loam
BHAP15	AC	20-30	8	2	5	53	13	33	sandy clay
BHAP15	C	30-50	10	3	2	67	20	13	sandy loam
BHAP16	A	0-60	2	4	9	13	27	60	clay
BHAP16	B	60-80	10	2	3	67	13	20	sandy clay loam
BHAP16	C	80-120	8	3	4	53	20	27	sandy clay loam
BHAP17	A	0-20	10	4	1	67	27	7	sandy loam
BHAP17	B	20-30	7	3	5	47	20	33	sandy clay loam
BHAP17	C1	30-60	10	2	3	67	13	20	sandy clay loam
BHAP17	C2	60-90	2	4	9	13	27	60	clay
BHAP17	C3	90-120	2	3	10	13	20	67	clay
BHAP17	C4	120-170	2	1	12	13	7	80	clay
BHAP18	A1	0-20	11	2	2	73	13	13	sandy loam

Appendix X. Soil Texture (continued)

Auger probe number	Horizon	Depth (cm)	Sand fill line	Silt fill line	Clay fill line	% Sand	% Silt	% Clay	USDA Soil Type
BHAP18	A2	20-40	10	2	3	67	13	20	sandy clay loam
BHAP18	AB	40-50	8	3	4	53	20	27	sandy clay loam
BHAP18	B	50-90	9	3	3	60	20	20	sandy clay loam
BHAP18	BC	90-100	10	3	2	67	20	13	sandy loam
BHAP18	C	100-150	6	3	6	40	20	40	clay
BHAP19	A	0-20	9	2	4	60	13	27	sandy clay loam
BHAP19	B	20-25	10	1	4	67	7	27	sandy clay loam
BHAP19	C	25-45	5	9	1	33	60	7	silt loam
BHAP20	A1	0-20	10	3	2	67	20	13	sandy loam
BHAP20	A2	20-40	8	3	4	53	20	27	loam
BHAP20	A3	40-60	8	2	5	53	13	33	clay loam
BHAP20	B	60-70	9	2	4	60	13	27	sandy clay loam
BHAP20	C1	70-120	8	3	4	53	20	27	clay loam
BHAP20	C2	120-170	6	1	8	40	7	53	clay
BHAP20	C3	170-230	9	1	5	60	7	33	sandy clay loam

Appendix XI. Trace Element Quantification using pXRF

	Element (ppm)									
Auger Probe, Horizon, Analysis Number	**Fe**	**Rb**	**Sr**	**Y**	**Zr**	**Ba**	**Zn**	**Ti**	**Mn**	**Pb**
BHAP1A-1	24651	13	345	23	48	1458	65	986	785	20
BHAP1A-2	23463	14	302	22	45	1355	64	1036	652	25
BHAP1B-1-1	25985	16	455	18	62	1634	48	1100	1460	15
BHAP1B-1-2	25809	14	208	20	65	1356	43	1238	630	19
BHAP1B-2-1	27783	13	594	20	67	2249	48	1619	1864	20
BHAP1B-2-2	28390	16	286	21	66	1463	39	1238	2023	20
BHAP2A1-1	26348	11	303	21	72	1347	75	967	239	20
BHAP2A1-2	26170	11	329	20	82	3151	60	2329	255	16
BHAP2A2-1	30797	17	269	22	82	1840	64	1634	473	26
BHAP2A2-2	30168	17	241	21	78	1459	65	1308	342	24
BHAP2B1-1	24920	9	285	18	66	1462	43	1185	287	19
BHAP2B1-2	24464	12	307	20	66	1461	59	1147	206	19
BHAP2B2-1	30861	17	257	19	86	1653	65	1475	301	25
BHAP2B2-2	30863	16	272	20	84	1435	52	1221	462	25
BHAP2B3-1	31382	11	453	17	91	1750	62	1223	62	21
BHAP2B3-2	31037	12	458	24	93	1672	59	1141	134	20
BHAP2B4-1	28159	10	473	22	93	1644	52	979	87	20
BHAP2B4-2	29881	12	432	18	91	1610	62	1087	14	18
BHAP3A1-1	22082	7	212	17	56	1126	68	349	403	15
BHAP3A1-2	25915	13	287	19	70	1287	74	682	226	20
BHAP3A2-1	24128	20	230	23	77	1197	70	1020	502	31
BHAP3A3-1	24286	16	238	22	71	1193	83	910	551	29
BHAP3A3-2	26238	19	265	27	79	1392	79	1201	720	33
BHAP3A4-1	26408	19	324	33	83	1396	74	971	984	23
BHAP3A4-2	26264	22	286	22	86	1307	75	1006	699	22
BHAP3A5-1	27440	25	250	23	81	1246	78	1097	2069	21
BHAP3A5-2	26477	25	238	23	90	1223	64	1098	1621	20
BHAP3A6-1	25050	17	257	24	78	1212	51	850	537	19
BHAP3A6-2	24675	18	263	28	78	1311	58	937	1523	18
BHAP3B1-1	26477	10	309	21	68	1322	56	515	124	18
BHAP3B1-2	27101	9	291	19	69	1239	51	718	132	16
BHAP4A-1	28688	19	230	23	71	1445	85	1356	804	29
BHAP4A-2	29473	15	206	25	76	1499	99	1421	598	26
BHAP4B-1	27076	17	210	24	76	1216	50	985	183	19
BHAP4B-2	27348	18	216	20	79	1172	57	970	638	21
BHAP4C-2	28257	15	283	24	88	1324	53	894	55	15
BHAP5A-1	30504	17	138	23	67	1291	62	1334	1125	28
BHAP5A-2	30646	18	145	21	67	1264	84	1304	1102	30
BHAP5B1-1	30244	20	171	24	66	1419	63	1451	1201	28

Appendix XI. Trace Element Quantification using pXRF (continued)

	Element (ppm)									
Auger Probe, Horizon, Analysis Number	**Fe**	**Rb**	**Sr**	**Y**	**Zr**	**Ba**	**Zn**	**Ti**	**Mn**	**Pb**
BHAP5B1-2	28216	16	140	22	63	1002	76	915	1058	24
BHAP5B2-1	31672	15	123	20	75	1244	55	1285	152	15
BHAP5B2-2	30467	19	115	22	72	1195	64	1296	238	22
BHAP5B3-1	30905	14	154	23	84	1394	65	1441	1323	19
BHAP5B3-2	32297	15	150	22	73	1603	69	1633	939	18
BHAP5B4-1	29802	14	133	23	77	1273	54	1331	1479	21
BHAP5B4-2	27983	15	136	22	68	1036	47	883	400	17
BHAP6A-1	32946	20	98	22	60	1402	59	1592	1607	21
BHAP6A-2	31514	18	85	20	64	1012	60	1147	1114	23
BHAP6AC1-1	32849	20	120	21	50	1301	55	1405	910	23
BHAP6AC1-2	31433	19	99	22	57	1344	62	1519	1453	24
BHAP6AC2-1	18008	14	126	14	32	987	67	699	561	21
BHAP6AC2-2	17062	14	135	14	28	1017	60	517	618	19
BHAP6C1-1	14742	12	168	12	26	1024	58	508	843	19
BHAP6C1-2	15361	13	176	13	23	1068	72	726	739	22
BHAP6C2-1	18670	14	155	15	28	1016	57	660	863	21
BHAP6C2-2	18486	14	165	14	26	1023	73	723	988	20
BHAP7A1-1	30451	20	188	20	53	1274	76	1242	751	27
BHAP7A1-2	30858	18	165	19	52	1273	72	1285	893	32
BHAP7A2-1	31415	17	161	23	56	1342	66	1390	2378	26
BHAP7A2-2	31119	17	150	23	51	1568	64	1611	874	24
BHAP7B1-1	31093	13	141	24	53	1293	58	1379	2208	20
BHAP7B2-1	25667	10	108	16	44	1025	88	1058	335	21
BHAP7B2-2	28757	12	127	22	48	1400	67	1521	2471	22
BHAP7C-1	30361	11	103	18	51	996	93	1061	208	18
BHAP7C-2	27354	11	95	17	45	1076	85	1067	68	23
BHAP8A-1	25577	10	174	19	58	1170	91	1055	566	23
BHAP8A-2	25494	14	150	18	47	1103	75	1017	764	23
BHAP8B1-1	17899	9	229	17	39	1083	71	458	281	20
BHAP8B1-2	19241	11	239	17	38	1178	70	720	499	22
BHAP8B2-1	16978	8	188	16	33	1072	59	328	242	21
BHAP8B2-2	17291	8	190	16	36	1125	63	574	412	17
BHAP8C1-1	9059	10	136	14	27	1069	82	339	163	23
BHAP8C1-2	9688	12	146	14	24	987	70	213	208	21
BHAP8C2-1	14537	9	249	16	35	1179	74	618	621	20
BHAP8C2-2	13426	12	234	17	27	1190	56	553	574	19
BHAP8C3-2	17838	9	249	20	44	1155	86	523	572	20
BHAP8C4-1	13867	6	229	17	47	1200	56	395	480	18
BHAP8C4-2	13807	8	220	19	30	1162	65	557	488	19

Appendix XI. Trace Element Quantification using pXRF (continued)

	Element (ppm)									
Auger Probe, Horizon, Analysis Number	Fe	Rb	Sr	Y	Zr	Ba	Zn	Ti	Mn	Pb
BHAP8C5-1	15409	3	137	19	41	991	51	258	297	14
BHAP8C5-2	15221	6	148	19	42	986	64	532	413	20
BHAP8C6-1	18304	8	160	22	47	1013	63	717	596	22
BHAP8C6-2	15771	13	128	17	41	976	83	647	587	21
BHAP9A-1	29045	14	86	21	57	925	93	940	638	26
BHAP9A-2	29805	17	109	19	60	1207	83	1321	636	19
BHAP9AB-1	27312	19	77	22	56	844	86	924	485	22
BHAP9AB-2	28567	15	81	22	58	992	82	1118	1586	19
BHAP9B1-1	28989	15	79	19	61	1047	66	1208	835	21
BHAP9B1-2	26782	13	68	20	51	823	91	748	146	18
BHAP9B2-1	28140	14	71	23	62	869	75	1022	982	20
BHAP9B2-2	25455	13	54	17	57	867	94	851	380	24
BHAP9C-1	26206	9	209	23	47	1171	104	907	2801	22
BHAP9C-2	26197	8	186	24	51	1135	120	1045	2567	24
BHAP10A-1	29036	15	105	19	54	902	101	899	617	26
BHAP10A-2	28588	18	106	20	61	1093	75	1148	631	22
BHAP10AB-1	26054	10	120	19	51	1029	56	939	108	23
BHAP10AB-2	25788	10	100	20	52	1020	64	1033	267	20
BHAP10B-1	25839	14	120	18	53	917	84	778	262	19
BHAP10B-2	19553	9	82	14	37	872	115	729	25	21
BHAP10C-1	33898	10	228	23	54	1297	96	941	66	21
BHAP10C-2	33892	11	236	20	66	1277	67	1054	163	18
BHAP11A-1	32919	17	66	16	48	1244	105	1467	531	20
BHAP11A-2	30450	12	56	20	48	1194	80	1405	496	23
BHAP11AB-1	27514	12	51	12	37	1156	177	1407	147	23
BHAP11AB-2	29782	17	67	15	45	987	89	1163	120	21
BHAP11B-1	3532	3	6	10	20	790	324	943	548	49
BHAP11B-2	32108	14	73	20	45	1124	151	1300	500	24
BHAP11C1-1	17115	12	173	14	23	1054	70	701	399	20
BHAP11C1-2	17590	13	177	16	26	1070	58	405	442	23
BHAP11C2-1	11657	8	191	13	18	1076	68	504	384	24
BHAP11C2-2	11565	13	195	13	23	1141	64	603	394	20
BHAP12A-1	18061	13	115	14	30	904	76	640	327	22
BHAP12A-2	17731	13	106	14	32	934	71	739	293	23
BHAP12AC-1	16768	13	170	15	28	1079	73	316	180	21
BHAP12AC-2	16257	16	170	13	27	1057	40	483	237	20
BHAP12C-1	11350	12	110	12	19	902	81	577	63	26
BHAP12C-2	11390	11	148	10	17	3	154	1005	11390	11
BHAP13A-2	19578	16	110	19	38	875	86	557	615	21

Appendix XI. Trace Element Quantification using pXRF (continued)

	Element (ppm)									
Auger Probe, Horizon, Analysis Number	**Fe**	**Rb**	**Sr**	**Y**	**Zr**	**Ba**	**Zn**	**Ti**	**Mn**	**Pb**
BHAP13AC-1	11748	12	86	16	26	851	74	538	302	21
BHAP13AC-2	12868	9	100	16	30	952	63	498	393	22
BHAP13C-1	7144	11	93	11	19	922	69	396	159	20
BHAP14A-1	29279	18	80	20	40	968	112	1112	703	27
BHAP14A-2	29572	17	83	17	43	955	103	1001	746	25
BHAP14AB-1	33836	20	54	16	48	1203	81	1472	452	23
BHAP14AB-2	30947	10	47	19	44	916	95	1101	640	23
BHAP14B-1	33524	13	50	17	36	891	106	1118	1071	22
BHAP14B-2	34459	14	67	20	46	1573	109	1745	508	23
BHAP14BC-1	33304	10	123	16	26	978	113	891	317	18
BHAP14BC-2	33764	11	130	19	23	1088	110	1070	405	19
BHAP14C1-1	29413	15	142	13	20	1059	146	870	574	26
BHAP14C1-2	30168	11	152	14	21	1119	102	868	251	19
BHAP14C2-1	25719	13	134	13	19	1065	110	987	292	22
BHAP14C2-2	26260	8	147	10	14	1036	116	611	183	18
BHAP15A-1	29455	14	79	20	41	926	68	1037	864	31
BHAP15A-2	29514	16	80	20	43	1035	92	1154	736	27
BHAP15AC-1	13004	10	67	18	26	810	57	495	258	21
BHAP15AC-2	14464	13	63	17	29	832	98	624	333	21
BHAP15C-1	8498	10	90	13	21	903	79	282	221	21
BHAP15C-2	7883	10	86	14	20	816	71	398	303	22
BHAP16A-1	20932	16	243	22	47	1238	107	962	668	35
BHAP16A-2	21317	22	187	19	52	1216	124	1034	646	37
BHAP16B-1	19490	11	148	18	47	981	86	712	320	28
BHAP16B-2	18251	11	146	18	48	998	114	730	441	23
BHAP16C-1	16317	12	106	16	43	925	87	761	503	22
BHAP16C-2	17296	11	126	19	34	933	75	509	420	19
BHAP17A-1	21465	14	282	20	54	1229	73	760	501	29
BHAP17A-2	23791	14	311	26	56	1422	82	1038	411	30
BHAP17B-1	24848	12	212	24	72	1155	76	922	344	22
BHAP17B-2	26325	14	225	23	63	1193	80	883	226	22
BHAP17C1-1	25000	9	221	28	69	1195	64	925	541	20
BHAP17C1-2	24836	9	212	32	62	1193	72	864	620	15
BHAP17C2-1	23765	10	221	21	60	1127	45	763	672	22
BHAP17C2-2	24606	12	228	25	84	1154	63	741	488	19
BHAP17C3-1	23384	14	219	22	69	1232	65	943	278	22
BHAP17C3-2	25601	18	207	26	74	1204	56	853	173	20
BHAP17C4-1	22661	11	225	25	64	1193	82	860	1208	23
BHAP17C4-2	24597	14	205	22	72	1266	67	1128	710	18

Appendix XI. Trace Element Quantification using pXRF (continued)

	Element (ppm)									
Auger Probe, Horizon, Analysis Number	**Fe**	**Rb**	**Sr**	**Y**	**Zr**	**Ba**	**Zn**	**Ti**	**Mn**	**Pb**
BHAP18A1-1	22163	20	247	21	51	1186	110	614	576	38
BHAP18A1-2	21868	24	274	22	54	1175	112	733	681	44
BHAP18A2-1	20781	18	278	25	49	1210	102	620	753	51
BHAP18A2-2	21765	16	280	21	53	1241	87	620	591	49
BHAP18AB-1	21628	18	283	18	55	1368	59	1139	508	30
BHAP18B-1	22880	12	259	20	66	1318	68	1052	287	18
BHAP18B-2	21954	15	279	20	66	1371	59	1088	130	20
BHAP18BC-1	19651	9	251	17	61	1311	74	985	174	23
BHAP18BC-2	23215	13	332	19	66	1472	90	1146	366	20
BHAP18C-1	20808	12	343	19	55	1350	90	817	332	18
BHAP18C-2	20823	14	316	21	57	1491	91	1187	462	25
BHAP19A-1	21084	20	270	20	50	1247	261	844	626	54
BHAP19A-2	22449	21	282	20	53	1281	262	882	559	50
BHAP19B-1	23857	14	214	21	60	1073	149	698	462	29
BHAP19B-2	24016	14	238	18	61	1157	137	764	518	31
BHAP19C-1	26659	10	387	19	70	1429	70	732	106	21
BHAP19C-2	26806	8	405	20	74	1416	80	698	529	24
BHAP20A1-1	20444	18	288	20	53	1208	142	654	535	55
BHAP20A1-2	19653	19	274	20	50	1174	141	558	413	53
BHAP20A2-1	22194	18	271	19	47	1367	120	1068	640	37
BHAP20A2-2	18623	18	272	18	58	1173	119	589	510	43
BHAP20A3-1	19886	15	229	24	61	1162	78	715	739	27
BHAP20A3-2	19835	13	218	23	69	1145	60	718	628	24
BHAP20B-1	20658	12	257	21	67	1216	74	594	384	25
BHAP20B-2	19870	10	253	23	63	1244	52	714	345	21
BHAP20C1-1	20764	11	230	20	69	1198	84	883	57	23
BHAP20C1-2	21364	17	261	21	74	1232	72	806	37	22
BHAP20C2-1	23632	11	208	17	69	1175	101	933	17	23
BHAP20C2-2	24871	11	198	16	77	1180	98	1008	-31	22
BHAP20C3-1	21430	12	241	19	68	1148	70	557	171	20
BHAP20C3-2	24160	13	246	19	80	1190	83	733	310	21