THE INVESTIGATION OF HISTORICAL RICE CULTIVATION USING ADVANCED GEOSPATIAL TECHNIQUES AND ARCHAEOLOGICAL METHODS AT WORMSLOE HISTORIC SITE, GEORGIA

by

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(Under the Direction of Marguerite Madden)

ABSTRACT

Despite much of the environmental history of Wormsloe State Historic Site on the Isle of Hope, Georgia, having previously been documented and described, there are still some unanswered questions. For example, whether rice cultivation was ever performed at Wormsloe has been a question without a definitive answer up until now. The primary goal of this study, therefore, is the investigation of clues within the Isle of Hope landscape that may provide legacy evidence of rice cultivation and place Wormsloe within the agricultural context of the Southeastern U.S. coast in the 18th and 19th centuries. Through advanced remote sensing techniques such as terrestrial laser scanning (TLS) and unmanned aerial systems (UAS), as well as archaeobotanical techniques such as phytolith analysis, the micro topography of the island was mapped and soil components identified to provide archaeological evidence of historical rice cultivation. Terrestrial laser scanning was employed to create a high resolution 3D bare earth digital elevation model (DEM) of the area under investigation where present-day topographic features such as ditches and embankments were indicative of water control within a potential rice field. Furthermore, the use of UASs allowed the collection of multiple images of the terrain from different angles that were employed to create a 3D model of the landscape through the photogrammetric technique known as Structure from Motion (SfM). Finally, phytolith analysis was employed to analyze microscopic silica bodies in the soil which can be indicative of historical crop cultivations. Ground inspection of former rice fields throughout the Low Country was performed in order to appreciate the different environmental settings, scales, and methods employed to cultivate the crop. The results from the samples reveal the presence of rice phytoliths, and combined with micro topographic features of legacy water control, suggest the area was indeed historically used for the cultivation of rice in the form of subsistence agriculture. This study fills a gap in Wormsloe's environmental history, increases Wormsloe's cultural, archaeological, and historical significance within the Southeastern coast, and provides advanced geospatial methods for assessing landscape legacies.

INDEX WORDS: Wormsloe, Isle of Hope, Rice cultivation, Terrestrial laser scanning, Unmanned aerial systems, Bare earth digital elevation model, Structure from Motion, Phytolith analysis, Cultural landscape

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DEDICATION

This dissertation is dedicated to my grandparents Giuseppina, Marino, Serafina, and Angelo, who would be proud of this achievement.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Located on the Georgia coast just south of Savannah, Wormsloe State Historic Site represents one of the most significant historical, cultural, and natural sites in Georgia and in the southeastern United States. In particular, Wormsloe is located on the Isle of Hope, which represents a peninsula among the numerous barrier islands of the Southeastern United States created during the Pleistocene Epoch over 2.5 million to 11,700 years before present (Figure 1.1). The area where Wormsloe is located has a long history beginning with the Native Americans who lived in the area approximately 6,000 years before European colonization. The site witnessed the arrival of the first British colonists in 1733 led by General Oglethorpe who founded the city of Savannah and the colony of Georgia. The uniqueness of Wormsloe is represented by the fact that it has been owned and managed by the descendants of Noble and Sarah Jones – the Jones, De Renne, and Barrow families – from its establishment in 1736 up to the present, thus representing the oldest continuously owned family estate in Georgia. Since its establishment, Wormsloe has served as a military outpost, plantation, and country residence in the 1700s and 1800s, while in the 1900s it became a farm and a tourist attraction (WIEH, 2015). Since 1973, much of the area has been managed by the State of Georgia through the institution of the Wormsloe State Historic Site, which opened to the public in 1979. The Barrow family – direct descendants of Noble Jones – still lives on the property and, through the Wormsloe Foundation and the Wormsloe Institute for Environmental History, recently donated 15 acres to the University of Georgia for the development of the "University of Georgia Center for Research and Education at Wormsloe" (Savannah Morning News, 2013). The main goal is to support collaborative interdisciplinary research in the fields of Geography, Archaeology, History, Ecology, and Environment and Design in order to improve the current understanding of Wormsloe's land use and historical development. The relatively undisturbed landscape of Wormsloe, in fact, makes it a perfect place to better understand the historical development and land use change of the Low Country environment, and the dynamics between human and natural interactions. Today, Wormsloe's historical legacy can be appreciated by observing the physical remnants of its past land uses immersed in the natural landscape provided by the dense maritime forest where live oaks, loblolly pines, and saw palmetto dominate the 822 acres of the property. For instance, visitors can appreciate the mile-long live oak avenue leading to the tabby ruins where Noble Jones established its first residence in the late 1730s, thus making it one of the oldest standing structures in Georgia; the main house built in 1828 where the Barrow family lives today; the restored wooden cabin originally built in the 1850s to house African Americans working on the plantation crops which today accommodates researchers on site; the family cemetery; the De Renne library which provided one of the most complete collections of historical documents on the Georgia history; the foundation of a dairy building and silo; and the visitor center, where visitors can learn more about the local history through videos, books, and historical recreations of colonial structures (Figure 1.2) (Swanson, 2012).

Another landscape feature of Wormsloe is represented by extensive drainage ditches that run throughout the property (Figure 1.3). It has been speculated that the ditches have been constructed and used mostly for draining agricultural land where sea-island cotton was cultivated, as well as for limiting the spread of mosquitos which could spread deadly diseases such as malaria and yellow fever. However, another interpretation on how drainage ditches might have been used was advanced by Roger Pinckney, who suggested ditches could have been used to cultivate rice on the property. Since this particular aspect of Wormsloe's environmental history has never been completely understood, a multidisciplinary and multiscalar study has been performed with the purpose to investigate whether rice cultivation was ever practiced at Wormsloe. This study, supported by the Wormsloe Foundation, the Wormsloe Institute for Environmental History, and the Center for Geospatial Research at the University of Georgia, employs advanced remote sensing technologies and archaeobotanical analysis in order to provide a better understanding to this particular aspect of Wormsloe's environmental history.

1.1 STUDY AREA

Surrounded by saltwater tidal creeks and marshes, the Isle of Hope is generally flat, with elevations ranging between sea level and approximately 4.5 meters above mean water. The local soil is mostly sandy, with some swampy areas characterized by less permeable and poorly drained soils. Freshwater ponds are seasonal and mostly rely upon precipitation. With regard to the vegetation, the area is mostly characterized by the presence of regenerating mixed oak-pine forest following extensive agriculture and pine harvesting in the mid-1970s, with areas of remnant maritime live oak-palmetto forest stands. The surrounding tidal salt marsh is dominated by *Spartina alterniflora* (cordgrass) as well as *Juncus roemerianus* (black needlerush). Local wildlife includes white-tailed deers, raccoons, American alligators, copperhead and water moccasin snakes, frogs, and turtles.

1.2 LITERATURE REVIEW

As mentioned above, despite much of Wormsloe's history being documented and previously described (Bragg, 1999; Coulter, 1955; Kelso, 1979; Swanson, 2012), there are still some aspects that require a deeper investigation in order to adequately reconstruct a full historical legacy of the site. For example, whether or not rice cultivation was ever performed at Wormsloe represents one of those questions that have not yet been completely answered. Although in his recent book entitled "Remaking Wormsloe Plantation" Swanson (2012) suggests that at the moment "*there is no concrete evidence that rice of any type was ever cultivated at Wormsloe*", additional hints in this respect warrant further study. First of all, rice represented the most important and successful colonial staple in the 1700s and the 1800s in the South Carolina and Georgia Low Country, thus providing great financial opportunities to the planters (Smith, 2012). Not surprisingly, in fact, the Jones family raised rice at the plantations of Lambeth, Newton, and Poplar Grove, which are all located in the surroundings of Wormsloe. In addition, as suggested by Swanson (2012), "*if Wormsloe's fields ever grew rice, it was probably associated with Noble W. Jones's experimentation with the upland variety provided by Franklin*". In a 1772 letter to Noble Wimberly Jones, in fact, Benjamin Franklin enclosed a sample of upland rice from Vietnam to suggest the experimentation of such culture at

Wormsloe; in replying back to Franklin, Noble W. Jones optimistically stated that "*there is little doubt of [the rice] doing well*" (Swanson, 2012). This then suggests the possibility that upland rice became one of the many experiments aimed at finding the most suitable cultures that would adapt both in the unique environment of Wormsloe and in that of the Georgia colony.

As suggested by Low Country author Roger Pinckney (pers. comm.), the potential for rice cultivation at Wormsloe is supported by the presence of existing ditches running through the property that may have been used to control water flow of rice fields through devices known as 'rice trunks'; in particular, the presence in the historical records of notes left by Noble Jones commissioning the production of trunks and gates supports the possibility that rice fields could have existed (Swanson, 2012). Moreover, from the analysis of scanned and rectified historical maps within the Wormsloe database collected by the University of Georgia (UGA) Department of Geography's Center for Geospatial Research (CGR), it is apparent that the area was characterized by the presence of artesian wells, which may have provided freshwater to irrigate rice fields; at any rate, the presence of wells indicates the presence of a freshwater aquifer underground, despite the belief of some scholars such as Sullivan that "[at Wormsloe] *there was not enough of a freshwater access for there to be a way much, if any, rice could be grown*" (Sullivan, pers. comm.). Another interesting hint leading to the belief in the potential production of rice at Wormsloe is represented by the purchase of "*fourteen broad hoes and six sickles*" by Noble Jones (Swanson, 2012), who also declared that his seven slaves working at Wormsloe were engaged in food production but that "*he had not rais'd more than food to feed the ensuing year*" (Swanson, 2012). Therefore, as Swanson (2012) argues, these points "*demonstrate that Jones grew at least some subsistence crop for his family and slaves, though that sort of produce rarely made its way into records*". The subsistence nature of rice production at Wormsloe may explain the lack of explicit historical records related to its cultivation. As Swanson suggests, in fact, "*raising crops for home consumption was so vital that almost everyone did so to some extent, but because these products usually failed to enter a defined economic structure (they were not generally taxed, exported, or manufactured outside the home), they were rarely recorded*" (Swanson, 2012). However, the 1880 agricultural census – listing Wormsloe's freedmen tenants and their land use during the 1879 season – reports that one of the tenants, Peter Campbell, raised 510 pounds of rice. As Swanson suggests, although it is unclear what land these tenants could have used, it is likely that they had individual plots close to their accommodation at the slave cabins, probably where the old quarters field was located (Swanson, 2012).

Previous studies aimed to find evidence of rice cultivation at Wormsloe may have dismissed the importance of field survey, accurate topographic analysis, and archaeobotanical analysis for locating archaeological evidence of old rice fields. As archaeologist Andrew Agha and historian Charles F. Philips report, "*researchers should not rely on historical plats, maps, and accounts alone. Even the best plats never show all of the structures that make up fields […] it is imperative to visit the location where former rice fields are expected to exist. This is the only way to positively establish the existence of the fields, assess their present condition, and gather an accurate understanding of the construction and operation of the fields and how field features relate to each other*" (Charleston County, 2010). The potential of laser scanning sensors for the detection and mapping of topographic features in historical landscapes has been widely demonstrated over the last years, both using airborne sensors (Bollandsås *et al.*, 2012; Chase *et al.*, 2011; Corns and Shaw, 2009; Doneus *et al.*, 2008; Lasaponara and Masini, 2009; Lasaponara *et al.*, 2011; Štular *et al.*, 2012; Werbrouck *et al.*, 2011) and terrestrial or ground-based sensors (Dietz *et al.*, 2012; Lerma *et al.*, 2010; Pirotti *et al.*, 2013). Laser scanners employ the LiDAR (Light Detection and Ranging) technology to measure the distance of a target without being directly in contact with it. As Fowler *et al*. (2007) explain, "*all laser scanning devices operate by directing structured light to the object to be measured, then detecting and measuring the signal from light reflected by the object surface*". Therefore, by knowing the speed of light, the distance between the sensor and the object can be derived by "*timing the round trip of the transmitted beam and reflection of that beam*" (Fowler *et al.*, 2007). Laser scanners have the ability to quickly collect large quantities of 3D measurements in the form of point clouds, i.e. X, Y, and Z coordinates, thus allowing very accurate measurements of objects and topographic surfaces. In particular, many scanners are provided with multiple return capability lasers (also known as full-waveform lasers) that can reach the ground even in vegetated areas, thus enabling the mapping of bare earth topographic features that are covered by the vegetation (Bollandsås *et al.*, 2012; Chase *et al.*, 2011; Corns and Shaw, 2009; Doneus *et al.*, 2008; Guarnieri *et al.*, 2009; Lasaponara and Masini, 2009; Lasaponara *et al.*, 2011). This is performed through the use of filtering algorithms which enable LiDAR analysts to isolate elevation points (or measurements) at desired levels such as bare ground, shrub height, or top of the canopy. One of the most common products of this process is the generation of accurate digital elevation models (DEMs), which provide the elevation values of the bare earth topography only.

This study also employs the unmanned aerial systems (UAS) technology for the detection, mapping, and 3D reconstruction of topographic features which can be indicative of old rice fields. The rapid success of this new remote sensing technology over the last few years has produced an ever increasing consensus both in the public and the private sector (Colomina and Molina, 2014). In particular, the use of UAS has been rapidly adapted by scholars for the study of archaeological and historical landscapes (Casana *et al.*, 2014; Chiabrando *et al.*, 2011; Mozas-Calvache *et al.*, 2012; Plets *et al.*, 2012; Rinaudo *et al.*, 2012; Smith *et al.*, 2014; Verhoeven and Docter, 2013). One of the main advantages of UAS, in fact, is their ability to obtain aerial images of hard-to-reach areas, with short revisit times, and with a relatively limited budget (Madden *et al.*, 2015). The accuracy of data collected by means of UAS technology has been recently investigated in a study conducted by Mancini *et al.* (2013), which demonstrated that the average difference in the vertical values between terrestrial laser scanning and UAS data was on the order of 0.05 m (Madden *et al.,* 2015); another study (Uysal *et al.*, 2015) demonstrated that the vertical accuracy of a UAS-derived DEM was 6.62 cm, which was obtained by using imagery collected at a flying altitude of 60 m. Therefore, UAS represent a reliable means of conducting aerial surveys and topographic mapping.

The collection of aerial images from different, overlapping, vantage points permits the 3D reconstruction of an area or object through the Structure from Motion (SfM) photogrammetry technique (Fonstad *et al.*, 2013). Unlike conventional stereoscopic photogrammetry, SfM does not require the 3D location of the camera or the

3D location of a series of control points to be known a priori. In fact, "*camera pose and scene geometry are reconstructed simultaneously through the automatic identification of matching features in multiple images. These features are tracked from image to image, enabling initial estimates of camera positions and object coordinates which are then refined iteratively using non linear least-squares minimizations*" (Westoby *et al.*, 2012). Therefore, instead of a single stereo pair, SfM requires multiple, overlapping images to ensure a high number of matching features for 3D reconstruction (Alexander *et al.*, 2015). Once the 3D geometry of the object or area has been reconstructed, ground control points can be used to register the model to real world coordinates, thus enabling 3D measurements and mapping. The use of SfM for the 3D documentation of objects has been employed in many areas such as archaeology and cultural heritage (Alexander *et al.*, 2015; De Reu *et al.*, 2014; Smith *et al.*, 2014). In particular, De Reu *et al.* (2014) employed Structure from Motion to document the 3D geometry of a complete archaeological excavation in a former monastic abbey area in Belgium. By taking overlapping pictures of the excavation trench using both handheld and pole-mounted cameras, Photoscan software was used to analyze point cloud data and generate 3D models of the areas under investigation. In order to register the 3D models to real world coordinates and integrate them with existing datasets, ground control points were recorded using a RTK GPS device with differential correction capabilities. The results included the generation of orthophotos, digital surface models (DSMs) and vertical orthoimages that were used in the field the following day after data collection in order to replace manual recording strategies traditionally used during archaeological excavations such as drawings and tape measurements. The results indicate very high accuracy 3D documentation of the site from which metric information along the x, y, and z axes could be derived by archaeologists, sometimes even a few hours after data collection.

The accuracy of SfM-derived topographic measurements was investigated by Fonstad *et al.* (2013) who compared them against airborne LiDAR datasets, finding that both horizontal and vertical values were in the centimeter range; however, Gomez *et al.* (2015) warn users of the possible inaccuracies of SfM-derived models, especially in areas that can be difficult for 3D reconstruction such as vegetated areas and surfaces with irregular illumination.

Finally, this study performs an archaeobotanical analysis to investigate the presence in the soil of archaeological remains of rice. As Harvey and Fuller (2005) suggest, in fact, "*major cereals such as barley, wheat, and rice, as well as specific plant parts, can be identified using phytoliths*". The term phytolith literally means "*plant stone*", and indicates microscopic silica or calcium bodies that are common in plants and crops. The best case scenario when using phytoliths in paleoecological reconstructions occurs when there is a unique correspondence between phytolith morphologies and plants that produce them, so that no misinterpretation is possible. However, this is not always the case in nature, as problems of multiplicity and redundancy occur (Lu *et al.*, 2006; Lu and Liu, 2003b; Rovner, 1983); in particular, multiplicity occurs when the same plant produces more than one phytolith morphology, while redundancy occurs when the same phytolith morphology is common to different plants. Rice plants produce diagnostic types of phytoliths such as double-peaked, bulliform, and scooped bilobes or bilobates (Zhang *et al.*, 2010) (Figure 1.4). In particular, double-peaked are produced by rice husks, bulliforms are produced by leaves, while bilobates are produced by stems. Depending on the local environment and context, however, the interpretation of rice phytoliths may be limited by the problems of multiplicity and redundancy; nevertheless, the use of rice phytoliths has been widely employed as a reliable way to identify rice archaeologically over the last decades by using statistical analysis and contextual factors. Among the advantages of phytolith analysis is, for instance, the great ability of phytoliths to remain preserved even for thousands of years, given their inorganic nature which makes them resistant against bacteria action (Harvey and Fuller, 2005).

1.3 OBJECTIVES AND STRUCTURE

The present study has the main goal of investigating whether rice cultivation was ever performed at Wormsloe Historic Site. To do so, this study takes a multidisciplinary and multiscalar approach so as to achieve a more holistic understanding of the matter. In particular, this study benefits from analyses in the fields of history, archaeology, ecology, geography, geology, and plant science. Furthermore, the phenomenon under investigation is approached from different levels of analysis, such as regional (Low Country), local (topographic mapping), and microscopic (phytoliths) scales. This study has three main objectives, which include the following:

1. Increase the current understanding of Wormsloe's environmental history, and improve its cultural, archaeological, and historical significance by providing spatial and temporal evidence of rice cultivation and deriving a credible scenario of subsidiary rice production on the Isle of Hope.

2. Utilize an innovative approach to the acquisition of low altitude geospatial data and its integration with ground-based geospatial data to perform accurate topographic mapping and 3D reconstruction of the area where rice cultivation is suggested. This objective has the purpose to explore the feasibility of rice cultivation at Wormsloe.

3. Investigate the presence of archaeological remains of rice in the soil through the archaeobotanical analysis of phytoliths.

This dissertation is presented in manuscript style, and employs the following rationale in order to investigate whether rice cultivation was performed at Wormsloe:

- Obtain an understanding of how rice cultivation developed in the Low Country region and analyze historical rice fields to investigate what legacy features may look like today after years of land use change and development. This step had the objective of finding any parallelism between known examples of rice fields in the Low Country and Wormsloe in terms of areas used for cultivation, methods of irrigation, and scales of agricultural practices.
- Analyze at the local level the topography at Wormsloe in order to inspect micro topographic features that might be related to rice cultivation, and compare measurements taken at Wormsloe against measurements taken in known rice fields.
- Analyze at the microscopic level the presence of rice archaeological remains in the soil, and compare the results against known rice specimens from different geographic areas so as to have more confident results.

In particular, Chapter 2 provides a brief introduction on the history of rice cultivation in the Low Country, and describes the inspection of former rice fields which had the purpose to better understand the wide range of rice cultivation practices and methods; this helped set Wormsloe into a wider context of rice cultivation practices and advance the current understanding of Wormsloe's environmental history by documenting the presence of a cultural landscape area on site. Chapter 3 examines the use of remote sensing technologies such as terrestrial laser scanning and unmanned aerial systems for the accurate topographic mapping and 3D reconstruction of the area under investigation. Advantages and limitations in the use of these two technologies are also presented in order to provide a better understanding of their capabilities for cultural and natural landscape mapping. Chapter 4 describes the archaeobotanical analysis performed in the area where rice cultivation is suggested by local topographic features and ground inspection. The presence of rice phytoliths in the soil suggests that rice cultivation was performed to some extent in the area. In particular, this study helped increase Wormsloe's cultural, historical, and archaeological significance, and provided evidence of subsistence rice agriculture in close proximity to tidal salt water. Finally, Chapter 5 revisits the main objectives of this dissertation research, and examines how this study met the proposed objectives. The chapter concludes by proposing future research directions in order to extend and continue the understanding of this particular aspect of Wormsloe's environmental history.

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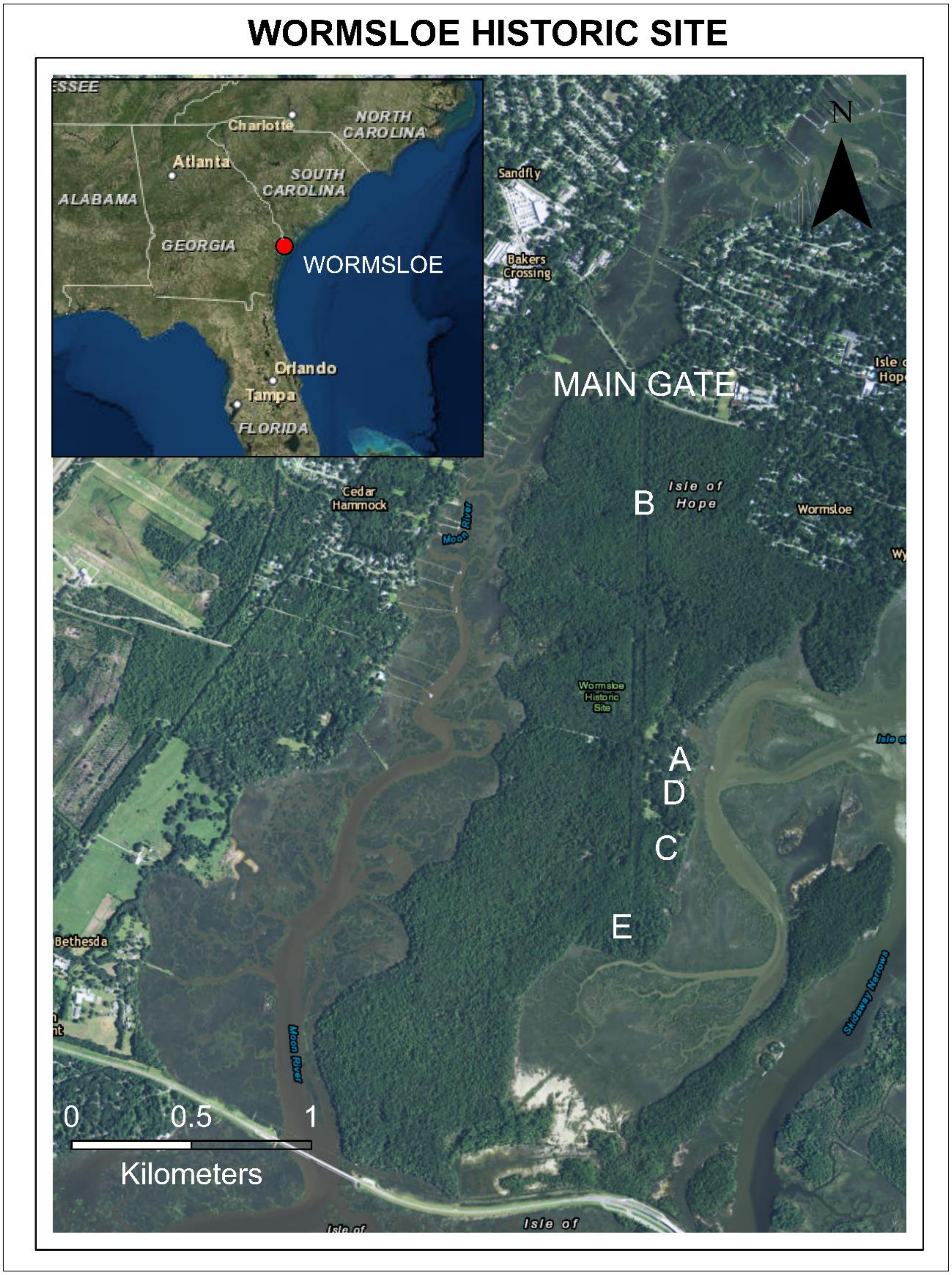

Figure 1.1. The geographic location of Wormsloe. The letters indicate key landmarks of Wormsloe as shown in Figure 1.2.

Figure 1.2. Key landmarks at Wormsloe: the main house (A); the live oak avenue (B); the slave cabin (C); the De Renne library (D); the tabby ruins (E). Some photos were taken from the WIEH geodatabase available at the Center for Geospatial Research.

Figure 1.3. Drainage ditch at Wormsloe.

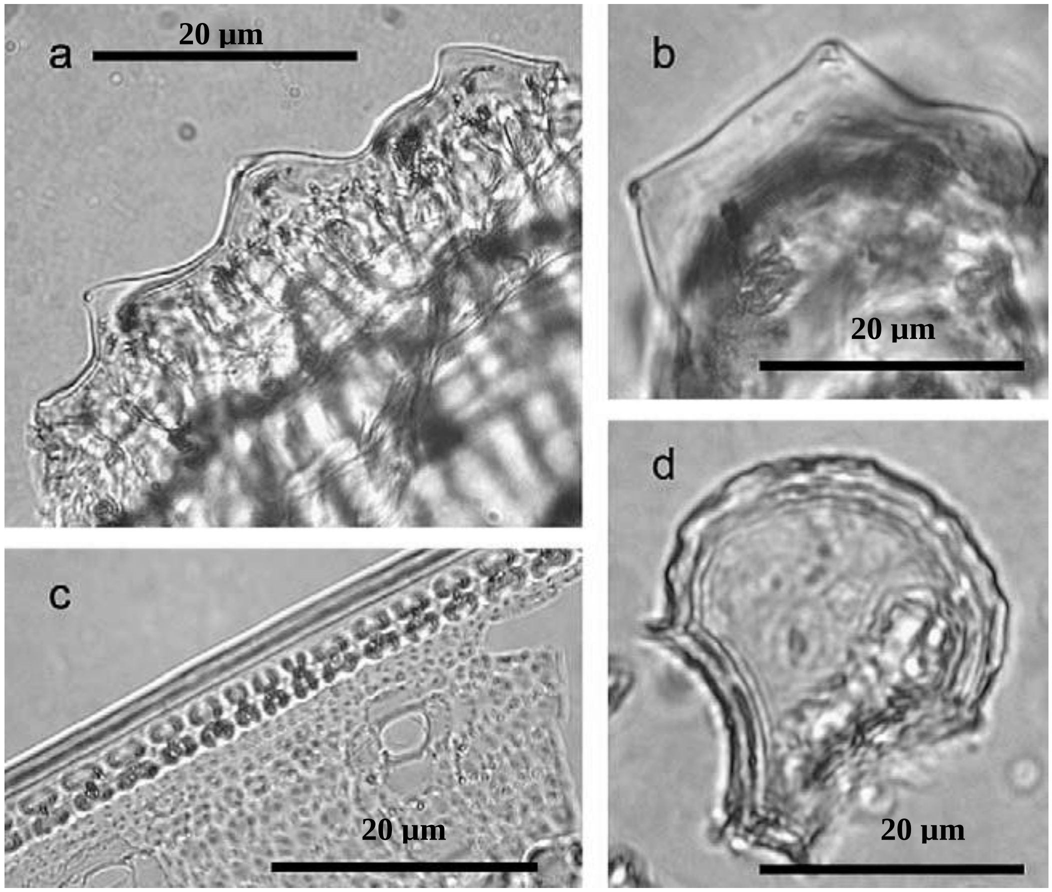

Figure 1.4. Rice phytoliths. (a) phytoliths from the husk; (b) double-peaked phytolith from the husk; (c) parallel bilobates from the leaf and stem; (d) bulliform from the leaf and stem. Scale bar is 20 µm. (adapted from Harvey and Fuller, 2005).

CHAPTER 2

LEGACY LOW COUNTRY RICE CULTIVATION AT WORMSLOE HISTORIC SITE AND THE GEORGIA-SOUTH CAROLINA COAST[1]

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ABSTRACT

This paper provides a brief introduction to the history and development of rice cultivation in the Low Country, with particular attention to the historical, cultural, and geographic context within which it developed. In particular, the three main irrigation systems employed in rice cultivation are described in order to better understand the technology employed in rice production, i.e., the providence or upland irrigation system, the inland or reservoir irrigation system, and the tidal irrigation system. Furthermore, known examples of rice fields from both the literature and ground reconnaissance are analyzed with the purpose of understanding legacy landscapes related to rice cultivation and seeing whether they present similarities with Wormsloe, with a particular focus on subsistence rice examples. Particular attention is placed on the hydrology, topography, and ecology that characterize former rice fields across the Low Country so as to place the experience of rice cultivation at Wormsloe within a wider context than that of the Isle of Hope alone, and formulate a plausible scenario of historical rice cultivation at Wormsloe. In this way, a more complete understanding of Wormsloe's environmental history is provided, thus increasing Wormsloe's current cultural, historical, and archaeological significance.

Keywords: Rice cultivation, Low Country, Wormsloe, African American culture, Subsistence, Cultural landscape, Environmental history

2.1. INTRODUCTION

Rice cultivation in the Georgia and South Carolina Low Country represents an important piece of history not only for Georgia and South Carolina, but also for the United States in general, as it represented a main aspect of the South Carolina and Georgia economies during their first years as British colonies. The development of rice cultivation was so successful that by 1750 nine of the ten richest men in British North America lived in the South Carolina Low Country (Charleston County, 2010). Without rice cultivation, the success of the South Carolina and Georgia colonies would have been much more difficult to achieve, if not impossible. The importance of rice cultivation in the Georgia and South Carolina Low Country was such that their legacy can still be appreciated in the modern landscape. For instance, the layout of historical rice paddies can still be seen in many areas along the tidal rivers of the South Carolina and Georgia coast, such as the Ashley river, the Ogeechee river, and the Altamaha river (Figure 2.1).

This Chapter aims to investigate the aspect rice cultivation at Wormsloe at the regional level, so as to achieve a more comprehensive understanding of the subject under study. In particular, one of the goals of this Chapter is to better understand both the system of rice cultivation as well as how planters adapted to the local landscape in order to cultivate the crop. Another important aspect of this Chapter is the analysis of what historical rice fields and related features such as dikes, ditches, and trunks may appear today following 200 years of land use change and development. This information will be gathered by inspecting remnants of old rice fields throughout the Georgia and South Carolina Low Country so as to analyze legacy landscapes features and ecological patterns (Figure 2.2). Additional examples of historical rice fields from the literature will be reviewed and analyzed together with legacy landscape evidence gathered from field inspections. This reference information will be then compared to the case of Wormsloe, where historical rice cultivation is hypothesized, in order to see potential similarities both in terms of historical contexts and landscape features. In this way, the experience of rice cultivation at Wormsloe may be understood not only locally, but also within the regional and broader historical context of rice cultivation agriculture in the Low Country.

Within the Low Country environmental context, Wormsloe represents one of the most significant cultural, historical, and natural sites. Located just south of Savannah on the Isle of Hope, coastal Georgia, Wormsloe is located in a relatively undisturbed and undeveloped area where successional maritime forest occupies most of the uplands (Figure 2.3). Tidal salt waters and salt marshes around Wormsloe provide an ecosystem rich in fauna and flora typical of the southeastern coastal United States. Wormsloe's environmental history predates colonial arrival in 1733, as archaeological evidence revealed the site was used by Native Americans. With the establishment of British colonists, the site became the residence of Noble Jones, surveyor of the Georgia colony, who established Wormsloe in 1736. Since then, the site has been used as a military outpost, an antebellum agricultural plantation, a farm, a Depression Era tourist attraction, an historic site, and an educational facility with the establishment of the University of Georgia Center for Research and Education at Wormsloe. The site has been managed by the same family since its establishment in 1736, thus representing the oldest continuously owned estate in Georgia.

The exact circumstances related to the introduction of rice culture in the colonies of South Carolina and Georgia remain somewhat unclear. Perhaps the most popular theory among traditional accounts attributes the introduction of rice in South Carolina to the accidental mooring at Charleston's port of a ship in distress coming from Madagascar. John Thurber, the captain of the ship, offered the local people who helped r epair his ship a small quantity of rice as a sign of gratitude; from there, rice spread throughout South Carolina (Gray and Thompson, 1933; Heyward, 1937; Salley, 1919). Although for some this event occurred around 1685 (Heyward, 1937; Salley, 1919), in 1694, or 1696 (Gray and Thompson, 1933), Salley (1919) affirms that "*it is certain that rice culture was begun before 1690 and that it was not begun as the result of an accident but as a part of a prearranged plan for development of Carolina by the Proprietors thereof*". In particular, Whitten (1982) reports that "*within two years of the establishment of the colony at Charles Towne, experiments with rice culture had been undertaken. Land warrants indicate that rice was being grown there by 1684*".

Regardless of whether rice was introduced in the colonies by chance or on purpose, the rice industry quickly became one of the main exports already by the end of the 1600s (Porcher Jr and Judd, 2014). By the time the colony of Georgia was founded in 1733, therefore, rice culture was already well established in South Carolina. During the first years of the Georgia colony, many were the experiments aimed at finding the most appropriate plants and cultures that would take root in the Georgia's climate and latitude, such as indigo, wine, silk, and oranges; as a matter of fact, the Georgia Trustees established an experimental garden of 10 acres in Savannah, while individuals performed personal experiments in their private lands (Gray and Thompson, 1933). Among these individuals was Noble Jones, who was given in lease five hundred acres on the southern portion of the Isle of Hope in 1736 to establish his residence, which he named Wormsloe.

In line with the rest of early Georgia settlers, during the first years of Wormsloe Jones cultivated crops such as corn and cotton, and introduced plants such as mulberry trees, grapes, pomegranates, peaches, and olives in order to help establish successful cultivations for the colony (Swanson, 2012). However, it was only after the legal introduction of slavery in Georgia – which occurred on January 1, 1751 – that Wormsloe, and the colony of Georgia, started developing into one, thriving commercial enterprise. The availability of slaves, in fact, supplied the labor force necessary for the commercial production of crops such as sea island cotton, which became the main crop cultivated at Wormsloe during the 1800s. On the other hand, to date there is no concrete evidence of rice being cultivated at Wormsloe, and its cultivation has always been dismissed for lack of suitable lands and/or freshwater access necessary to grow the crop (Swanson, 2012; Sullivan, pers. comm.). However, two hints related to the presence of rice at Wormsloe may be sufficient to assume that rice cultivation was at least attempted for a short period of time. The first of these hints is represented by the 1880 agricultural census record listing Peter Campbell, a freedman living at Wormsloe, who grew 510 pounds of rice during the 1879 agricultural season (Swanson, 2012). The second hint, instead, is represented by the 1772 letter sent to Noble Wimberly Jones, son of Noble Jones, by Benjamin Franklin, who enclosed a sample of upland (or dry) rice from Cochin China (modern Vietnam) in order to suggest its cultivation at Wormsloe as well as in Georgia (Figure 2.4). Despite the optimistic reaction of Noble Wimberly Jones on the potential rice adaptability, however, there is no concrete evidence of its cultivation at Wormsloe.

The three rice cultivation methods, i.e., upland or providence, inland or reservoir, and tidal, are illustrated in Figure 2.5. More specifically, these three systems can be differentiated based on the method of irrigation used to grow the rice crop. In particular, the upland method was the first employed by rice planters in South Carolina around the end of the 1600s. This method mostly relied upon the availability of adequate moisture in the soil coming primarily from rainfall or water runoff from adjacent uplands to grow the crop; despite the name, however, this type of culture was mostly practiced in natural low moist lands (Porcher Jr and Judd, 2014). Since the upland rice system mostly relied on rainfall for irrigating the crop, it did not require the creation of canals to bring water to the fields or embankments to keep the field flooded; rather, the system depended upon the providential chance of rain, thus the term providence culture may be more apt to define this method (Porcher Jr and Judd, 2014). In terms of moisture, providence culture required at least 5 to 6.5 feet a year over three or four months during the growing season, as droughts would have compromised the crop; freshets, i.e., violent water torrents occurring after hurricanes or storms, were equally devastating for the crop, therefore a balanced amount of moisture would have determined the successful cultivation of the crop (Porcher Jr and Judd, 2014). Since the providence method involved just small quantities of rice, it was mainly employed for subsistence purposes during the first experimental years by early planters and enslaved Africans who knew about rice cultivation from their homelands. However, this system produced low yields.

The inland rice system, on the other hand, became the first economically successful form of rice cultivation along the Southeastern coast of the United States, thus becoming quickly a cash crop for Low Country planters. In contrast to upland rice, in fact, inland rice generated a higher yield, thus allowing landowners to establish large plantations across the Low Country, and to obtain profits from its sale. In particular, inland swamps – mostly cypress bottomlands – were "*drained, divided into squares separated by ditches, and surrounded with banks to prevent reinundation*" (Chaplin, 1992). Furthermore, earthen dams were constructed across both the lower end of the field "*to prevent salt water from overflowing the parts of the swamp to be planted*" (Heyward, 1937), and the top of the swamp, where a freshwater reservoir was created to irrigate the fields by gravity flow. In addition to water collected from atmospheric precipitation, freshwater could also be taken from nearby rives, artesian springs, or manmade wells reaching aquifers underground (Porcher Jr and Judd, 2014; Smith, 2012a). For example, the unique hydrogeology of the Biggin Basin in South Carolina allowed local inland rice planters to draw freshwater from limestone springs and artesian wells to irrigate their fields (Smith, 2012a). The ability to draw a steady amount of water, therefore, was crucial for the successful cultivation of inland rice, as water would kill infesting weeds and insects at crucial stages of the crop's growth (Figure 2.6). Similarly, the ability to manage water flow played a crucial role, as it allowed planters to adequately control the amount of water needed to flood or drain the rice fields. Water control in inland rice fields was achieved through the employment of structures known as sluice gates – located in ditches, dams, and dikes – which were employed to allow or retain the unidirectional flow of the water from the reservoir to the fields by sliding up or down their door (Figure 2.7).

Given the difficulties in providing a constant water supply as well as the aspirations for increased productivity, around 1738 rice planters began experimenting with a third system, the tidal system, which took place on the tidal marshes and swamps along freshwater rivers of the Low Country (Porcher Jr and Judd, 2014). Similarly to the inland system, the tidal system required a complex network of canals, embankments, and sluice gates to irrigate the fields at different stages of the crop's growth. However, rather than being based upon an elevation gradient to move water from the reservoir, this system relied on the tidal influence of bordering rivers to irrigate and drain the fields. More specifically, the fields were irrigated at high tides, and drained at low tides, through sluice gates placed in the banks similar to those used for inland fields. As Smith (2012a) explains, these gates were known as "rice trunks", as they were originally made from hollowed out trees – usually *Sabal* palm and cypress. Unlike inland systems, however, where the flow of water was unidirectional – flowing from the reservoir down to the fields due to the elevation gradient – in tidal systems the flow of water was bidirectional with the tides, meaning that sluice gates could allow water in from either side of the gate. As Heyward (1937) describes "*these trunks were long wooden boxes made of thick plank, with a door at each end. The doors were hung on uprights and were capable of being raised and lowered automatically with the rise and fall of the tide*" (Figure 2.8).

As Carney (1996) noted, the development of wet rice methods of cultivation required a "*sophisticated knowledge of soils, particularly moisture retention properties*". In order to successfully cultivate inland and tidal rice, in fact, poorly drained soils – usually that of cypress bottomlands, small stream floodplains, or swampy areas – were most suitable due to their low permeability and hydraulic conductivity, which allowed them to easily retain water in both the reservoirs and the fields. As Smith (2012a) notes, in fact, these soils were rich in nutrients and generally composed of 'loams' of different kinds – such as Lenoir, Wahee, and Meggett – which contain a mixture of sand, clay, and silt. In addition, the particular composition of these soils favored the growth of certain species of vegetation such as cypress and gum trees, which allowed planters to obtain insights into the nature of the soil by observing the local vegetation (Smith, 2012a).

The cultivation of rice in the rest of the Georgia colony, however, followed a different path. Similarly to what happened in South Carolina, in fact, rice became widely spread throughout Georgia, and quickly became one of the main cash crops of the colony. Along with the availability of slave labor, the rapid development of commercial rice cultivation in Georgia was also favored by the investments of nearby South Carolina planters who were eager to establish new plantations in Georgia (Gray and Thompson, 1933). The development of the rice industry in Georgia, however, did not occur in the same order to that of South Carolina, where rice was first cultivated through the providence, then inland, and finally tidal method; as Smith (pers. comm.) suggests, in fact, by the time rice cultivation came of age in Georgia, the tidal technology had already been developed, so that it became the first, rather than the last, way in which rice was cultivated in Georgia.

It is now widely accepted that the success of rice cultivation in the colonies of South Carolina and Georgia mostly relied on the labor, skills, and ingenuity of West African slaves, who had refined their knowledge about rice cultivation in their own country before being enslaved by European colonists (Carney, 1996; Carney, 1993). For this reason, colonists preferred slaves coming from the so-called Rice Coast – which included Senegambia, Guinea, Sierra Leone, Ivory Coast, Benin, and Gold Coast – not only because they possessed the skills for building and managing rice fields, but also because they were deemed suitable for working in the hot and humid environment of the Low Country.

The reclamation of inland swamps and preparation of inland rice fields, in fact, required a "*careful observation of topography and water flow*" (Carney, 1996) as well as a great deal of manpower and time. Vegetation had to be removed to clear the swampy land, then ditches and sluice gates had to be constructed to drain and move water across the rice fields. Finally, earthen embankments and dams had to be constructed to retain water on the fields, and to create reservoirs for collecting fresh water. Therefore, the development of colonial rice plantations was directly linked to the ability of planters to obtain an ample supply of slave labor; as a matter of fact, "*the dramatic rise in the number of Africans imported into Charleston corresponds directly with the enormous rise in rice production*" (Charleston County, 2010). The role played by African slaves into colonial rice production was so influential, that scholars such as Carney (1996) proposed the term "technology transfer" to indicate the African ingenuity and expertise that brought to rice production devices such as rice "trunks".

The characteristics of rice make it a highly adaptable crop that can grow in a wide variety of ecological settings, e.g., ranging from the uplands to deep water lands, thus allowing rice to basically grow almost anywhere. For instance, many rice fields were obtained from less desirable or attractive areas such as salt marshes or peripheral, low lying wetlands on plantations. Apparently, the use of salt marshes for rice fields has occurred since the beginnings of its cultivation, as demonstrated by the discovery of Neolithic rice fields in China (Yunfei, 2009). During the first experimental years in South Carolina, also, coastal swamps by the ocean near Charleston were reclaimed by early planters to grow rice since they had little vegetation, while better lands further inland were still under Indian control (Carney, 1996; Hawley, 1949; Smith, 2012a). Since salt and brackish waters are detrimental to growing rice, deep knowledge of the land and careful planning was required in order to reclaim lands so close to the ocean, thus separating saline from fresh water zones; in particular, this was achieved by building earthen barriers at the lowest end of the field to prevent salt water intrusion at high tide (Smith, 2012a; Tuten, 2012). Furthermore, as Porcher Jr and Judd (2014) suggest, the employment of salt marshes as rice fields had the great advantage of having no or little vegetation, so their use would have been pretty convenient for growers with little resources, such as those with little experience, no labor force, or simply subsistence growers.

Other areas that were used for cultivating rice included unwanted lands on the plantation periphery where enslaved Africans grew rice and other subsistence crops such as millet, sorghum, sweet potatoes, okra, Guinea squash, black-eyed peas, muskmelons, pumpkins, and corn (Campbell, 1991; Smith, 2012b). In particular, subsistence lands were rather small in size, and usually required little labor as they were tended during the slaves' free time. These "provision grounds" were either appropriated by the slaves (usually around or nearby their dwellings) or explicitly given by the planters in an attempt to reduce the slaves' weekly rations of food and their costs, such as in the French colony of Martinique (Tomich, 1991), in Suriname (Price, 1991), or in Jamaica (Turner, 1991). Despite most commercial rice fields ceased to operate around the turn of the 20th century, however, some subsistence rice fields continued to be operational until even as late as 1935 in the sandy pinelands of Mars Bluff in Florence County, South Carolina. There, rice was grown either as a dry or wet crop for personal use by African Americans, who took advantage of freshwater collected naturally through precipitation or wells;

sometimes, they did not even require the construction of embankments or ditches to cultivate the crop, as rice was planted in naturally low grounds where seasonal high water tables would reach six feet or more, thus providing the necessary moisture to grow the crop. Rice fields ranged from half acre to two and a half acres in size (Vernon, 1995). As reported by Coclanis and Marlow (1998), other than during the first experimental years of the colonies, the cultivation of subsistence rice occurred particularly after the Civil War, when a new social, cultural, and economic context developed. In that period – roughly between 1880 and 1920 – white and black farmers alike began utilizing lands outside the Low Country for cultivating smaller quantities of the crop, such as in Clinch, Berrien, Thomas, Worth, Coffee, and Irwin counties in Georgia, and Orangeburg, Sumter, Darlington, Marion, and Marlboro counties in South Carolina (Coclanis and Marlow, 1998).

This paper has the purpose of introducing the history of rice cultivation in the Low Country and describing its methods of cultivation. Through the analysis of known examples of rice fields taken both from the literature and ground surveys, evidence related to historical rice cultivation legacy landscapes, features, and environmental histories are analyzed and compared to Wormsloe in order to see potential similarities and support the hypothesis of historical rice cultivation at Wormsloe. In this way, the experience of rice cultivation at Wormsloe is placed into a broader context so as to provide further insights into better understanding Wormsloe's environmental history.

2.2. METHODS

In order to better assess the nature of the area under investigation at Wormsloe, several ground surveys of known rice fields throughout the Low Country have been performed between October 2013 and August 2014. In particular, rice fields of both commercial and subsistence nature have been inspected in South Carolina and Georgia, ranging from tidal plantations to small agricultural practices on the sea islands (see Figure 2.2). While inspecting the rice fields, features of interest were photographed and mapped with a Garmin ETrex GPS handheld device, and notes on the local soil and vegetation were taken in order to see potential similarities with the study area at Wormsloe.

2.3. RESULTS

The inspection of former rice fields has revealed interesting insights into the nature and state of legacy landscapes related to historical rice cultivation in the Low Country. These insights resulted in a better understanding of what legacy features (both topographic and non) might still be present in abandoned rice fields, as well as of how rice fields operated. The following rice fields are presented by following the chronological order with which they were inspected.

Butler Island Plantation, Darien, Georgia

Like many former rice fields, the abandoned rice fields at Butler Island are now managed by the Georgia Department of Natural Resources, and are being currently used as waterfowl hunting and bird watching areas. Butler Island, together with Champney and

Rhett’s Islands, was part of a tidal rice plantation on the Altamaha River active during the 1800s. The diked impoundments, water trunks, and canals are still visible today (Figure 2.9). Some of the former fields today are under lush vegetation, which however could not be identified. Soil samples collected from the former rice fields presented a pretty clayey and plastic texture, a greyish color with the presence of organic remains, and a lot of moisture at the bottom of the sample column, i.e., around 60 cm deep. Samples from the dike, instead, presented a general greyish color with a reddish tone given by the presence of iron; the sample also was pretty clayey, but with a higher percentage of sand.

Skidaway Island State Park, Skidaway Island, Georgia

The former rice fields at Skidaway Island are now part of the Skidaway Island State Park, which is currently being managed by the Georgia Department of Natural Resources. The rice fields at Skidaway have been identified on a 1933 historical map available from the Wormsloe Institute for Environmental History (WIEH) database served by the Center for Geospatial Research database at the University of Georgia which labels the area “abandoned rice fields” (Figure 2.10). The former fields are now fingers of salt marsh between vegetated hammocks where the southern red cedar, maritime pine forest, and saw palmetto vegetation develop; in some areas, the difference in elevation between the marsh and higher ground is around 30 cm only. In the marsh, the prevalent vegetation type is constituted by *Juncus roemerianus* (black needlerush) and *Salicornia* (sea asparagus), while on the former dike *Borrichia frutescens* (sea oxeye) is present. In terms of topographic features, one of the two rice dikes (of the approximate length of 65 m) was identified on the ground and photographed (Figure 2.11). Also, one canal and its embankment have been observed, which probably channeled water to the fields from freshwater sources inland such as artesian springs.

Fishbrook Plantation, Santee Experimental Forest, South Carolina

Located in the Francis Marion National Forest, the Fishbrook Plantation was an inland rice plantation owned by the Quash family which was active approximately between the 1730s and the 1820s (Smith, pers. comm.). This inland system relied upon the waters of the Nicholson Creek, which is part of the wider Carolina Bay system based on the Hellhole Bay. Today, the former fields are part of the Santee Experimental Forest, which is characterized by loblolly and longleaf pine trees, as well as by bottomland hardwoods. Given the lack of a proper coring device, only a superficial soil sample from the former fields could be collected, which revealed a pretty sandy soil; however, as Smith (pers. comm.) affirmed, Meggett soil represents the predominant type of soil in the area. During field inspection, the dense vegetation and almost 200 years of land use change made the layout of the former rice fields difficult to appreciate, so that topographic features such as rice embankments are now but subtle topographic relief changes of the terrain (Figure 2.12). However, topographic features such as a flanking canal and its embankment could be easily identified.

Drayton Hall, South Carolina

In the 1700s, Drayton Hall was a plantation where enslaved Africans were employed for the commercial cultivation of rice and indigo; later, during the 1800s and the early 1900s, the phosphate-mining business became one of the main activities on the property. Rice was grown in the salt marshes along the Ashley River through the construction of dikes and embankments which prevented salt water intrusion; inland reservoirs collecting rainwater were used to irrigate the fields when needed, while rice trunks regulated the water flow. Today, rice dikes, embankments, and canals are still present. On the other hand, the former rice fields have now reconverted to salt marshes characterized by dense vegetation such as black needlerush (Figure 2.13). Vegetation on higher grounds includes live oaks, palms, saw palmetto, and cedars.

Caw Caw County Park, South Carolina

Once part of the Laurel Hill Plantation, the former rice fields are now part of the Caw Caw Interpretive Center, which manages the area for attracting wildlife such as alligators and birds. The former rice dikes, trunks, quarter drains, and embankments are still visible today, and are being maintained by the Center (Figure 2.14). The areas where rice was once cultivated are now being kept with a mixture of brackish and freshwater which allows the development of vegetation such as *schoenoplectus robustus* (sturdy bulrush), *setaria faberi* (giant foxtail), *eleocharis parvula* (dwarf spikerush), *typha* (cattails), *sesbania herbacea* (bigpod sesbania), and *triadica sebifera* (Chinese tallow) which attract many migrating birds.

Daufuskie Island, South Carolina

The agricultural plantations on Daufuskie Island were commercially cultivating sea-island cotton and indigo, while rice was only cultivated for personal use. Rice growers were using freshwater coming from water runoff, rainfall, and artesian springs

(Pinckney, pers. comm.). The embankments used for rice cultivation are sometimes difficult to distinguish in the modern vegetated fields where pines, oaks, and saw palmetto grow today (Figure 2.15). Superficial soil samples collected in former rice areas denote pretty sandy soils, with a rather dark color. Rice fields were probably cultivated both during the 1700s, and in the aftermath of the Civil War, when former slaves continued to live on the island.

Sapelo Island, Georgia

The two crops that were grown commercially on the plantations of Sapelo Island were sugar cane and cotton, while rice was only grown for personal use by locals. In particular, as reported by local resident Stanley Walker – whose ancestors were employed as enslaved workers on the island’s plantations – rice is still being currently grown for personal use by himself in his garden (Figure 2.16A). Like Mr. Walker, other subsistence rice growers on the island planted rice until about the 1950s in naturally low moist areas, where high water table would provide the moisture necessary to grow the crop, with no need to create embankments or reservoirs (Figure 2.16B). Today, these areas are characterized by slash loblolly pines, bay leaves, and dog fennel vegetation (Walker, pers. comm.). Superficial soil samples collected in former fields revealed the presence of quite sandy soils with a dark color.

Lebanon Plantation, Savannah, Georgia

The Lebanon Plantation presents a very similar story to that of Wormsloe, since it was a place of experimentation during the early years of the colony of Georgia. Then, the salt marshes were diked to cultivate rice for commercial purposes and create freshwater areas. A visit on site revealed the presence of dikes and water control structures used to grow the crop (Figure 2.17). As reported by botanist Elliott Edwards (pers. comm.), modern vegetation includes goldenrod, rattlebox, and seed pods.

2.4. DISCUSSION

The results show the many aspects of rice cultivation, depending on what method of cultivation is employed, what topographic areas are chosen for its cultivation, the purpose of its cultivation, and the time and labor that growers can dedicate to growing the crop. Results also demonstrate the highly adaptability of the rice crop, which can basically grow anywhere, from dry to wet lands, from high to low grounds, provided that a sufficient amount of moisture is provided during the crucial stages of its growing cycle.

The cultivation of rice for subsistence purposes has shown to be a practice common to different environmental settings across South Carolina and Georgia. For instance, the examples of subsistence rice cultivation on Sapelo Island and Daufuskie Island may provide a good parallelism with what might have happened at Wormsloe. Despite rice was never grown commercially on those islands, in fact, local residents cultivated some rice for personal use (and some still do), while the rest of the island was being farmed with cash crops such as sea island cotton, sugar cane, and indigo. In particular, subsistence agricultural efforts were especially practiced by former slave families as a way to sustain themselves in the years during the Reconstruction period, when they were given patches of land on former plantation grounds through leasing or sharecropping. The end of subsistence rice cultivation for those growers was determined by a combination of factors: for some growers, it terminated when it was no longer convenient for them to do so, i.e., it was more convenient to buy rice rather than cultivating it; others, instead, saw their fields acquired by new investors, and thus were forced to move somewhere else, such as on Sapelo Island during the 1950s (Walker, pers. comm.); finally, others could not prevent rice from being eaten by birds, such as the case of Daufuskie Island (Burn, 1991).

Rice cultivation at Wormsloe might have followed a similar pattern, since rice was likely being cultivated for subsistence purposes only. In fact, no records of any type – except the agricultural census listing Peter Campbell – mentioning the commercial cultivation of rice at Wormsloe were ever found. As Swanson (2012) suggests, in fact, had rice been ever grown commercially, it would have made its way into the official records, so that the commercial nature of rice cultivation at Wormsloe needs to be dismissed. Furthermore, the information related to Peter Campbell mention the production of 510 pounds of rice in the 1879 agricultural season, but no mention was made on where, how, and for how long he cultivated the crop (Swanson, 2012); as Swanson (2012) suggests, Campbell might have used lands close to the slave quarters, where he probably lived as a tenant in 1879. Therefore, the area which is being suggested in this study as a rice cultivation locale may well represent the field used by Peter Campbell to grow rice, given its close proximity to the slave quarters where Campbell likely resided. However, it is not mentioned whether Campbell cultivated the crop for the first time, or if he continued his rice cultivation endeavors in the following seasons. As Cady (2015) reports, tenant farming on Wormsloe was introduced in the form of sharecropping in 1871, and continued through at least 1879; during that period, between

8 and 11 African American farmers were leased 5 acres each, and cultivated crops such as corn and sweet potatoes. Between 1880 and 1894, however, it still not clear whether sharecropping continued, though it is assumed black people still lived on the property; furthermore, it is still unclear what crops they raised and which lands they used (Cady, 2015). Therefore, the salt marsh area at Wormsloe may have also been used during other agricultural seasons for rice cultivation by Campbell himself or other sharecroppers before or after 1879.

The inspection of former rice fields throughout the Low Country revealed that salt marshes were also used to cultivate the crop, even commercially, such as in the case of Drayton Hall. Despite salt waters are detrimental to growing rice, in fact, growers could simply flush the salts out of the marsh with freshwater coming from rainfall or reservoirs inland. Furthermore, as suggested by Porcher Jr and Judd (2014), marshes presented the advantage of having little vegetation compared to hardwood bottomlands, thus were the ideal solution for growers with little time, force labor, and experience, such as it was likely the case at Wormsloe. The practice of rice cultivation in those areas would have been performed by single individuals who were growing the crop for themselves and their families, thus small patches of salt marsh proved ideal for their subsistence efforts. Similarly to Drayton Hall and the first experimental growers on the coastal swamps around Charleston, growers at Wormsloe may have simply constructed an earthen dam, or dike, to separate fresh water from saline water areas, thus protecting the field from salt water intrusion at high tide (Figure 2.18). As shown in Figure 2.11, the dike at Wormsloe strictly resembles that on Skidaway, which was built for controlling the tidal surges of the salty Skidaway River. Furthermore, the reclamation of salt marshes for the personal cultivation of rice was a practice common also on Sapelo Island (Walker, pers. comm.). However, as Porcher Jr (pers. comm.) mentioned, the use of salt marshes was also performed in order to obtain more land available for the cultivation of sea island cotton, once all the remaining land on the plantation was occupied. This could have been the case at Wormsloe too, since sea island cotton was the main commercial crop during its plantation years; however, no phytolith evidence related to cotton cultivation was found in the soil samples collected from the salt marsh under investigation, thus limiting the chances that the area was used for that purpose. Furthermore, ground reconnaissance surveys of the study area performed independently with Porcher Jr and archaeologist Andrew Agha revealed that the area was very likely used for rice cultivation; in particular, Agha observed that the lower dike follows a 20° N alignment with the only remaining slave cabin, which may somewhat indicate almost a spiritual connection between the workplace (salt marsh) and the house.

In order to cultivate the crop, rice growers at Wormsloe would have channeled freshwater through the still existing ditch down to the field from a reservoir which would have collected rainfall, water runoff from the surrounding higher grounds, and ground water by tapping into the rising water table or artesian wells, similarly to what rice growers did on Daufuskie and Sapelo Islands (Figure 2.19). Despite the dismissal of rice cultivation at Wormsloe due to the lack of freshwater sources (Sullivan, pers. comm.; Swanson, 2012), in fact, freshwater could have been accessed by tapping into the local aquifer, as shown in this topographic map from 1912 (Figure 2.20); the presence of artesian wells at Wormsloe is also documented in 1857, when G. Wimberly Jones ordered the construction of a well house (Cady, 2015). Since rice cultivation required both the flooding and the draining of their fields, freshwater flow would have been regulated through the instalment of water control structures known as trunks. In particular, lift-gate or swing-gate trunks would have been placed at the end of the reservoir, as well as at both dikes delimiting the rice field in the marsh in order to both allow the unidirectional flow of the water and block tidal influx. Furthermore, as Cady (2015) reports, between 1856 and 1859 G. Wimberly Jones ordered the construction of five trunks with double gates, ditches and dams, and a mill house on Wormsloe, as part of his agricultural improvements to the estate. Furthermore, he also purchased seed rice and a full time overseer. Although these new works may have been initially intended to drain the uplands for the cultivation of cotton, corn, and potatoes, trunks and ditches may have also been harnessed after the Civil War by sharecroppers for the cultivation of rice. Furthermore, the purchase of seed rice by G. Wimberly Jones may also indicate his intention to attempt commercial rice production on Wormsloe or on adjacent Long Island, where similar constructions had been ordered. Today, no remnants of trunks are present, but a photograph taken at Wormsloe, probably during the 1930 as suggested by Cady (2015), of an unknown area might reveal the presence of a water control structure (Figure 2.21). As Figure 2.22 shows, it might also be speculated that the historical photograph was taken from the study area, probably to show the presence of agricultural areas at Wormsloe at the beginning of the 20th century. As Cady (2015) reports, in fact, farming on Wormsloe continued until around the late 1930s, so it is possible that farmers may have continued to use the area for rice cultivation to sustain themselves or for even selling some rice to the local market in Savannah. This was, for instance, the case for subsistence growers on Daufuskie Island, who would sell part of their produce to the

Savannah Old Market (Burn, 1991); the practice of selling products cultivated on subsistence grounds was a practice common to many African Americans after the Civil War, as also reported by Campbell (1991) and Wood (1995).

In order to better understand when rice could have been cultivated at Wormsloe, it is also necessary to analyze the impact that hurricanes might have had on the Georgia coast, and on Wormsloe in particular. As reported by Porcher Jr and Judd (2014) in fact, the damages caused by hurricanes and tidal surges were one of the main reasons for the demise of rice cultivation along the Georgia and South Carolina coasts around the turn of the 20th century. Hurricanes would break dams, dikes, and trunks, and would inundate rice fields with salt water which is fatal for rice. In particular, major hurricanes in the second half of the 19th century that might have caused serious damages in the Savannah area, and at Wormsloe as well, occurred in 1854, 1881, 1893, 1896, and 1898 (Fraser Jr., 2006; Hurricancity.com, 2015; NorthFLSouthGAwx.blogspot.com, 2015). The time it takes for rice fields to recover after salt water intrusion depends on how much salt water entered the fields, as well as how much freshwater would be available to flush the salts out of the fields. Therefore, months or even years might be needed for the fields to recover after being inundated with salt water. Furthermore, as Porcher Jr and Judd (2014) stated, repairing broken dams, dikes, and trunks was a tremendous task requiring time, skills, and labor which gradually became unavailable. At Wormsloe, rice cultivation could have been attempted a first time between the late 1850s and early 1860s under the direction of G. Wimberly Jones, and through the Civil War until the years of sharecropping, which officially started in 1871. In particular, between 1865 and 1869, Wormsloe was farmed by individuals who attempted the cultivation of some crops, although little is known about what and where they planted, thus rice might have been one of the crops that were tried in those years (Cady, 2015). The hurricane of 1881 might have caused serious damages to the rice field at Wormsloe, so that its cultivation might have been temporarily discontinued. Others might have tried cultivating rice again in the following years through 1893 – when another major hurricane struck the Georgia coast – as it is assumed black farmers were still living on Wormsloe through 1894. The hurricanes of 1896 and especially 1898 probably caused damages so serious to the rice dikes and trunks at Wormsloe to halt its cultivation, given also their high frequency which perhaps did not give the fields enough time to recover from the damages and contamination.

The cultivation of rice required careful planning and hard work. Farmers had to clear the land, remove all the vegetation, level the ground to the best of their abilities, and plow the fields with their tools; furthermore, ditches had to be clean, and dikes had to be repaired from the previous season. Among the tools used for rice cultivation was the sickle, which was employed for harvesting, while shovels and hoes were used for working the rice field. At Wormsloe, farming tools such as hoes have been unearthed near the marsh in the garden area of the only remaining slave cabin, and may represent one of the tools employed for cultivating rice in the nearby salt marsh (Figure 2.23). In general, the amount of rice produced would vary between planters, depending upon the cultivation method used, the soil fertility, the amount of labor force available to tend the field, and other factors such as storm and hurricanes. According to Coclanis (1989), for instance, estimates of rice yields in the early 18th century in the Low Country corresponded to about 1000 pounds of clean rice per acre, when dry cultivation was employed; when wet irrigation was introduced, however, estimates increased to at least 1500 pounds per acre, although higher yields did occur. Estimates for the first half of the 1800s, instead, are provided by Bagwell (2002), who reports an average yield of 40 bushels per acre in South Carolina, and 50 bushels per acre in Georgia, i.e., 1800 pounds per acre in South Carolina, 2250 pounds per acre in Georgia. Great variation was however present among planters, with values ranging between 30 and 60 bushels per acre across plantations. Finally, Coclanis and Marlow (1998) provide rough estimates for subsistence inland growers from eight townships in Orangeburg County, South Carolina in 1880 (Figure 2.24A); also, average yields for male rice growers are provided according to their tenure status (owner, renter, sharecropper) (Figure 2.24B). Given that the salt marsh area at Wormsloe is approximately 0.34 acres in size, and that 510 pounds (11.3 bushels) were produced, the estimated yield per acre at Wormsloe is about 1500 pounds (33.3 bushels). These estimates correspond exactly to the early 18th century estimates which report yields of about 1500 pounds per acre for wet rice culture. On the other hand, if we compare the Wormsloe estimates with those from subsistence planters in South Carolina in 1880, some discrepancies can be noted. In particular, Wormsloe displays much higher values than those reported for subsistence rice cultivated at the same time in South Carolina. However, the values reported for Orangeburg County include 653 farmers, who cultivated different acreages with different methods, e.g., dry, wet, or a combination of these two methods. Therefore, every rice field would yield different amounts of the crop, depending also on the fertility of the soil, and the skills of the planter. The discrepancy between Wormsloe and contemporary rice growers in South

Carolina, therefore, might be due to difference in soil fertility, amount of precipitation, infesting weeds, cultivation method, and even rice variety.

Finally, the preliminary analysis of soil and vegetation types from former rice fields has revealed interesting insights into identifying ecological patterns in abandoned rice fields. As Smith (2012) mentions, early planters who did not have much knowledge and experience in soil compositions employed vegetation as a proxy for assessing areas that would prove proper for rice cultivation. For instance, hardwood bottomlands vegetation such as cypress, sweetgum, tupelo gum, and live oaks provided useful insights into locating good lands for rice, given their poor drainage soils where moisture could be retained for growing the crop. Today, many abandoned rice fields and swamps have naturally reconverted to hardwood forests, while others are now characterized by maritime forest where pines, saw palmetto, and cedars now grow; this is the case, for instance, of former rice fields on Sapelo and Daufuskie Islands. Wormsloe presents similar vegetation characteristics in the immediate surroundings of the salt marsh, thus demonstrating the compatibility of the Wormsloe soil with rice cultivation. In particular, a botanical investigation performed on site revealed the presence of typical southeastern coastal vegetation in the area, such as cedars, cabbage palms, live oaks, saw palmetto, sweetgums, pines, as well as *Panicum virgatum* (switchgrass), *Spartina patens* (saltmeadow cordgrass) and *Dichantelium spp.* (rosette panic grasses) (Bradley, pers. comm.). In particular, a botanical inventory including 943 plant and grass species of the Savannah National Wildlife Refuge abandoned rice fields reports that *Panicum virgatum* is common on rice dike berms of the area, thus providing another parallelism between Wormsloe and known abandoned rice fields (Mellinger and Mellinger, 1961). In the marsh, *Juncus roemerianus* (black needlerush) and *Spartina alterniflora* (cordgrass) dominate the area, while no wild rice species such as *Zizania aquatica* (annual wildrice), *Zizaniopsis miliacea* (giant cutgrass), or other members of the rice subfamily, e.g., *Leersia spp.* (rice cutgrasses) were found in the area (Bradley, pers. comm.). The former rice fields at Drayton Hall and Skidaway Island, instead, have now naturally reconverted to salt marshes, where black needlerush is the predominant vegetation, similarly to what happened at Wormsloe. The muddy soil of the Wormsloe marsh, finally, would have provided the proper locale for rice cultivation, due to its poor drainage and moisture retention capabilities given by its high clay and silt content.

In conclusion, this paper demonstrated the affinities between Wormsloe and other rice cultivation experiences throughout the Low Country, arguing that Wormsloe was characterized by subsistence rice agriculture. In particular, the case studies of inspecting sites of known historical rice cultivation along the South Carolina and Georgia coasts presented evidence of how rice cultivation might be performed in a variety of environmental settings, with a variety of methods and techniques. The experience of rice cultivation at Wormsloe, therefore, provides yet another example of the ingenuity, determination, and skills of farmers in the Low Country who transformed the land according to their needs even in precarious ecosystems such as a tidal salt marsh.

2.5. CONCLUSIONS

The main purpose of this paper was to introduce a brief history of rice cultivation in the Low Country, and present case studies where rice cultivation was performed historically in different ways and for different purposes. In particular, former rice fields were inspected with the purpose to gain a better understanding of how they operated, as well as what abandoned rice fields may look like today. Furthermore, different typologies of rice fields, as well as different environmental settings, were observed in order to obtain a more complete understanding of how rice was cultivated throughout the Low Country, and see potential affinities and similarities with Wormsloe. In particular, subsistence rice agriculture performed on Sapelo and Daufuskie Islands showed similarities with what might have happened at Wormsloe, given their similar environmental settings and colonial histories. Furthermore, the use of salt marshes at Drayton Hall and Skidaway for rice cultivation proved how rice could have been grown almost anywhere, even in areas where salt water intrusion was a constant menace, such as at Wormsloe. The analysis of historical records, coupled with the analysis of similar environmental contexts, therefore, suggests that rice was cultivated at Wormsloe, and that it was likely performed by sharecroppers like Peter Campbell who cultivated crops to sustain their families or to sell some to the local market in Savannah in the second half of the 19th century.

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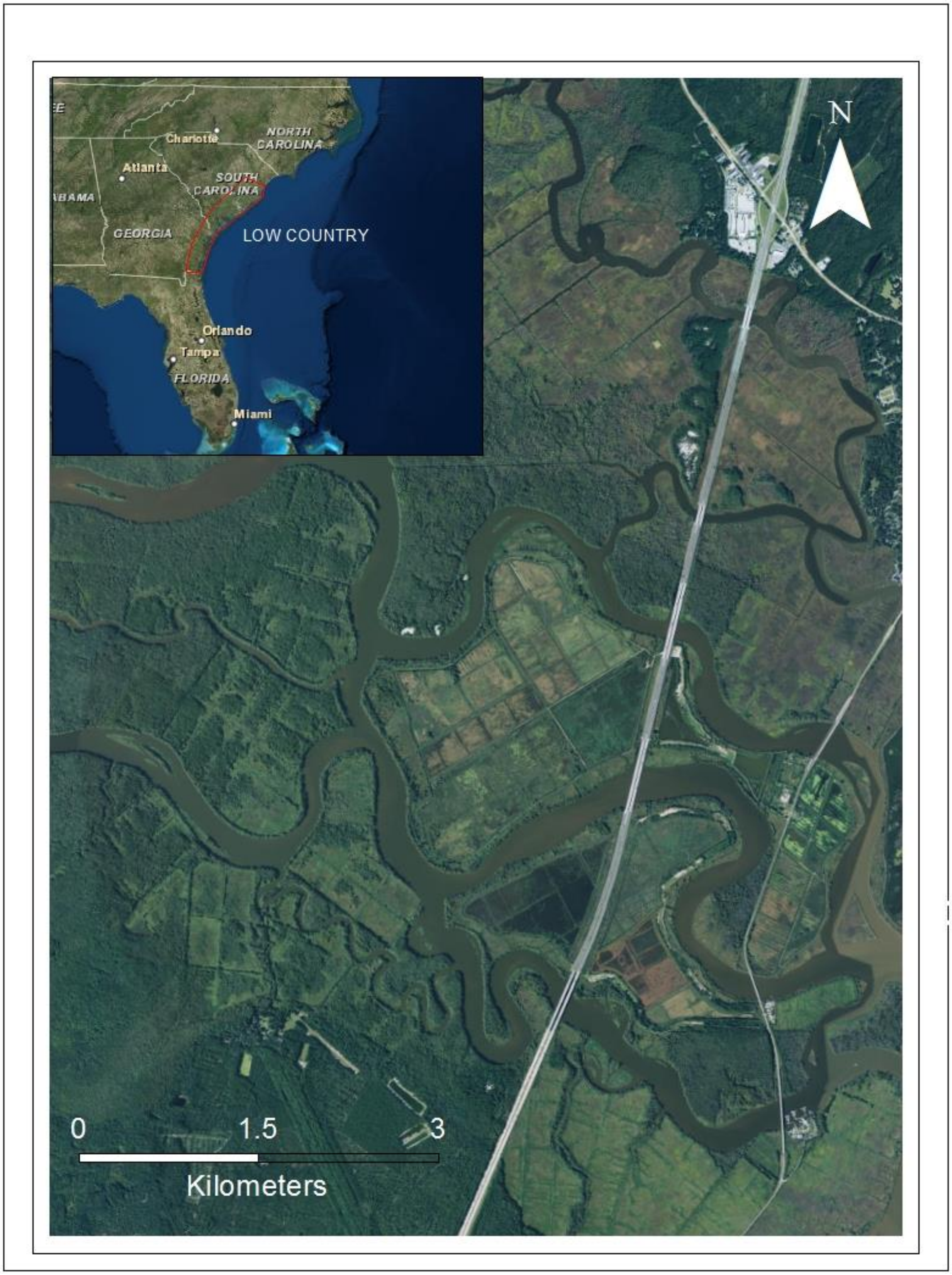


Figure 2.1. Layout of rice fields south of Darien, Georgia, along the Altamaha and Butler rivers.

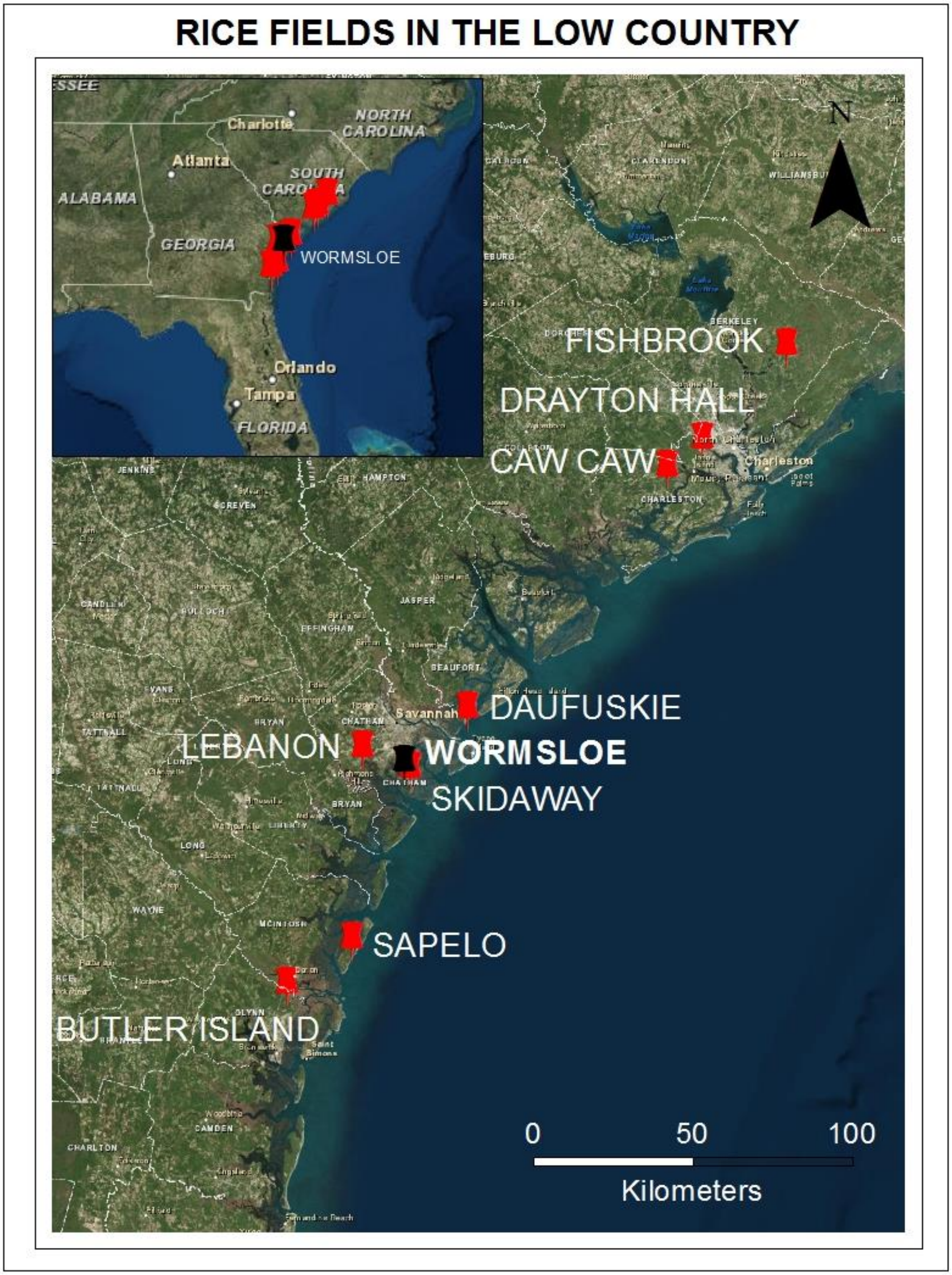


Figure 2.2. The rice fields inspected throughout the Low Country.

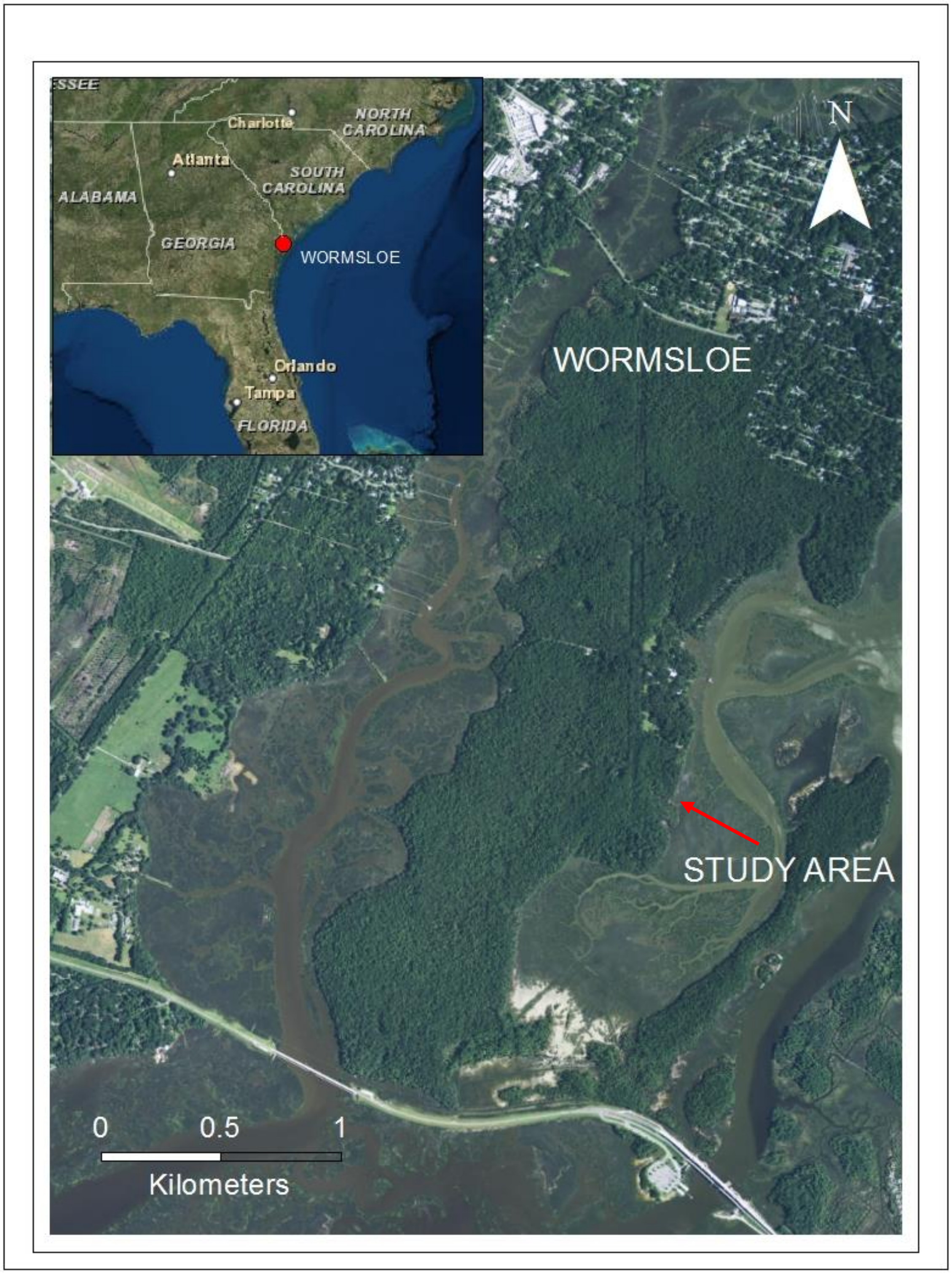
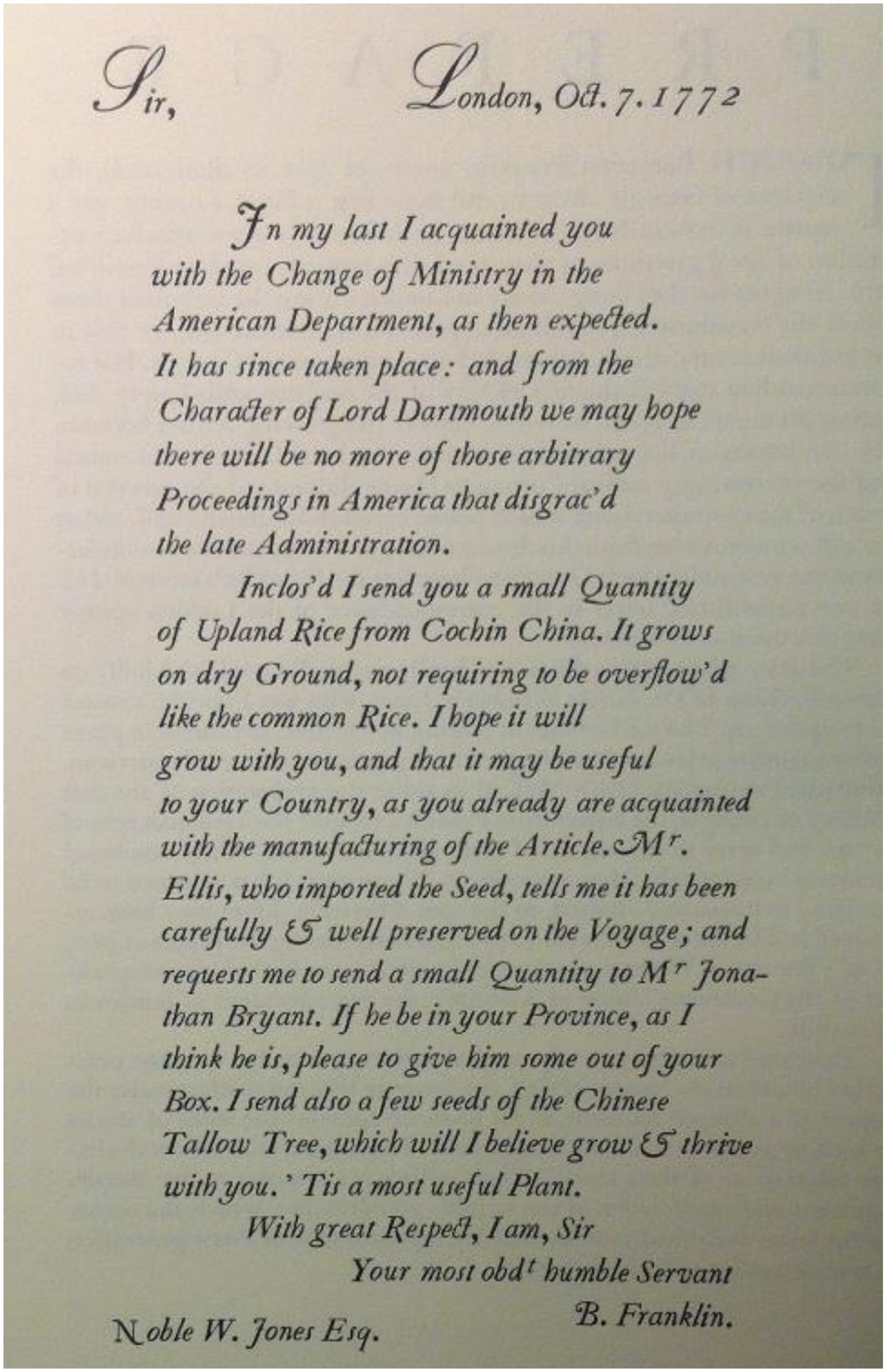


Figure 2.3. Wormsloe within the Low Country context.



Sir, London, Oct. 7. 1772

In my last I acquainted you with the Change of Ministry in the American Department, as then expected. It has since taken place: and from the Character of Lord Dartmouth we may hope there will be no more of those arbitrary Proceedings in America that disgrac'd the late Administration.

Inclos'd I send you a small Quantity of Upland Rice from Cochin China. It grows on dry Ground, not requiring to be overflow'd like the common Rice. I hope it will grow with you, and that it may be useful to your Country, as you already are acquainted with the manufacturing of the Article. Mr. Ellis, who imported the Seed, tells me it has been carefully & well preserved on the Voyage; and requests me to send a small Quantity to Mr Jonathan Bryant. If he be in your Province, as I think he is, please to give him some out of your Box. I send also a few seeds of the Chinese Tallow Tree, which will I believe grow & thrive with you. 'Tis a most useful Plant.

With great Respect, I am, Sir

Your most obdt humble Servant

B. Franklin.

Noble W. Jones Esq.

Figure 2.4. Letter of Benjamin Franklin to Noble Wimberly Jones (Bell III, 2013)

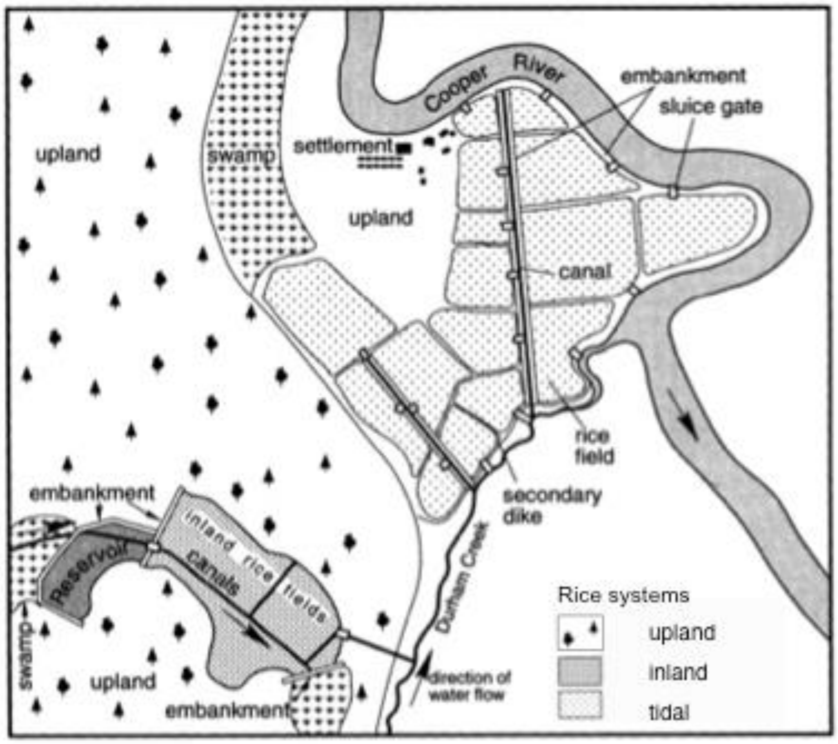


Figure 2.5. The three systems of rice cultivation, west branch of the Cooper River, South Carolina. Modified from Carney (1996).

Stage	*Date*	*Activity*	*Duration*
Planting	3/10–4/10 or 6/1–10	planting	
Sprout Flow	April	germination	4–20 days
Dry Growth	May	hoeing	10–20 days
Point Flow	May	kills weeds	3–7 days
Dry Growth 2	June	hoeings 1 & 2	20 days
Stretch Flow	June	suppress grass	3–10 days
Dry Growth 3	June–July	hoeings 3 & 4	14–20 days
Lay-by Flow	July–August	60–70 days	
Harvest	September		
Curing	September	1–4 days	
Threshing	September–October		

Figure 2.6. Rice annual cultivation cycle (Tuten, 2012).

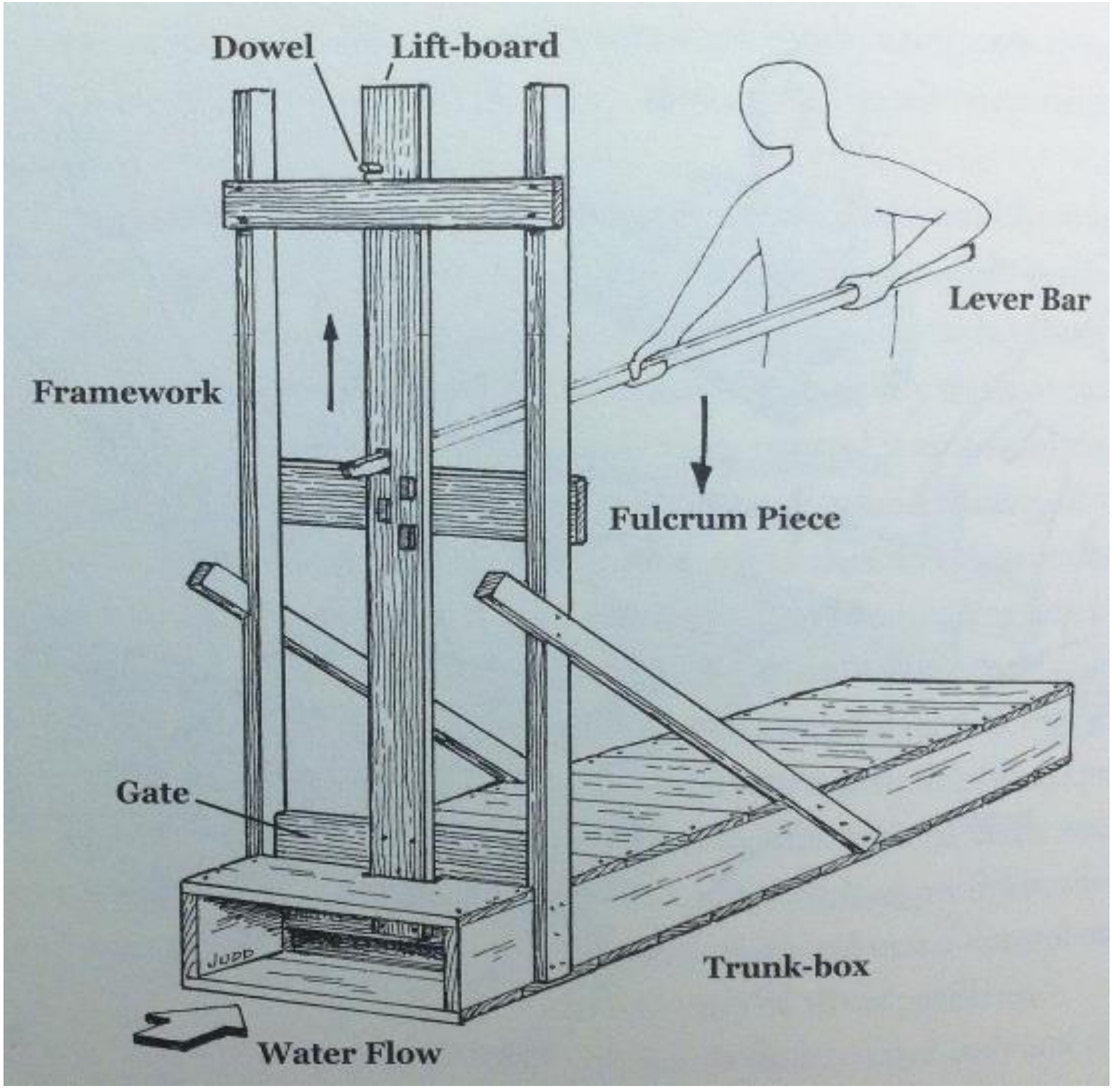


Figure 2.7. A lever-gate trunk. Illustration by William Robert Judd (Porcher Jr and Judd, 2014).

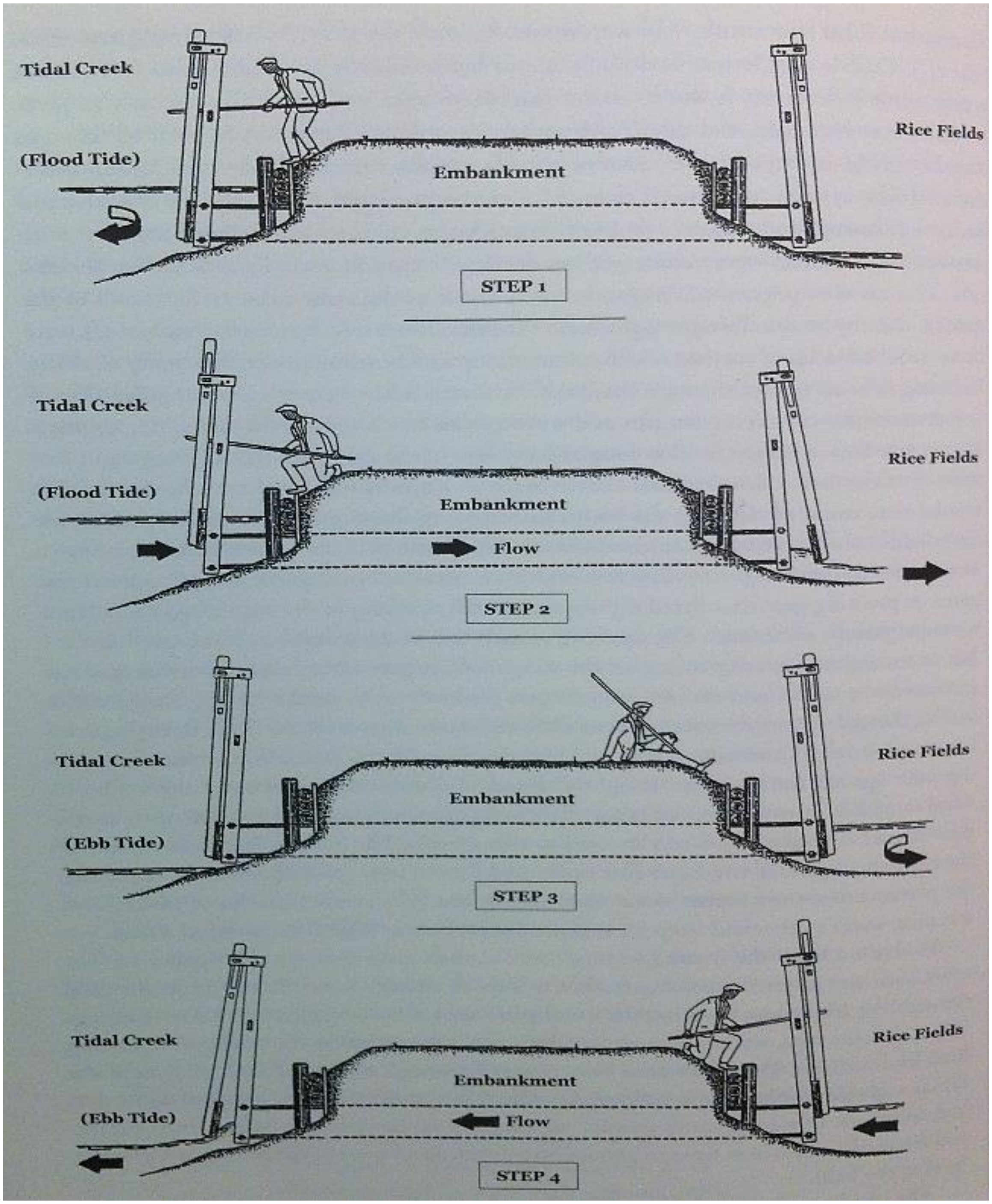


Figure 2.8. Operation of a tide trunk. Illustrations by William Robert Judd (Porcher Jr and Judd, 2014).

Figure 2.9. Former rice fields (A) and rice trunk (B) at Butler Island Plantation.

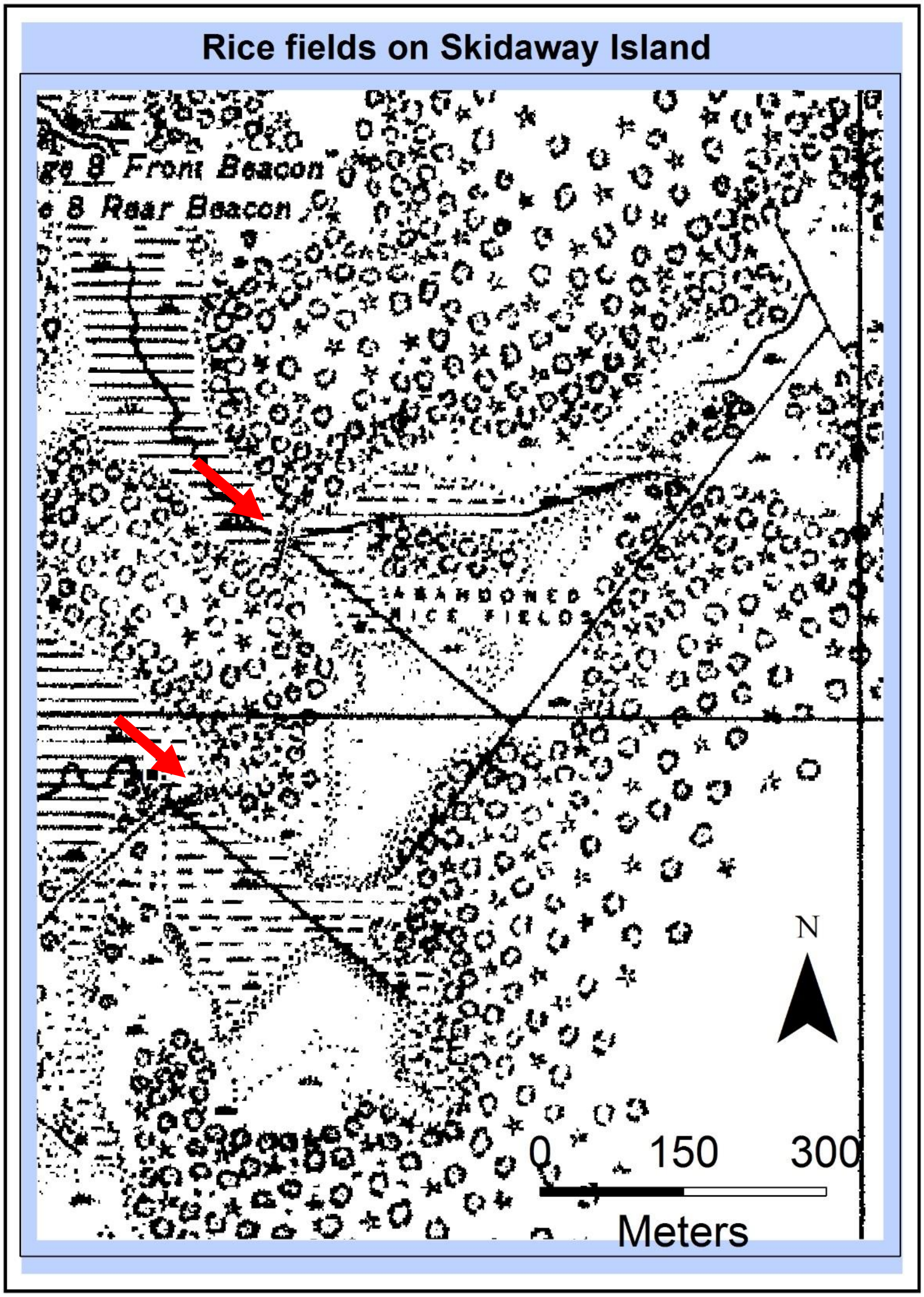


Figure 2.10. 1933 historical map showing abandoned rice fields on Skidaway Island, which are now part of the Island State Park. The red arrows indicate rice dikes.

Figure 2.11. Former rice dike at Skidaway Island.

Figure 2.12. Former rice fields of the Fishbrook plantation, now part of the Santee Experimental Forest.

Figure 2.13. Former rice fields at Drayton Hall viewed from an old dike. A tree line in the distance indicates the presence of a second rice dike.

Figure 2.14. Rice embankments at the Caw Caw cypress swamp (A). Former rice fields with quarter drains at Caw Caw (B).

Figure 2.15. Rice embankments observed in the summer (A) and winter (B) at Daufuskie. Picture B is courtesy of Roger Pinckney.

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Figure 2.16. Rice cultivated for personal use on Sapelo (A); low, moist areas used for subsistence rice cultivation on Sapelo Island (B).

Figure 2.17. Water control structure with former rice fields on the back which are now tidal salt marshes (A); rice dike now used as an internal road (B).

Figure 2.18. Rice dike at Wormsloe.

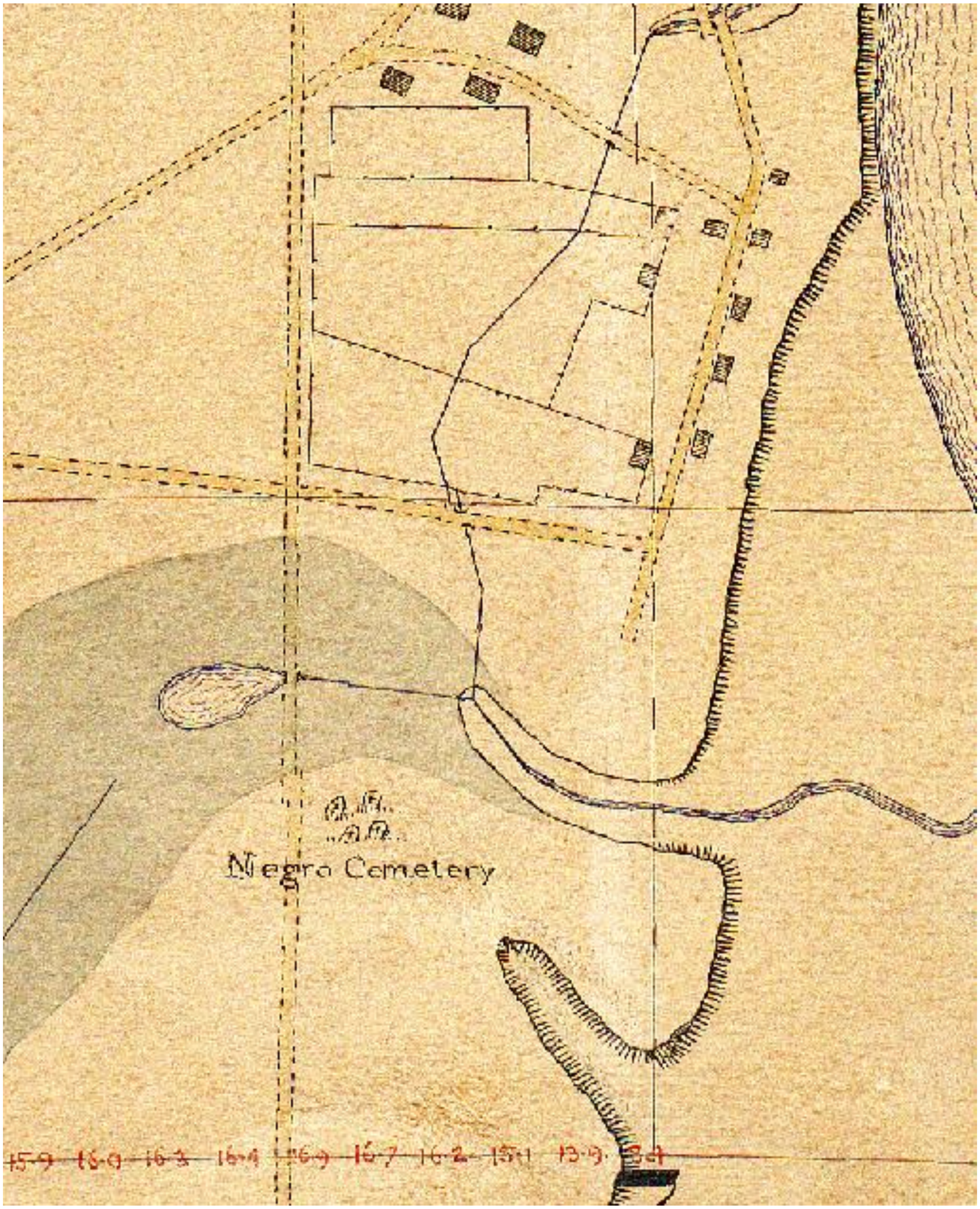

Figure 2.19. Blandford map from 1890 showing the former slave settlement, cemetery, and study area. Note the ditch connecting the reservoir to the salt marsh where rice was likely being grown. Map available from the WIEH database served by the Center for Geospatial Research.

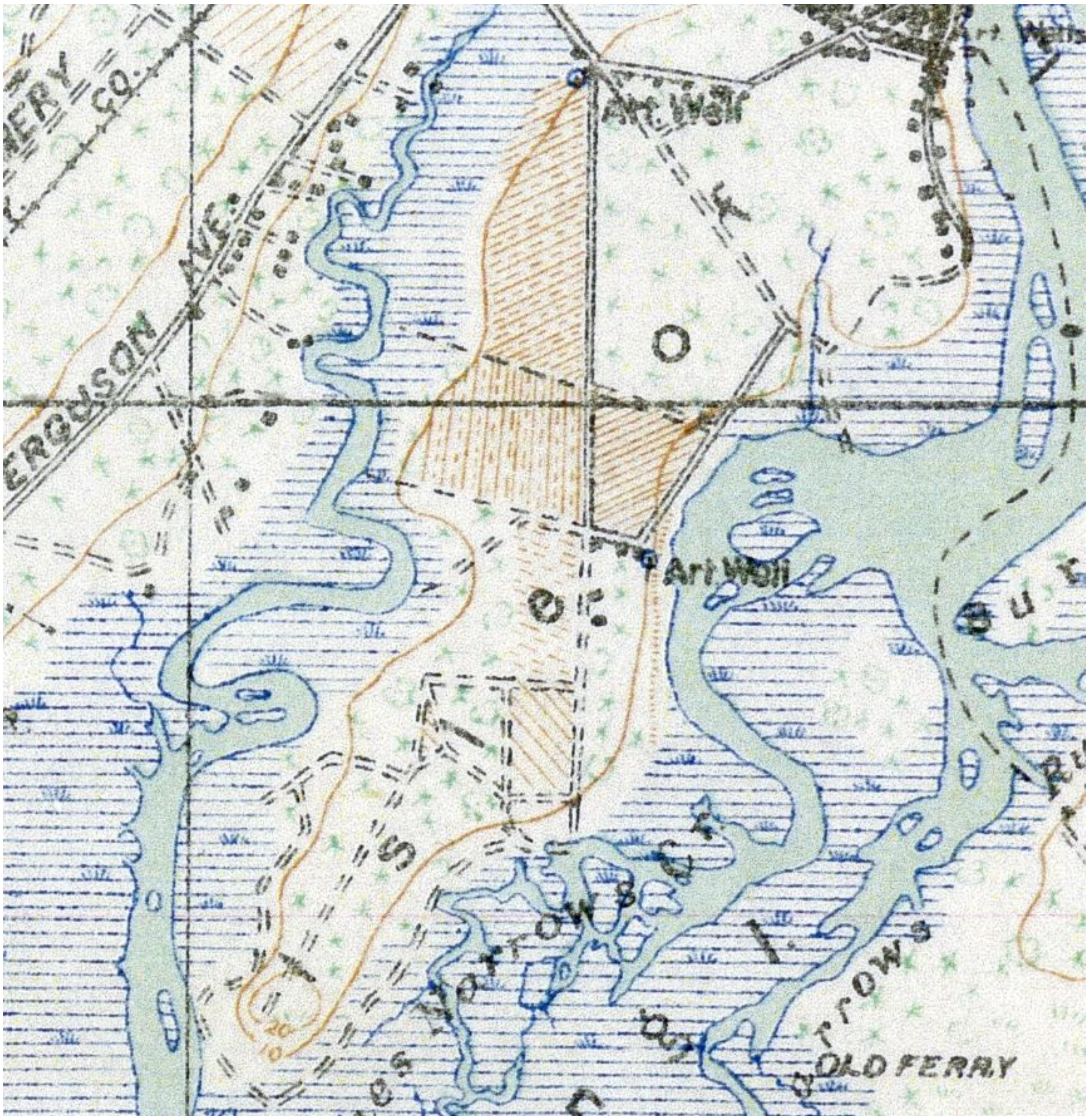

Figure 2.20. Topographic map from 1912 showing the presence of artesian wells on the Isle of Hope. Map available from the WIEH database served by the Center for Geospatial Research database.

Figure 2.21. Photograph showing a diked flooded area and a water control structure at Wormsloe. Photo available from the Georgia Historical Society. Courtesy of Paul Cady, 2015.

Figure 2.22. Modern photograph of the rice dike at Wormsloe showing similarities with the historical photograph.

Figure 2.23. Old hoe discovered in the garden area of the slave cabin at Wormsloe.

A

	WM	WF	BM	BF	MuM	MuF	Average Per Acre Yield By Township*
A	273	644	363	322	421	0	320
B	320	306	286	272	245	293	302
E	377	303	264	300	304	0	335
C	301	282	249	490	395	0	276
G	580	472	527	0	452	0	557
H	426	396	388	931**	0	0	418
L	430	354	295	0	311	0	374
O	257	211	226	0	354	0	245

*In pounds of clean rice per acre.

**Calculated on the basis of one grower with only about 1/8 acre of rice.

B

Male Rice Growers

		Number	Average Rice Acreage	Mean Yield Per Acre (lbs. clean rice)
White	Owners	187	3.1	442
	Renters	18	2.8	370
	Sharecroppers	35	1.5	375
Black	Owners	63	1.8	338
	Renters	108	1.3	319
	Sharecroppers	128	1.6	394
Mulatto	Owners	11	2.2	368
	Renters	15	1.3	333
	Sharecroppers	15	1.9	315

Figure 2.24. Average yield per acre by race and gender in eight Orangeburg County townships in 1880 (A); average yields per acre of male rice growers by tenure status in 1880 (Coclanis and Marlow, 1998).

CHAPTER 3

TERRESTRIAL LASER SCANNING AND UNMANNED AERIAL SYSTEMS FOR 3D RECONSTRUCTION OF CULTURAL LANDSCAPES AT WORMSLOE HISTORIC SITE[2]

[2] Pasqua, A., T. R. Jordan, and M. Madden. To be submitted to *Photogrammetric Engineering & Remote Sensing*.

ABSTRACT

Studies of historical landscapes benefit from the use of remote sensing technologies such as terrestrial laser scanning (TLS), airborne light detection and ranging (LiDAR), and unmanned aerial systems (UAS) to perform non-invasive and detailed mapping of micro topography that can be used to reconstruct legacy land use of cultural landscapes. In particular, this study assesses the use of TLS, LiDAR, and UAS to investigate present-day topographic features such as dikes and subtle elevation changes across a marsh that may indicate 19th century rice cultivation at Wormsloe Historic Site in coastal Georgia. The use of multiple, overlapping images collected by means of UAS allows the 3D reconstruction of the area, thus enabling researchers to readily map and measure topographic landscape features. The 3D reconstruction is based upon Structure from Motion (SfM) photogrammetric algorithms which have been used for archaeological and cultural heritage documentation over the last few years. This study compares topographic features derived from UAS-SfM to those from TLS and LiDAR in order to illustrate the potential and limitations of these remote sensing techniques for the accurate mapping of complex landscapes such as legacy agricultural practices and tidal salt marsh hydrology of the coast of Georgia.

Keywords: Terrestrial laser scanning, Unmanned aerial systems, Airborne laser scanning, Bare Earth Digital Elevation Model, Topographic mapping, Structure from Motion, 3D reconstruction, Wormsloe

3.1. INTRODUCTION

Salt marshes and freshwater wetlands are highly productive, yet fragile environments that are rich in nutrients and microorganisms, act as nurseries for fish and shell fish industries, and provide physical buffers against storms and hurricanes (Mitsch and Gosselink, 2000). Since 1970, the salt marshes of Georgia including those surrounding the Isle of Hope and Wormsloe Historic Site have been protected from development and other impacting activities by the Coastal Marshlands Protection Act (CMPA) (Georgia Department of Natural Resources, 2015). At the Wormsloe Historic Site on the Isle of Hope along the Georgia coast, however, historical alteration of marsh and upland topography have impacted coastal wetlands. For example, the construction of earthen dams built by Civil War Confederate soldiers and followed, in 1972, by the Diamond Causeway connecting the mainland to Skidaway Island. These alterations affected the composition of original salt marshes and tidal equilibrium, whereby low marshes have gradually transformed into higher marshes (Rice *et al.*, 2005). This, in turn, affected local vegetation communities such as salt marsh dominated by *Spartina alterniflora* (cordgrass), and favored the gradual expansion of marsh species such as *Salicornia* (grasswort or sea asparagus), *Juncus roemerianus* (black needlerush), and *Distichlis spicata* (saltgrass) (Rice *et al.*, 2005; Wiegert and Freeman, 1990).

The island and surrounding marshes have been the site of human inhabitation since 4,000 years before present and under ownership by the same family since the land was granted to Noble Jones in 1736. It has been protected as the Wormsloe State Historic Site since 1973, when the State of Georgia purchased the majority of the island and designated it as a state historic site given its historical, ecological, and cultural significance. Wormsloe has been uniquely preserved due to its heritage of land stewardship and conservation, evidence of prehistoric inhabitation, colonial settlement, antebellum plantation agriculture, post-Civil War subsistence farming, Depression Era tourism, and modern use for historical and environmental education as a state historic park. The relatively undisturbed and undeveloped landscape of Wormsloe make it a perfect site for reconstructing land use change and the environmental history of the Low Country landscape. Although the historic activities of Wormsloe are well documented, the question of whether or not rice was ever cultivated on the island has remained a mystery. The only hints related to rice cultivation at Wormsloe are represented by the letter sent by Benjamin Franklin to Noble Wimberly Jones in 1772 in which an upland rice sample was enclosed to suggest its cultivation at Wormsloe, as well as by the 1880 agricultural census mentioning the cultivation of 510 pounds of rice by a freedman living on site named Peter Campbell (Swanson, 2012).

This study focuses on the use of advanced remote sensing techniques such as terrestrial laser scanning (TLS), airborne light detection and ranging (LiDAR), and unmanned aerial systems (UAS) to detect, map, and measure topographic features in a tidal salt marsh area where historical rice cultivation is suggested. As Lillesand *et al.* explain (2014), "*remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation*". The potential of laser scanning sensors for the detection and mapping of topographic features in historical landscapes has been widely demonstrated over the last years, both using airborne laser sensors (Bollandsås *et al.*, 2012; Chase *et al.*, 2011; Corns and Shaw, 2009; Doneus *et* *al.*, 2008; Lasaponara and Masini, 2009; Lasaponara *et al.*, 2011; Štular *et al.,* 2012; Werbrouck *et al.*, 2011) and terrestrial or ground-based laser sensors (Figure 3.1) (Dietz *et al.*, 2012; Lerma *et al.*, 2010; Pirotti *et al.*, 2013). Laser scanners employ the LiDAR (Light Detection and Ranging) technology that actively sends a narrow beam of light out from the instrument and receives the reflected energy to measure the distance of a target without being directly in contact with it. As Fowler *et al*. (2007) explain, "*all laser scanning devices operate by directing structured light to the object to be measured, then detecting and measuring the signal from light reflected by the object surface*". Therefore, by knowing the speed of light, the distance between the sensor and the object can be derived by "*timing the round trip of the transmitted beam and reflection of that beam*" (Fowler *et al.*, 2007). Since the pulse of light is sent out at a rapid frequency, i.e., 150,000 pulses per second, laser scanners have the ability to quickly collect large quantities of high resolution 3D measurements in the form of point clouds of X, Y, and Z coordinates, thus allowing very accurate measurements of objects and topographic surfaces, as well as their 3D reconstruction . Although similar in their operating system, TLS and airborne LiDAR sensors differ in the way measurements are taken, i.e., by means of terrestrial sensors mounted on the ground, vehicles, or boats, or through sensors mounted on an airplane, respectively. In particular, many scanners are provided with multiple return capability lasers (also known as full-waveform lasers) that can reach the ground even in vegetated areas, thus enabling the mapping of bare earth topographic features that are covered by the vegetation (Bollandsås *et al.*, 2012; Chase *et al.*, 2011; Corns and Shaw, 2009; Doneus *et al.*, 2008; Guarnieri *et al.*, 2009; Lasaponara and Masini, 2009; Lasaponara *et al.*, 2011).

The analysis of bare earth topography is performed through the use of filtering algorithms which enable LiDAR analysts to isolate elevation points (or measurements) based on their return order (i.e., first, last, or intermediate return pulses) and/or their position in X, Y, and Z space. One of the most common products of this process is the generation of accurate digital elevation models (DEMs), which provide the elevation values of the bare earth topography only. For instance, airborne LiDAR-derived DEMs have been employed to study the hydrological connectivity of salt marshes in Texas (Colón-Rivera *et al.*, 2012). However, as suggested by Guarnieri *et al.* (2009), the use of ground-based LiDAR systems (i.e., TLS) with average point densities of 200 points per square meter, may potentially overcome the limitations of airborne systems, as the spatial resolution of airborne LiDAR-derived DEMs may suffer from the low canopy penetration in densely forested areas and the low point densities, which are on the order of 10 points per square meter. In this way, the resulting DEM is of limited point density and large footprints, unsuitable for mapping low relief topography in challenging environments such as tidal salt marshes. Despite the advantages of obtaining higher resolution DEMs from terrestrial laser scanners datasets, this technology does present some challenges. For instance, the scan geometry of ground-based systems is very different from that of airborne systems, which have a better angle to penetrate vertically through the canopy within their field of view (Figure 3.2). The scan geometry of ground-based systems, instead, due to the wide horizontal angle at which light pulses travel, determines a much larger field of view, greater fallout in point density and resolution with distance from the sensor, and cone-shaped data gaps around the sensor (Pirotti *et al.*, 2013). Other factors that may affect the use of these technologies are represented the topographic conditions of the area under investigation, since heavily vegetated terrain may limit the ability of lasers to reach the ground, as lasers can only map features along their line-of-sight. Atmospheric conditions may also affect LiDAR lasers, as haze, fog, and extreme temperatures may cause noise in the data and/or limited visibility and laser penetration. LiDAR data processing requires the use of particular computers, software packages, and skillsets to analyze the large and complex LiDAR dataset and extract geospatial information. Finally, the cost of LiDAR equipment may be an issue for users with a limited budget, as the use of airborne LiDAR may cost hundreds of thousands of dollars, while TLS sensors may range between $10,000 and 100,000. It is therefore apparent that both airborne and terrestrial laser scanning systems have limitations, thus choosing between the two will depend on several factors such as the purpose, scale, available resources, and topographic nature of the area under investigation.

This study also employed the unmanned aerial systems (UAS) technology for the detection, mapping, and 3D reconstruction of topographic features which can be indicative of old rice fields (Figure 3.3). The rapid success of this new remote sensing technology over the last few years has produced an ever increasing consensus both in the public and the private sectors (Colomina and Molina, 2014). In particular, the use of UAS has been rapidly adapted by scholars for the study of archaeological and historical landscapes (Casana *et al.*, 2014; Chiabrando *et al.*, 2011; Mozas-Calvache *et al.*, 2012; Plets *et al.*, 2012; Rinaudo *et al.*, 2012; Smith *et al.*, 2014; Verhoeven and Docter, 2013). One of the main advantages of UAS, in fact, is their ability to obtain aerial images of hard-to-reach areas, with short revisit times, and with a relatively limited budget (Madden *et al.*, 2015). Their relatively low cost, i.e., $1,000 - $3,000, as well as their relatively straightforward mode of operation makes UAS an easy-to-use method for even non-professional users for the collection of low altitude geospatial data. The accuracy of data collected by means of UAS technology has been recently investigated in a study conducted by Mancini *et al.* (2013), which demonstrated that the average difference in the vertical values between terrestrial laser scanning and UAS data was on the order of 0.05 m (RMS 0.19 m); similarly, another study performed by Uysal *et al.* (2015) demonstrated that the RMSE vertical accuracy of a UAS-derived DEM was 6.62 cm, which was obtained by using aerial imagery collected at a flying altitude of 60 m. The ability to obtain 3D measurements at the centimeter-level is essential for the study of micro topographic features in legacy landscapes such as dikes and elevation changes across the marsh at Wormsloe. Therefore, UAS represent a reliable means of conducting aerial surveys and topographic mapping.

The collection of aerial images from different, overlapping, vantage points permits the 3D reconstruction of an area or an object through the Structure from Motion (SfM) photogrammetric technique (Figure 3.4) (Fonstad *et al.*, 2013). Unlike conventional stereoscopic photogrammetry, SfM does not require the 3D location of the camera or the 3D location of a series of control points to be known a priori. In fact, "*camera pose and scene geometry are reconstructed simultaneously through the automatic identification of matching features in multiple images. These features are tracked from image to image, enabling initial estimates of camera positions and object coordinates which are then refined iteratively using non linear least-squares minimizations*" (Westoby *et al.*, 2012). In particular, the 3D reconstruction process is performed by two algorithms: the Scale Invariant Feature Transform (SIFT) and the

Bundle Adjustement (BA), which are responsible for finding matching points in multiple images and for iteratively estimating the camera positions and parameters, respectively (Westoby *et al.*, 2012). Therefore, instead of a single stereo pair, SfM requires multiple, overlapping images with 80 to 90 % forward overlap to ensure a high number of matching features for 3D reconstruction (Alexander *et al.*, 2015). Once the 3D geometry of the object or area has been reconstructed, ground control points can be used to register the model to real world coordinates, thus enabling 3D measurements and mapping. The use of SfM for the 3D documentation of objects and areas has been employed in many fields such as archaeology and cultural heritage (Alexander *et al.*, 2015; De Reu *et al.*, 2014; Dellepiane *et al.*, 2013; Smith *et al.*, 2014). The accuracy of SfM-derived topographic measurements was investigated by Fonstad *et al.* (2013) who compared them against airborne LiDAR data, finding that both horizontal and vertical values were in the centimeter range; however, Gomez *et al.* (2015) warn users of the possible inaccuracies of SfM-derived models, especially in areas that can be difficult for 3D reconstruction such as vegetated areas and surfaces with irregular illumination.

Following an investigation of the feasibility of using UAS for wetlands mapping by Madden *et al.* (2015), this study aims at performing a detailed topographic mapping and 3D reconstruction of a study area at Wormsloe that was potentially a site of historical rice cultivation. In addition to UAS-derived micro topography, terrain information obtained with airborne LiDAR and TLS data available for the study area were compared so as to appreciate advantages and limitations of each technique for wetland and cultural landscape mapping in a salt marsh environment. In particular, specific objectives of this study include the creation of a bare earth digital elevation model (DEM) of the salt marsh in order to analyze and measure the bare earth topography currently hidden by the vegetation in terms of providing evidence supporting historical rice cultivation at Wormsloe. Finally, this study performs the 3D reconstruction of the salt marsh through the collection of overlapping UAS aerial images and compares the three techniques for 3D mapping and geovisualization of micro topography.

3.2. STUDY AREA

The study area (Figure 3.5) is a small tidal salt marsh inlet within the Wormsloe State Historic site of approximately 1,416 m^2 in size (0.34 acres). The area is located on the eastern side of the Isle of Hope along the Skidaway River, coastal Georgia, and has roughly a rectangular shape measuring approximately 70 x 20 m (Figure 3.6). The site is subject to daily tidal flooding, and vegetation types include *Juncus roemerianus* (black needlerush) and *Spartina alterniflora* (cordgrass) in the marsh, and maritime forest of cedars, pines, palms, and saw palmetto in the immediate upland surroundings. In particular, the study area presents topographic features that may suggest the site was once used for agricultural purposes. For instance, it was noted the presence of what appears to be a manmade dike, which could indicate a structure put in place for controlling and preventing salt water influx at high tide. Second, the area is characterized by two drainage ditches which converge and discharge their waters in the marsh; these could have served as canals to bring freshwater to the cultivated field located in the lower marsh. Third, from the analysis of the 1890 Blanford historical map, it was noted that the area was connected to a water body through one of the two still existing ditches, thus suggesting the presence of a reservoir which would have collected freshwater in the form of ground water or precipitation. Fourth, the poorly drained soil of the marsh may have provided the right type of land for the wet cultivation of rice. Finally, the area is located approximately 173 m south of the only surviving 19th century slave cabin at Wormsloe. The cabin was part of the so-called “slave quarters”, and was built in the first half of the 1800s to accommodate enslaved laborers working on the sea island cotton crop cultivated and harvested at Wormsloe (Swanson, 2012). Being in such close proximity to the slave settlement, the area might have been chosen for subsistence agricultural purposes by the African-American population living nearby.

3.3. METHODS

3.3.1. Terrestrial and airborne laser scanning

Terrestrial LiDAR data were collected during the morning hours of March 8, 2014, under low tide conditions in order to scan the exposed bare earth topography and avoid water interference. At the time of collection, however, vegetation in the study area was higher and denser than expected, thus further reducing the ground area that was exposed. Chester Jackson from Georgia Southern University and UGA Skidaway Institute of Oceanography performed data collection and initial data processing. A RIEGL VZ-1000 was used for scanning the area (Table 3.1). In particular, this scanner has a rotating head mounted on a tripod to ensure high stability on the ground. This sensor is also featured with a multiple return capability to penetrate through vegetated areas and reach the ground. High precision mounting pads enabled the use of a digital camera for the collection of high quality color images while scanning the study area. The TLS scanner, scanning at a range of 450 meters with a 20 mrad laser beam, was positioned at four different locations within the marsh in order to better cover the area. When standing in the marsh, wooden boards were used to support the tripod in the muddy soil. Four retroreflective targets were placed around the study area to allow the four scans to be co-registered in the same coordinate system. The positions of the scanner and of the targets were recorded with a Trimble R8 Real-Time Kinematic (RTK) GPS device to allow centimeter-level accurate georeferencing.

Finally, this study employed full waveform airborne LiDAR of Chatham County that was collected in the spring of 2009 as a result of a partnership between NOAA, U.S. Department of Commerce, Office for Coastal Management, and the National Ocean Service. Data were acquired at a flight altitude of 1100 m (above ground level), with a field of view of 30º, and with a point spacing of 0.57 m (NOAA, 2015). Data were retrieved from the Center for Geospatial Research at the University of Georgia database.

Data processing

The four TLS scans were registered and georeferenced using the RISCAN PRO software package available with RIEGL (Riegl, 2015). The coordinate system used for georeferencing the data was UTM 17N, NAVD 88, Geoid 20 (Jackson, pers. comm.). A first analysis of the data revealed vertical and horizontal accuracies of +/- 5 cm (Jackson, pers. comm.). The data were then delivered to the Center for Geospatial Research at UGA where further analysis was performed. The raw data consisted of four point clouds (.las format) provided with X, Y, Z coordinates and R, G, B values, for a total of almost 209 million photo imaged and 3D points (Figure 3.7). The meshed point cloud presented a point spacing of 0.02 m, and a point density of 2230 points per square meter. LASTools

1.3 (http://rapidlasso.com/lastools/), an open-source software package designed for the analysis of LiDAR data, was employed for filtering the points above the ground following the workflow presented in Table 3.2. Given the large number of total points, each point cloud was processed separately, and transformed into the compressed las format (i.e., .laz) format. The initial filtering consisted of removing points with an elevation higher than 3 meters from the ground so as to sensibly reduce the number of total points to be processed. The ground points were then automatically classified and separated from the low vegetation points, presenting a point density of 662 points per square meter and a point spacing of 0.04 m for the last return. Furthermore, when processing ground points, LASTools provides the option of specifying whether the LiDAR data are airborne or terrestrial nature, as this causes different laser and scan geometries. Finally, the ground points of each scan were merged into one and a bare earth digital elevation model was obtained. Quick Terrain Modeler (QT Modeler) software package was employed to analyze and visualize the results.

On the other hand, the point cloud data for the Isle of Hope obtained by means of airborne LiDAR presented a 0.43 m point spacing, a point density of 5.396 points per square meter, and 4 pulse returns (Figure 3.8). The 3D point cloud was processed using LASTools to convert coordinates into UTM 17N ground coordinates, identify the ground points, and remove points above the ground. Ground points had a density of 3.05 points per square meter and a spacing of 0.57 m. A bare earth digital elevation model at a 0.2 m spatial resolution was obtained.

3.3.2. Unmanned aerial systems

Aerial imagery of the study area was collected using a DJI Phantom 2 Vision quadcopter in First Person View (FPV) mode on February 19, 2015 at both low and high tide conditions (Table 3.3). This particular date was chosen as it presented the highest (and the lowest) tides of the month, as one the objectives of the investigation consisted of assessing whether the dike could still effectively hold back salt water influx at high tide. Flight planning included a careful inspection of the study area in order to locate the best locations for placing the ground control points (GCPs) targets necessary for setting the coordinate system. In particular, nine 60 x 60 cm plywood and targets painted white with a black cross were well distributed around the marsh for a more uniform georeferencing, and care was taken in choosing locations which would ensure their visibility from the air during data collection (Figure 3.9). The targets' positions were accurately recorded with a Trimble GeoXH GPS device with differential correction capabilities. Furthermore, in order to give additional geometry to the 3D models, the ground distances between targets were measured in the field with a tape (Figure 3.10). Flight planning also included a practice flight over the marsh to test possible flight lines, and foresee potential problems while flying, e.g., tree branches. While operating the quadcopter, a remote controller provided with a mobile phone gave real-time telemetry data and flight parameters which could be adjusted at any time from the ground for optimal data collection, e.g., camera tilt. In particular, the quadcopter was operated at two different flying altitudes, i.e., 85 and 60 feet (25.9 m and 18.2 m) above the ground, in order to capture aerial images at different levels of details. Aerial data were collected in HD video format and stored on-board on a memory card for later download.

Data processing

Using the open-source VLC Media Player application (http://www.videolan.org/), the HD videos collected at high and low tide conditions were inspected in order to select and retrieve individual frames with sufficient overlap (around 80%). Such overlap is required for performing successful image matching in consecutive frames, thus allowing accurate 3D geometry reconstruction using the Structure from Motion (SfM) principle. Following the parameters described in Table 3.4., the selected frames were then imported into Agisoft Photoscan commercial software for 3D reconstruction and point cloud generation (Figure 3.11). The number of pictures used to reconstructing the high tide and low tide models was 534 and 180, respectively. The targets' positions were used as ground control points to georeference the model in real-world coordinate systems, i.e., WGS 84, UTM 17N, using the guided marker approach in Photoscan. For additional geometric strength, scale bars including the known linear distances between targets were added to the model.

3.4. RESULTS

A 0.2 m spatial resolution bare earth digital elevation model (DEM) was obtained from terrestrial laser scanning, and was then registered in UTM 17N, NAVD 88 coordinates (Figure 3.12). The model presents absolute elevations ranging between 0.1 m and 2.9 m above sea level, as well as a point density of 25 points per square meter. The elevation change is displayed by colors ranging from blue (lower elevations) to red (higher elevations). From the model, the general layout of the salt marsh as well as topographic features such as the manmade dike can be appreciated.

The georeferenced 3D models at high and low tide conditions obtained from using SfM from UAS images are shown in Figure 3.13. In particular, the high tide model displayed an estimated total georeferencing error of 0.38 m, and errors of 0.30 m, 0.11 m, and 0.20 m for the x, y, and z axes, respectively; on the other hand, the low tide model presented an estimated total georeferencing value of 0.43 m, and errors of 0.30 m, 0.24 m, and 0.18 m for the x, y, and z axes, respectively. Scale bars presented estimated positional error values of 0.10 m and 0.30 m for the high tide and low tide model, respectively. With regard to the 3D point clouds that were obtained, the results show very high levels of detail, with point spacing values of 0.03 m and 0.04 m for the high and low tide models, respectively, as well as very high point density values corresponding to 1125 and 616 points per square meter for the high and low tide models, respectively (Figure 3.14). In terms of number of points obtained for 3D reconstruction, the high tide 3D point cloud presented around 8 million points, while the low tide model had almost 4 million points.

The airborne LiDAR-derived DEM is shown in Figure 3.15A. The difference in the level of detail with the terrestrial laser scanning DEM is apparent, due to their different point densities and point spacing values, in spite of having the same nominal spatial resolution, i.e., 0.2 m (Figure 3.15B). However, the general topography of the marsh can be appreciated with the presence of the two dikes delimiting the area; furthermore, features such as ditches can be clearly distinguished, thus providing additional landscape context to the study area.

3.5. DISCUSSION

Terrestrial and airborne laser scanning

The main purpose for employing terrestrial laser scanning in this study was to obtain an accurate, centimeter-level topographic map of the study area in order to analyze subtle topographic changes which may be related to rice cultivation. For instance, the elevation profile measured on the terrestrial laser scanning-derived DEM of the Wormsloe lower dike is shown in Figure 3.16A. It can be noted that there is an elevation difference of 1.2 m between the marsh level and the highest point of the dike. The length and width of the dike were also measured, reporting values of 10 m and 2.2 m, respectively. As Figure 3.15A shows, however, the area also presents another similar feature which is represented by the modern road delimiting the area along the west side. This topographic feature would have served as the upper dike of the rice field, and a water control structure – also known as rice trunk or gate – would have been placed there as well to regulate freshwater flow coming from the still existing ditch. As shown in Figure 3.11 though, this feature is not apparent in the DEM obtained from terrestrial laser scanning; however, this feature can be analyzed using the airborne LiDAR-derived DEM available for the area. In particular, the height of the upper dike at Wormsloe corresponds to around 0.5 m, while its width corresponds to about 3 m (Figure 3.16B). Furthermore, measurements of topographic features taken at Wormsloe may be compared against topographic measurements of known examples of rice fields, such as the former fields on Skidaway Island, located just across the Skidaway River from the study area. Elevation data and a 1 m spatial resolution DEM for Skidaway Island were obtained by processing in LASTools airborne LiDAR data collected over Chatham County in 2009 (Figure 3.17).

In particular, the dimensions of a former rice dike at Skidaway measure 0.6 m by 5 m, similar to the dimensions measured on the upper dike at Wormsloe (Figure 3.18).

Another topographic aspect that can be analyzed is, for instance, the capacity of the dikes to hold back high tide waters that could have potentially contaminated the rice field with their salt water. In order to get a sense of the tidal range occurring at Wormsloe, tide predictions for the year 2015 were consulted (NOAA, 2015). From their analysis, it is apparent that the highest tide prediction values of the year 2015 correspond to approximately 3.2 m (10.5 feet), occurring during the month of October. These values, however, are based on the Mean Lower Low Water (MLLW) datum, which is around 1.2 m (4 feet) lower than the NAVD88 datum upon which elevations of the LiDAR-derived DEMs are based (National Geodetic Survey, 2015). Therefore, the actual highest tide values predictions for the Isle of Hope correspond to around 2 m, a value which, as shown in Figure 3.19, would have been well contained by the dike, thus effectively protecting the rice field from salt water intrusion and contamination.

Another interesting consideration is related to how the topography changes across the width of the marsh, i.e. the elevation profile of the marsh. This is particularly important since rice fields require a certain elevation drop between higher ground and the fields, as well as level surfaces in the field with approximately a 2-3% slope to allow drainage of the fields when necessary (Smith, 2012). With regard to the elevation drop required between the rice fields and its higher surroundings, this may vary depending upon the local circumstances. As Smith (2012) reports, in fact, elevation differences between uplands and rice fields may generally range between 4 and 40 feet (1.2 m – 12.1 m), with cases of only 3 or 4 feet (0.9 m – 1.2 m) in swamps. Furthermore, ground reconnaissance at the former rice fields on Skidaway Island revealed elevation differences of approximately 80 cm (2.6 feet) between the embankments and the rice field. From the analysis of the terrestrial laser scanning DEM, it is apparent that the elevation profile of the marsh at Wormsloe presents an elevation drop of around 70 cm (2.3 feet) (Figure 3.20). Furthermore, it is also evident that the area presents a rather level, flat surface stretching for about 6 m across the marsh, thus providing a level field where rice might have been grown.

In addition to dikes and embankments, the topography of rice fields was also characterized by other significant features such as ditches and canals, which would regulate the flow of freshwater necessary for the wet cultivation of rice. In particular, inland rice ditches were built in such a way so that water would gently flow by gravity from the reservoir down to the fields (Smith, 2012). Therefore, the slope of the existing drainage ditch was investigated with the purpose to see whether it presented a similar slope that would allow the gravity flow of water. The analysis performed on the airborne LiDAR-derived DEM shows an elevation difference of about 40 cm across a 70 m segment, thus displaying a 0.5% slope which would have determined a gentle gravity flow of the water (Figure 3.21). In particular, this is especially significant since, historically, the ditch was connected to a water pond, which could have been the freshwater reservoir built for irrigating the rice fields located at the other end of the ditch (Figure 3.22).

Despite the great potential of terrestrial laser scanning for the detection of small topographic changes, however, some limitations and shortcomings have been encountered during data collection and analysis. For instance, as shown in Figure 3.16A, the inner side of the lower dike presents a rather gentle elevation drop, unlike the outer side; such gradual change, however, was not observed in the field, where a more definite, sharper elevation change was noticed. This discrepancy between LiDAR-derived measurements and ground values may be due to the positions of the terrestrial laser scanner in the field during data collection. The scanner was, in fact, positioned on the outer side of the dike, exactly where the cone data gap is shown in Figure 3.7. From that position, the scanner could not obtain a clear view of the inner side of the dike, as LiDAR scanners can only scan objects within their line-of-sight. Generally, blind spots during LiDAR data collection are avoided by positioning scan stations on opposite sides so as to obtain a complete view of the object or area under investigation; this study also followed the same guidelines by positioning the other three scan stations in such a way to allow a complete scan the area from multiple points of view. However, the results show that a quality scan of the inner side of the dike could not be obtained. In fact, although one scan station was positioned relatively close, along the southern side of the marsh, the thick vegetation as well as low tree branches may have acted as obstacles. The other two scan stations, instead, were both positioned on the modern road delimiting the marsh on the west side (upper dike), which is at a distance of approximately 70 m from the lower dike. At that distance, the resolution, hence the quality, of scanned targets, was lower, despite a laser range of 450 m. In fact, the laser was set up with a 20 mrad beam divergence which creates a 1.4 m increase in beam diameter over a 70 m distance (Figure 3.23). This determined a rather medium resolution in the scanning of more distant objects from the scanner, while a smaller beam divergence laser should have been employed instead to allow the detection of finer levels of detail; this definitely represents a shortcoming in data collection. Evidently, the high laser point density of the point cloud obtained with the scanner, i.e., 2786 points per square meter, was probably not enough to penetrate through the thick black needlerush vegetation. The terrestrial laser scanner geometry differs from that of airborne LiDAR systems in their scanning angle; terrestrial scanners have a rather oblique and horizontal scan angle, which determines longer travel times for the laser through the atmosphere and the vegetation. The longer the laser takes to reach the target, the more atmospheric scattering it will be subject to, thus reducing its effectiveness. This inevitably determines tradeoffs in bare earth detection, especially in areas with thick vegetation such as the study area. When vegetation is thick and low enough, it will form a dense, almost impenetrable layer beyond which the laser is not able to reach the ground, thus causing false bare earth detection. This may also cause noise in the data, such as spikes and holes in the DEM. In particular, spikes result from the presence of few anomalous elevation points that get interpolated in the ground algorithm with the rest of the ground points. The problem of obtaining an accurate bare ground mapping using LiDAR in salt marshes characterized by *Spartina sp.* and *Juncus sp.* vegetation is also reported by Schmid *et al.* (2011), who demonstrates how the vertical accuracy of LiDAR-derived measurements can be greatly affected by the density and height of the marsh vegetation. This problem could have probably been limited by better understanding the seasonal development of the local vegetation so as to choose time periods in which vegetation is less vigorous and tall, e.g., leaf-off conditions.

Other limitations in the analysis and processing of terrestrial laser scanning data were represented by cone gaps of data that are formed immediately around the scanner tripod; this is usually avoided by having the same area scanned from an opposite direction so as to cover the data cone gap. However, the location of the scanner made it impossible to fill the data gap from another point of view, resulting in the incorrect interpolation of ground points which generated a small mound (Figure 3.12A). Finally, as shown in Figure 3.12A, the marsh DEM obtained from terrestrial laser scanning data does not include the modern road (upper dike) or the ditches. This is probably due to a combination of factors including poor choice in the location of the scan stations, the presence of thick and tall vegetation, and a medium resolution laser beam which determined coarser scanning.

Unmanned aerial systems

Unmanned aerial systems were employed in order to detect, map, and visualize significant topographic features in a three-dimensional context. In particular, the collection of aerial images from multiple viewpoints had the purpose of reconstructing the 3D geometry of the study area using the Structure from Motion principle. As with terrestrial laser scanning data, the topographic features that are being investigated are the two dikes that delimit the study area, as well as the topographic changes across the site, the purpose being to evaluate their compatibility with rice cultivation. A cross section of the lower dike measured on the low tide point cloud shows how the quadcopter was able to detect an adequate profile of the dike (Figure 3.24). From the elevation profile, the width of the dike, as well as the height or elevation difference between the marsh and the top of the dike, were also measured, and reported values of approximately 1 m for width, and 50-60 cm for height. The elevation profile of the upper dike was also measured (Figure 3.25). Although the presence of vegetation somewhat interfered in obtaining an accurate ground profile, an approximate 70 cm elevation drop between the road level and the marsh can be noted. Furthermore, in order to appreciate topographic changes between the higher ground and the marsh, the elevation profile across the marsh was also measured on the low tide model, reporting an elevation change of approximately 1 m (Figure 3.26). Similarly to the upper dike profile, the accurate ground profile of the marsh is affected by the presence of vegetation up until 13 meters across, when the bare ground begins to be exposed. As shown in Figure 3.27, a flood analysis was also performed, which provides a very realistic view of how a 2m high tide would impact the study area. It is once again demonstrated that the dike would effectively stop the water, and protect the rice field from salt water intrusion even during the highest tides.

The 3D reconstruction of the study area, however, presents some inaccuracies and limitations, such as those represented by reprojection errors and data gaps which are present in the high tide model, in particular (Figure 3.28). This might have been determined by many different factors. First of all, the Structure from Motion principle is heavily dependent upon the frames chosen for performing the 3D reconstruction. Frames should, in fact, cover the area of interest from multiple points of view, and retain enough overlap between consecutive pairs so as to allow the algorithm to find several matching points that can be used to create a first approximation of the 3D geometry, i.e., sparse point cloud. The quality of the frames is, therefore, of primary importance.

Another important factor that might have played a role is represented by the view angle, which can be modified by maneuvering the camera tilt while operating the quadcopter. The camera tilt, in fact, can be set to either operate facing parallel or oblique with respect to the quadcopter horizontal axis. For the purpose of this study, the camera was operated with an oblique tilt while flying at a higher altitude so as to obtain an overview capture of the area below, and with a more parallel orientation while flying at a lower altitude in order to capture the hidden edges of the marsh. The intended goal of this method was to obtain a complete coverage of the area from different perspectives and levels of spatial detail by flying at different altitudes. However, some problems were encountered in Photoscan while trying to merge frames taken with different view angles and at different altitudes; many of the frames could not be aligned, which means their estimated camera position could not be calculated. This sensibly reduced the number of frames available for the sides of the marsh, thus affecting the ability of the algorithm to resolve the 3D geometry of those areas. For instance, of the 243 total frames selected for building the low tide model, only 180 were finally employed by the algorithm for obtaining the point cloud, thus reducing the density and level of detail of the final model. Furthermore, in order to obtain a suitable 3D reconstruction using Structure from Motion, it would be ideal to capture frames by following a 360º pattern around the target, so as to obtain a comprehensive view of the area from all sides. However, the intricate nature and particular layout of the study area made this task particularly challenging for obtaining a complete view of the north and south sides of the marsh as well as of the upper dike, i.e. the modern road. The presence of high trees, in fact, did not allow the capture of frames from different points of view by flying around those areas, but only through side views by flying in a parallel fashion. This limitation affected the ability of the algorithms to estimate camera positions, thus limiting the quality of the 3D reconstruction, as shown in Figure 3.28A.

Another factor that plays a role in affecting the quality of 3D reconstruction is illumination changes determined by sun position and sun angle at the time of flying. In fact, illumination changes between frames may hinder the recognition of matching points performed by the SIFT algorithm, thus reducing the density of the point cloud and, ultimately, the quality of 3D reconstruction. For instance, data for the high tide model were collected around 9 am, while data for the low tide model were collected around 3 pm on the same day. At 9 am, the sun was facing west, towards the upper dike, while at 3 pm the sun was facing east, towards the lower dike. Furthermore, the particularly oblique angle of the February sun determined the creation of shadows both inside and on the edges of the marsh, thus causing illumination changes across the same area. This may be responsible, for instance, for the data gaps in the high tide 3D model of the marsh, where shadows caused by trees may have determined sensible illumination differences across the area. (Figure 3.28B).

The presence of strong winds, also, might have affected the 3D reconstruction process, both in terms of data collection and data processing. During the flights, wind somewhat affected the ability to fly along linear, parallel lines, thus causing differences in data coverage between consecutive frames. In particular, winds were relatively strong in the afternoon, when low tide data were collected. Furthermore, the wind also affected ground features by moving the local vegetation during data collection. The Structure from Motion principle, however, tends to eliminate inconsistent, moving points across pictures since they do not provide appropriate anchor points necessary to approximate the 3D geometry. This is the reason why, for instance, chance people moving across the area being imaged will not appear in the 3D model. In this study, the moving vegetation might have reduced the number of matching points between pictures, thus reducing the density of the final point cloud model. This is particularly true for the low tide model, which presents poor vegetation reconstructions around the edge of the marsh (see Figure 3.13B).

Finally, it is surprising to note how the high tide model presents a greater number of errors than the low tide model, despite having used many more pictures (534 vs. 180) and having twice as many points as the low tide model. Therefore, it seems that for ideal 3D reconstruction more images does not necessarily mean a better model. In this case, 180 pictures proved sufficient for the 3D reconstruction of the marsh – which was the intended objective – across a particularly complex and large area. Nevertheless, the low tide model has half the point density of the high tide model, which may affect the ability to perform accurate measurements.

Comparing methods

The employment of advanced remote sensing techniques such as TLS, UAS, and airborne LiDAR produced differences in terms of the results and the level of detail that can be achieved for performing geospatial analysis. Therefore, it is possible to draw a few considerations about their advantages and limitations by analyzing their performances and characteristics. In terms of costs, for instance, the employment of unmanned aerial systems definitely represented the cheapest option, if compared to terrestrial and airborne laser scanning devices. In fact, unmanned aerial systems, such as the Phantom 2 Vision quadcopter, cost around $1,200, while laser scanning devices cost ten to one hundred times more. The price difference also determines a different accessibility to their use, as even users with a limited budget may afford an unmanned aerial vehicle for personal use, while the use of laser scanning devices requires specialized private companies which have the equipment, staff, and resources necessary for data collection and preliminary data processing. Furthermore, unmanned aerial systems are more portable due to their relatively light weight, while terrestrial laser scanning devices such as the RIEGL VZ 1000 are larger, bulkier, and more delicate. In this study, access to a terrestrial laser scanning was limited and availability of the device did not allow follow-up rescanning to correct data gaps.

In terms of flexibility and temporal resolution of data collection, unmanned aerial system arguably provide users an optimal solution to collect data, as they allow very short revisit times, if necessary. This can also be said for terrestrial laser scanners, if users have easy access to the equipment. Airborne laser systems, on the other hand, do not provide much flexibility regarding data collection, given the relatively high costs for deploying aircraft and establishing ground test sites for each mission. In this study, unmanned aerial systems represented the most flexible option for data collection, while terrestrial laser scanning was second. For instance, the study area was revisited two times during the same day using the quadcopter in order to collect aerial imagery at both high and low tide conditions. On the other hand, the terrestrial laser scanning device was only available for one morning, without having the possibility for a second scanning of the area in case of poor data collection. Airborne laser scanning data, were collected in the spring of 2009 as a result of a partnership between NOAA, U.S. Department of Commerce, Office for Coastal Management, and the National Ocean Service, and retrieved from the WIEH database served by the Center for Geospatial Research at UGA, where a vast collection of coastal Georgia and Wormsloe data are available.

In terms of spatial resolution and level of detail that can be achieved by these remote sensing techniques, airborne LiDAR data produced the DEM with the lowest level of spatial detail, followed by terrestrial LiDAR, while unmanned aerial vehicles provided the best levels of detail for the area under investigation. The different spatial resolutions and levels of detail experienced in using the three methods were also affected by their different point densities, i.e., how many points per square meters were measured for the 3D reconstruction, thus determining different levels of topographic detail that can be observed in the DEM (see Figure 3.26). The very limited spacing between points in the low and high tide models obtained from UAS imagery determined very high levels of spatial detail that could be observed in both models, although they did not have the highest point densities, i.e., 1125.851 and 616.531 points per square meter for the high tide and low tide point clouds, respectively (see Figure 3.14).

The different level of detail and accuracy obtained by using these three different methodologies can also be appreciated by analyzing how measurements differ between datasets. For instance, Figure 3.30A shows the three different elevation profiles measured on the terrestrial LiDAR (blue), high tide point cloud from UAS (green), and low tide point cloud datasets from UAS (red) for the lower dike. In particular, the terrestrial LiDAR profile shows an elevation difference of approximately 1.2 m between the dike and the marsh, while the quadcopter point cloud both show values around 0.50 m; as already mentioned, the inaccuracies in obtaining an optimal map of the dike by employing terrestrial LiDAR data are a consequence of scan locations and scan angle, as well as of a medium resolution laser beam. On the other hand, the difference between the high and low tide profiles can be due to co-registration differences and the presence of water in the high tide model, which determined the inability to measure a true elevation difference from the bare ground. Measurements of the upper dike, however, show similarities between datasets; for instance, measurements of its height obtained on airborne LiDAR-derived DEM show values of 0.5 m, while measurements taken on quadcopter 3D point clouds revealed a 0.7 m elevation difference between the dike and the marsh level. On the other hand, the upper dike could not be measured on the terrestrial laser scanning dataset, while the airborne LiDAR data allowed the analysis of the ditch slope, thus giving context to the study area.

Detection differences are also evident when analyzing a cross section profile of the marsh, as shown in Figure 3.30B. As already mentioned, the presence of vegetation determined an overestimation of the topography in the low tide model, i.e., between 9 and 12 m across, while the high tide model presented higher elevation values around the edge of the marsh than the low tide model. However, the two point clouds presented almost identical profiles starting at around 13 m across the marsh. On the other hand, the DEM obtained from terrestrial laser scanning consistently displayed lower elevation values than the two point clouds across all the marsh.

In terms of accuracy of measurements that can be achieved by employing these datasets, the targets used as ground control points were measured on the low tide point cloud, and then compared to ground measurements measured with a tape on site. The reference measurements obtained with the tape were 0.6 m for the side of the target, 0.31 m for the cross tract, and 8.1 m for the distance between targets. The results demonstrate a very good reliability of point clouds obtained from unmanned aerial systems to map features, showing values of 0.59 m, 0.33 m, and 8.09 m, respectively (Figure 3.31).

3.6. CONCLUSIONS

The main goal of this study was the investigation of a salt marsh at Wormsloe Historic Site, coastal Georgia, by means of remote sensing techniques such as airborne LiDAR, terrestrial laser scanning and imagery acquired from unmanned aerial systems. In particular, objectives included the creation of an accurate 3D digital elevation model (DEM) showing the bare earth topography of the salt marsh, and the 3D reconstruction of the study area by employing the Structure from Motion (SfM) principle. The detailed topographic mapping of the area was intended for investigating the compatibility of the study area for rice cultivation by mapping local topographic features such as dikes, and elevation changes across the marsh that provide evidence for historical water impoundment and subsistence rice cultivation. The DEM obtained from terrestrial LiDAR represented a high resolution bare earth topographic model of the area, despite some limitations determined by the presence of thick vegetation, medium scanner resolution, and oblique scan angle. On the other hand, the point cloud data obtained by means of performing Structure from Motion using overlapping images collected with unmanned aerial systems provided finer scale 3D reconstructions under both high and low tide conditions. Accurate topographic measurements and elevation profiles were performed using both LiDAR and quadcopter datasets for comparisons, showing how unmanned aerial systems were able to achieve higher spatial detail on the order of centimeters than terrestrial laser scanning. Airborne LiDAR data were also analyzed, but their lower point density could not provide the same level of detail obtained from the other two datasets. However, the three datasets provide useful insights into understanding the micro topographic changes across the marsh, especially when used in combination with each other so as to minimize their respective limitations.

The choice of one method over another really depends on the purpose of the project, as well as the resources available to the user. For instance, if the purpose of the investigation includes mapping the bare earth topography in vegetated areas, this cannot be accomplished by means of unmanned aerial systems alone, despite their great ability to detect small topographic changes. Furthermore, the choice of one methodology also heavily relies upon the resources that users have to collect and process the data. For instance, users with a limited budget will not be able to afford laser scanning devices, unless special circumstances occur, e.g., knowing someone who has one. The availability of resources such as those represented by computer and software plays a big role in the decision as well; the analysis of point cloud data, in fact, involves the processing of millions of points which only certain machines and software programs can handle. Therefore, there is always a tradeoff between what users would like to do, and what users actually can afford to do, depending upon their resources.

In conclusion, this study demonstrated the higher reliability of unmanned aerial systems in obtaining high resolution topographic data in a complex environment such as a tidal salt marsh on coastal Georgia. Furthermore, it was also demonstrated that the study area presents topographic features and characteristics which are comparable to rice cultivation areas, thus suggesting the area was once used for growing rice.

3.7. REFERENCES

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Table 3.1. RIEGL-VZ 1000 nominal specifications (Riegl, 2015).

Field of view	100º vertical; 360º horizontal
Max range	Up to 1400m
Min range	2.5m
Pulse rate	Up to 122,000 measurements/sec
Repeatability	5mm
Accuracy	+/- 8mm
Beam divergence	0.3mrad
Laser wavelength	Near infrared

Table 3.2. Workflow for terrestrial laser scanning data

LAStools algorithm	**Function**
Las2Las	Convert .las files into .laz format
Las2Las	Remove points with elevation higher than 3 m above ground
LasGround	Classify automatically ground points (Class 2). Options used: not airborne; thinning
Las2Las	Retrieve ground points only (Class 2)
Blast2dem	Merge ground points from each scan, and create bare earth DEM (step 0.2)

Table 3.3. Specifications of Phantom 2 Vision Quadcopter (DJI, 2015).

Cost: around $1200 (now discontinued)
Weight: 1160 gr (including battery and propellers)
WiFi range: 300m
Flying time: up to 25 min
Camera: 14 Megapixel camera with 1080p HD video recording on a micro SD card
FOV: 120º/110º/85º

Table 3.4. Parameters for 3D reconstruction in Photoscan.

Camera alignment	High accuracy
Dense point cloud generation	High accuracy Mild depth filtering
Mesh generation	Arbitrary surface Dense could source data Enable interpolation to cover data holes
Texture	Generic mapping mode Blending mode mosaic; no color correction

Figure 3.1. RIEGL-VZ 1000 terrestrial laser scanner.

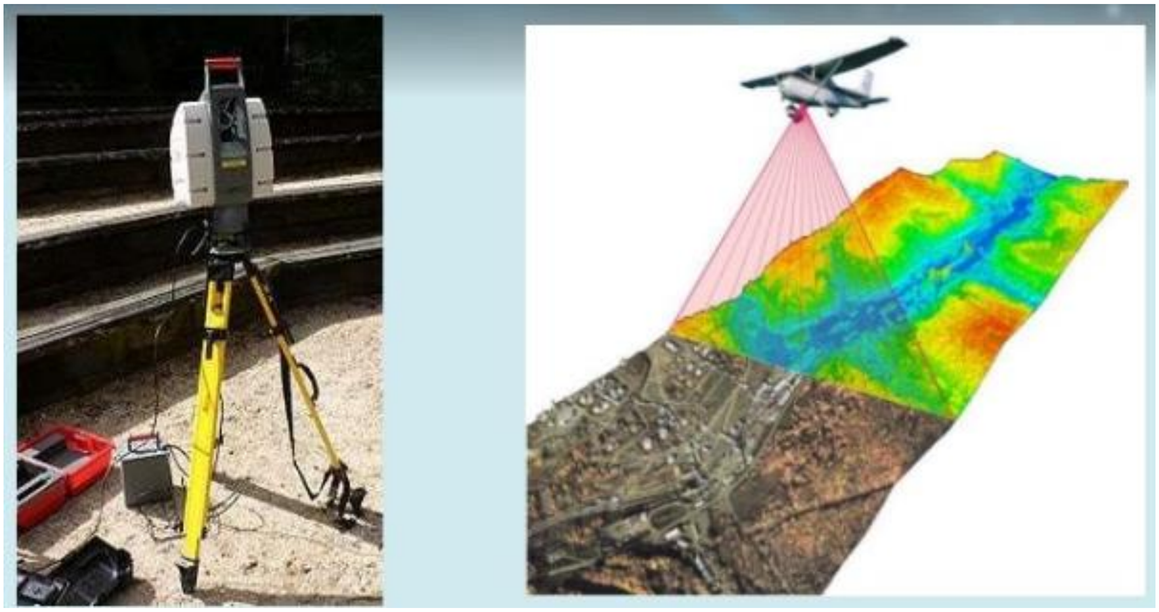

Figure 3.2. The different scan angle of TLS and airborne LiDAR (Slideshare, 2015)

Figure 3.3. Phantom 2 Vision quadcopter.

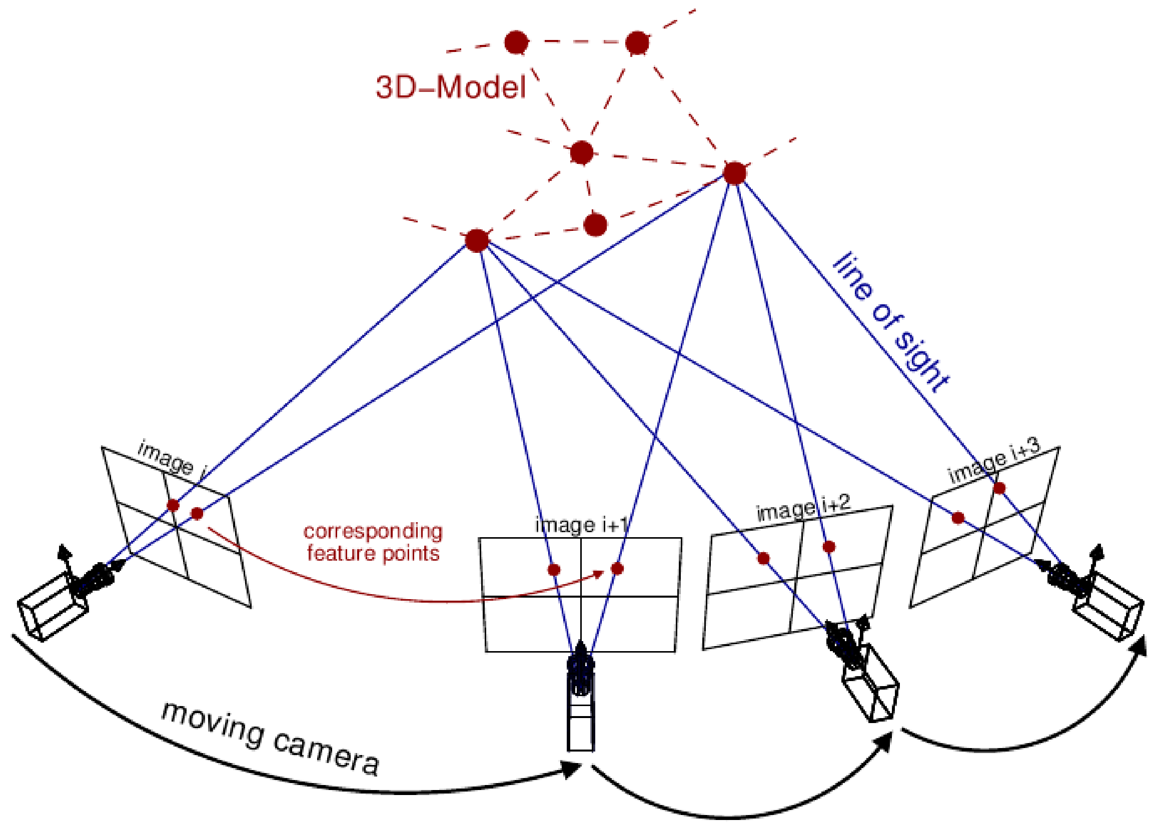

Figure 3.4. The Structure from Motion principle (Theia-sfm, 2015).

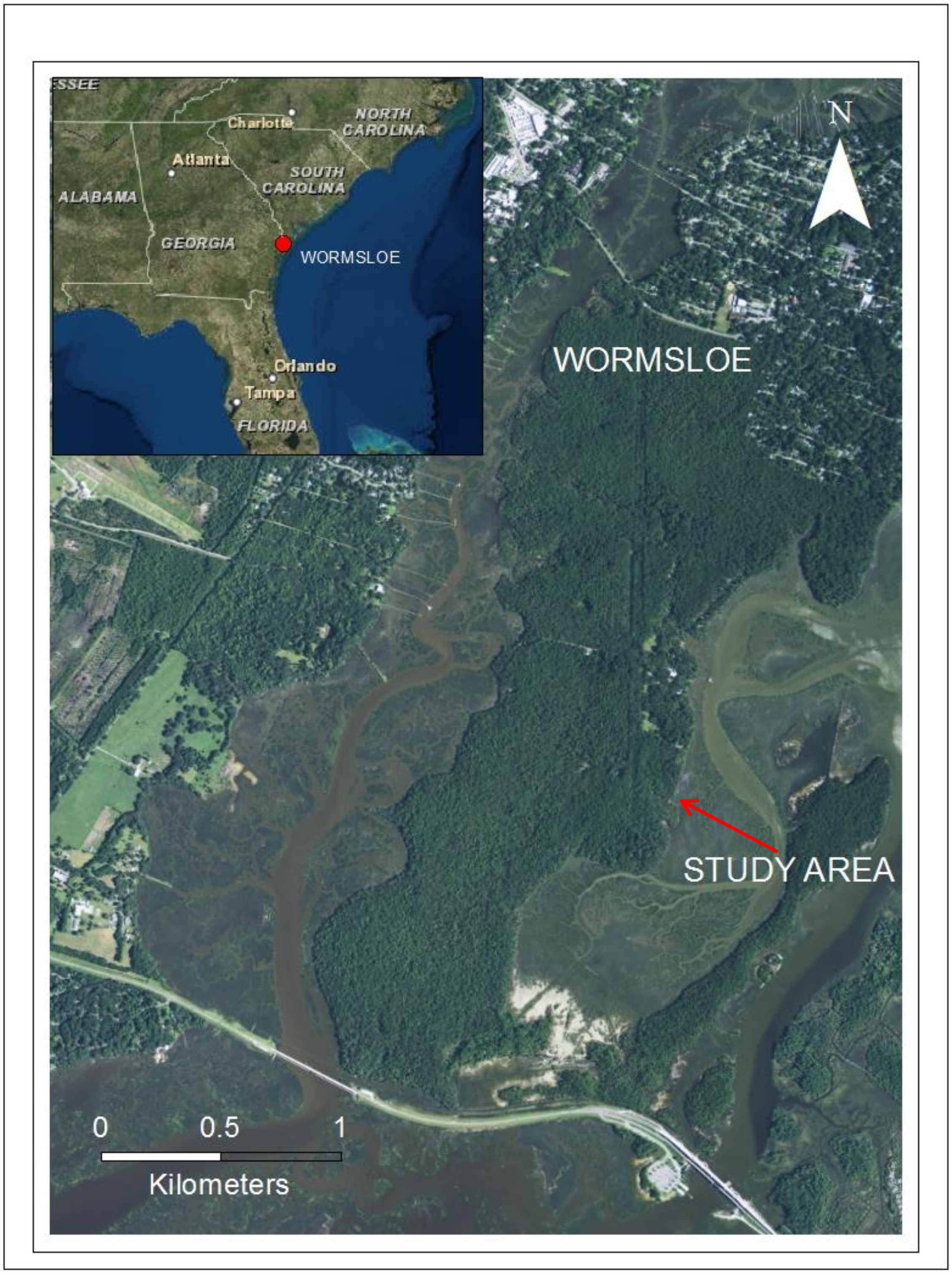

Figure 3.5. The geographic location of Wormsloe and the study area.

Figure 3.6. The study area at low (A) and high (B) tide conditions.

Figure 3.7. Colored point cloud from terrestrial laser scanning.

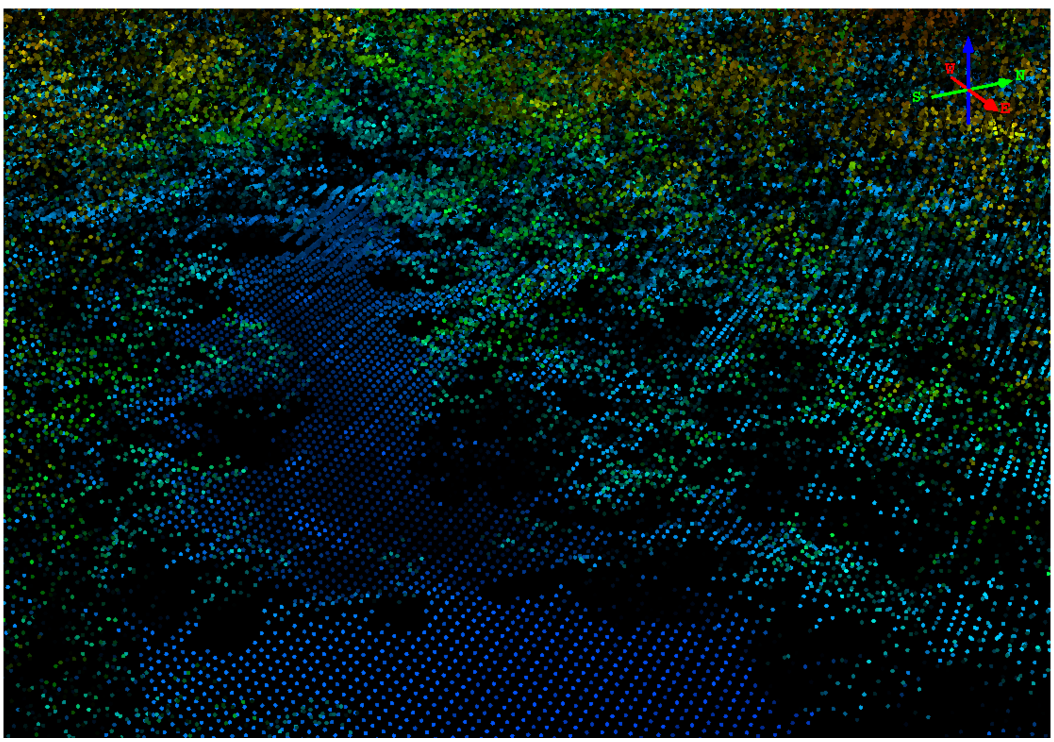

Figure 3.8. Airborne LiDAR point cloud of the study area.

Figure 3.9. Ground control target as seen in the 3D model reconstruction (left) and on the ground during data collection (right).

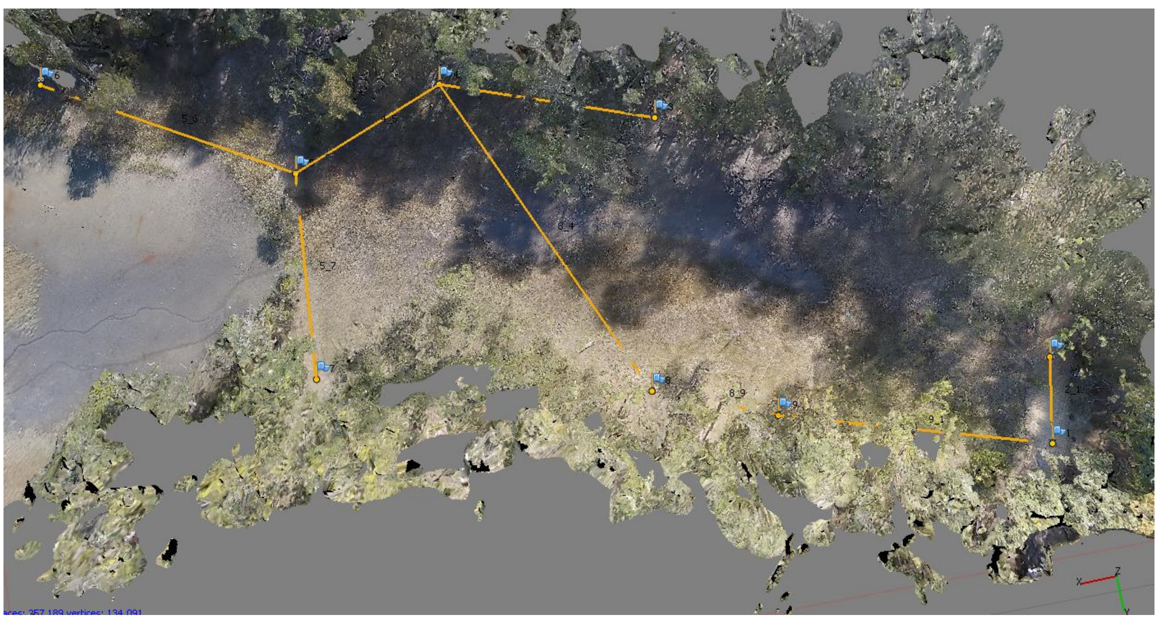

Figure 3.10. Ground control points and scale bar measurements used for georeferencing the low tide model.

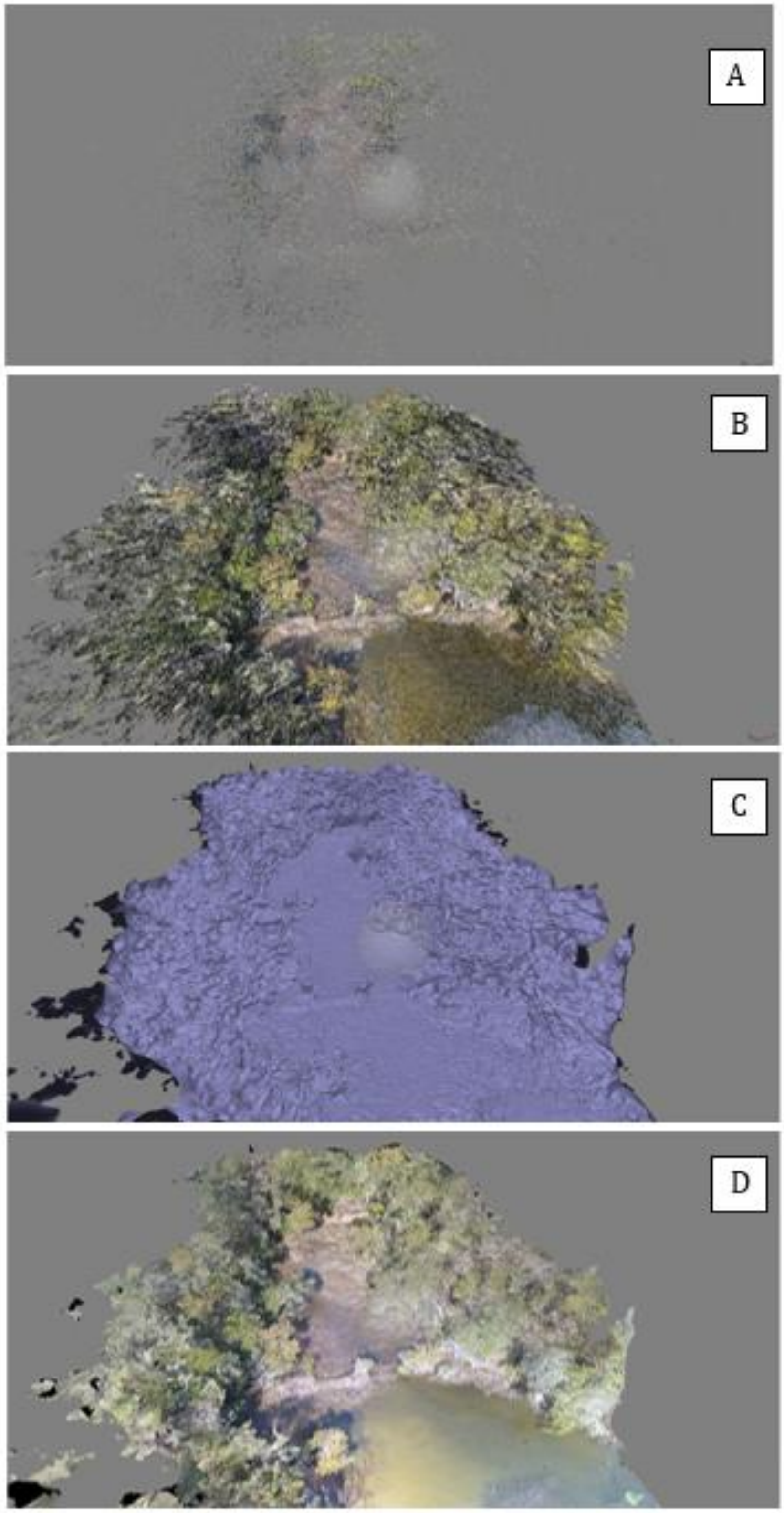

Figure 3.11. Workflow for 3D reconstruction in Photoscan: sparse point cloud (A); dense point cloud (B); mesh (C); colored model (D).

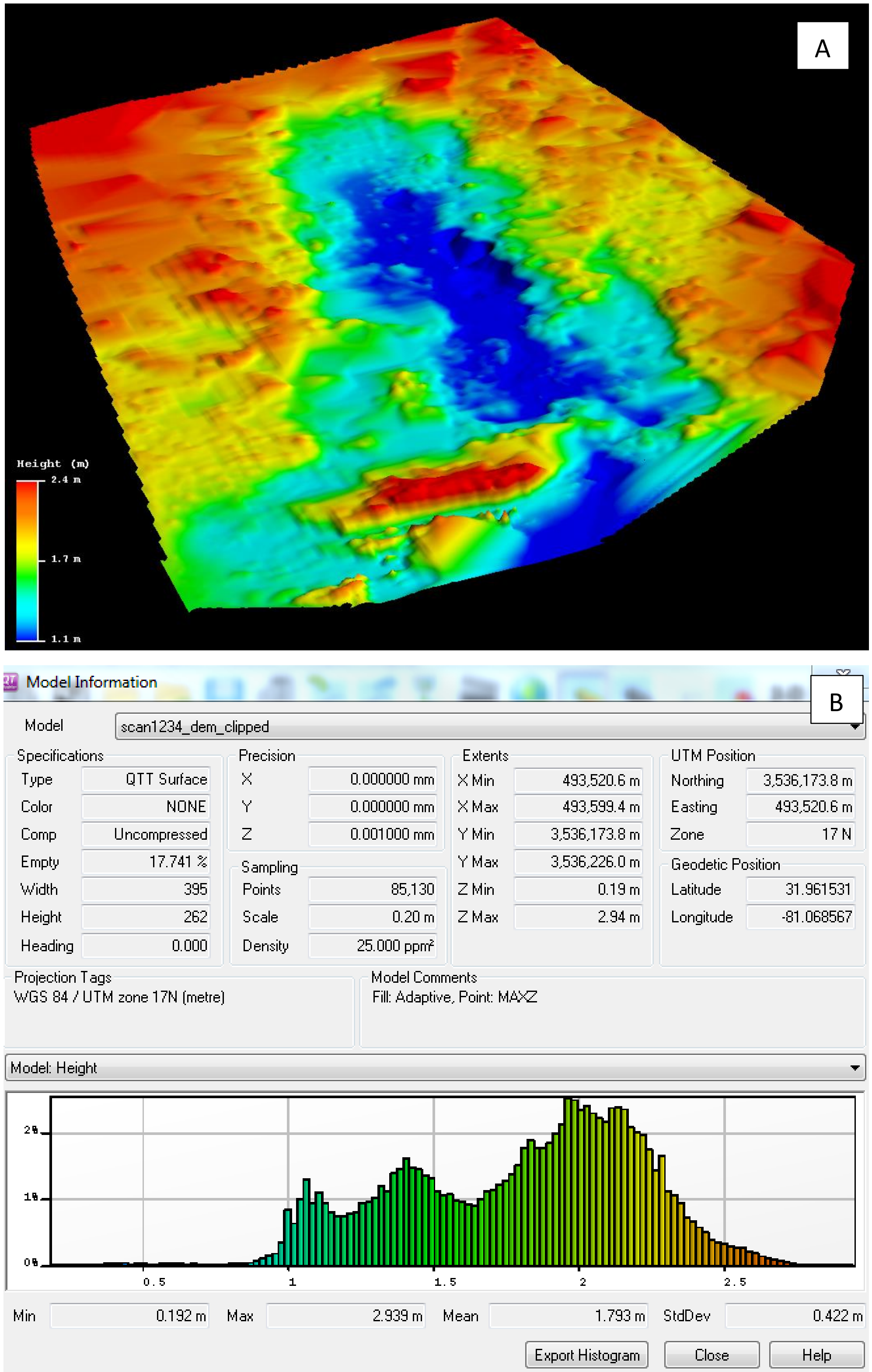

Figure 3.12. Terrestrial laser scanning DEM (A) and DEM info (B).

Figure 3.13. 3D models of the study area at high tide (A) and low tide conditions (B). Note the two dikes delimiting the site, i.e. lower dike (left) and upper dike (right).

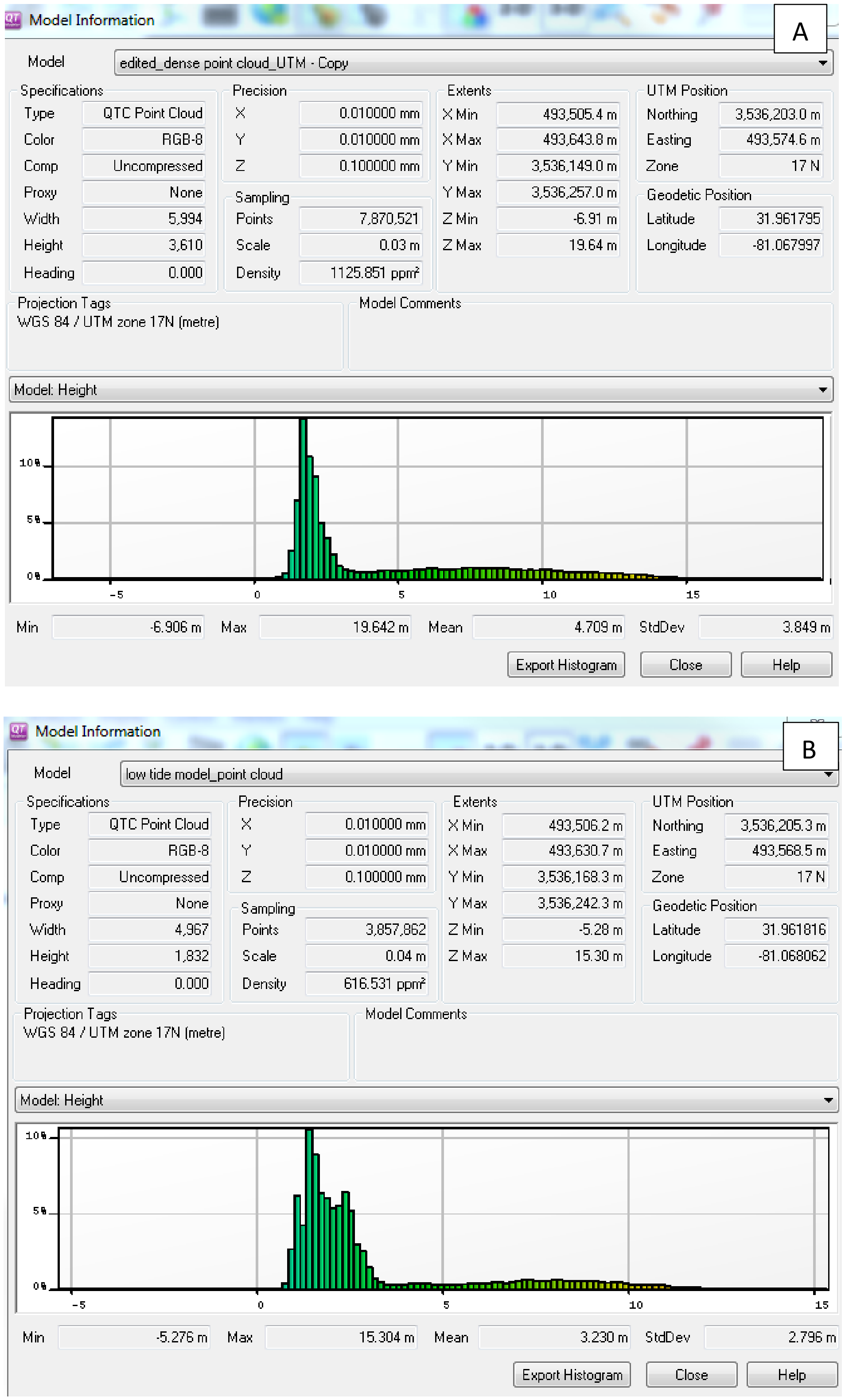

Figure 3.14. 3D point cloud info for the high tide (A) and low tide (B) models with histograms showing height values of the point clouds.

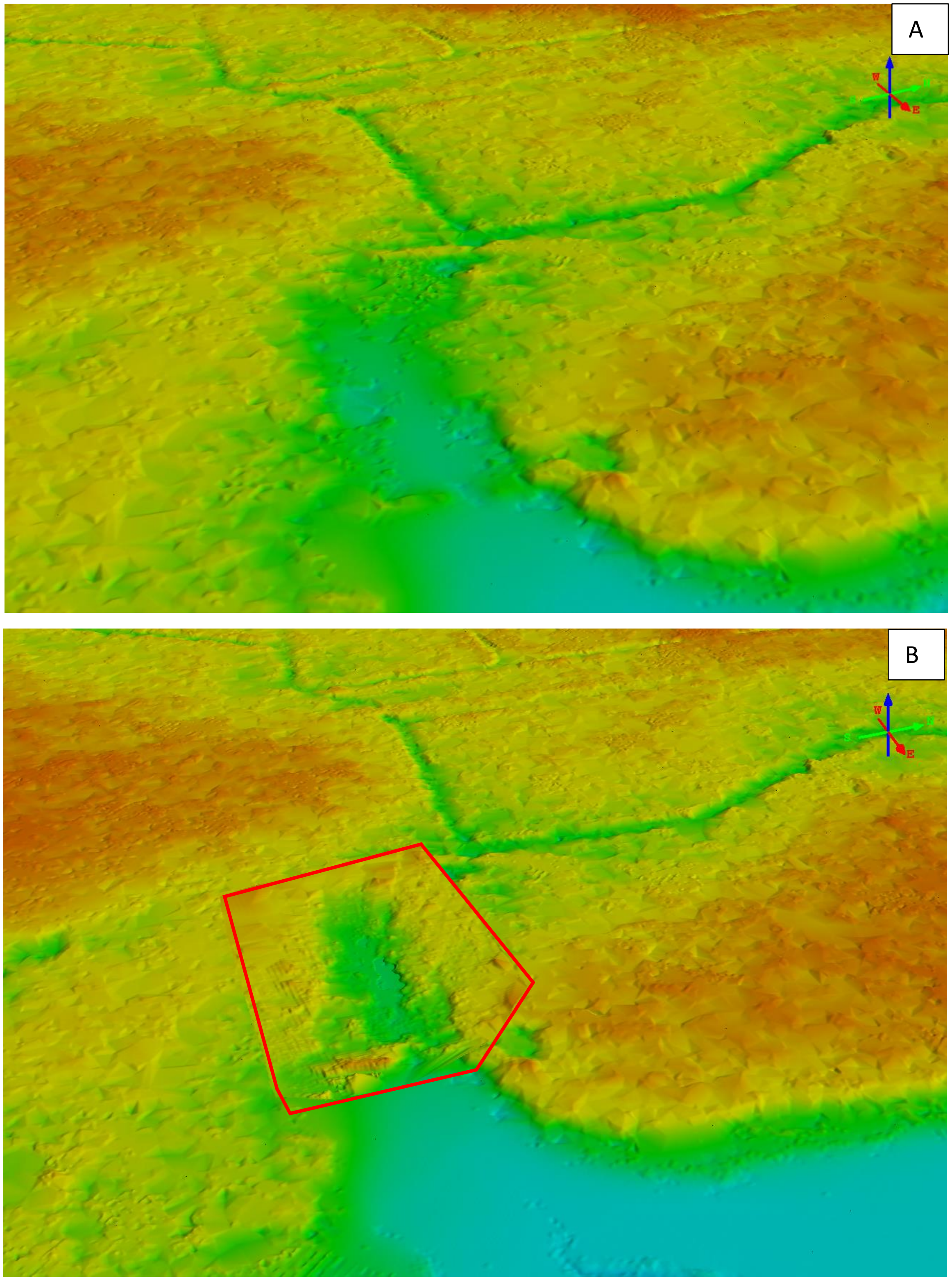

Figure 3.15. DEM from LiDAR data for the study area at Wormsloe: airborne LiDAR (A); terrestrial LiDAR (B).

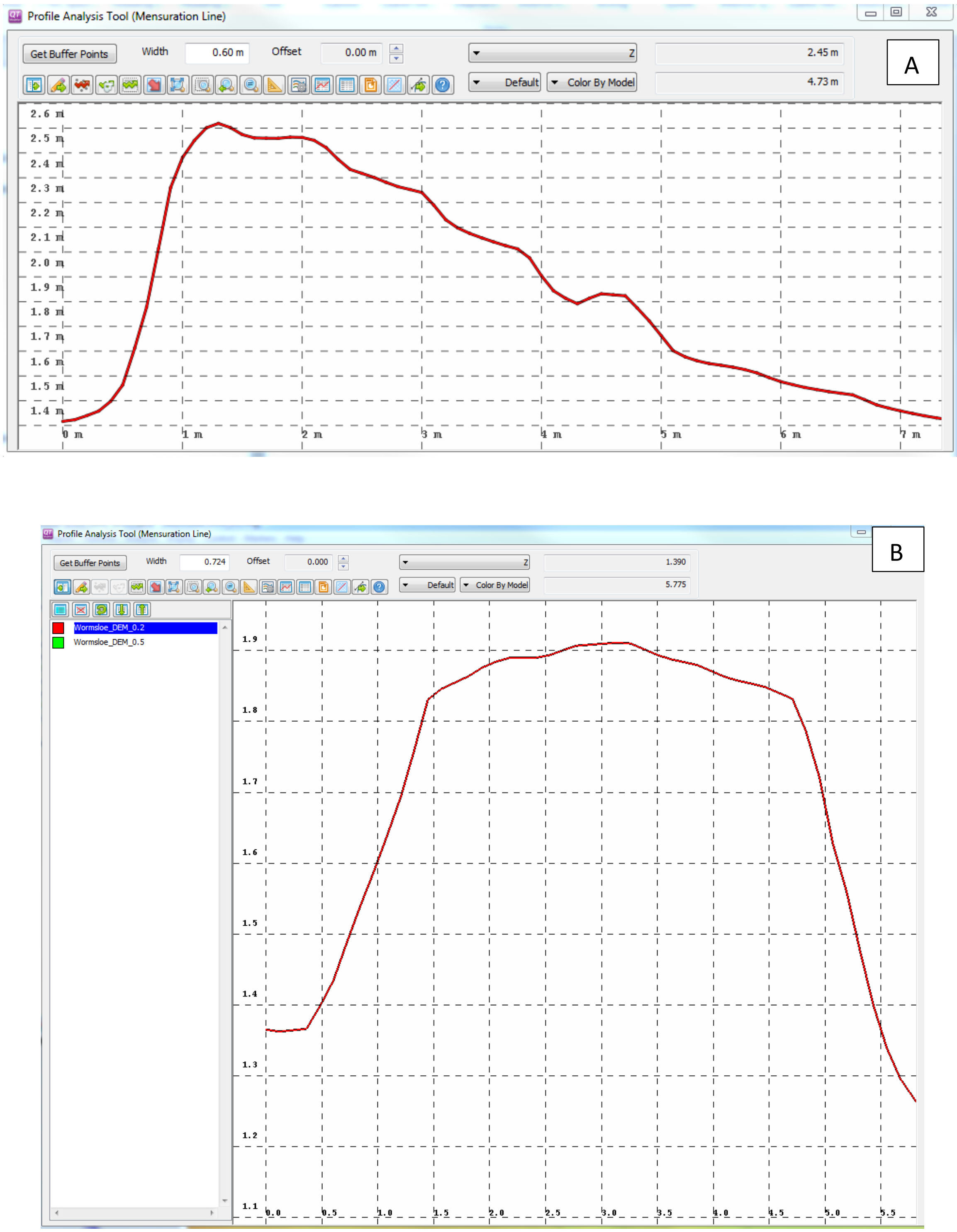

Figure 3.16. LiDAR elevation profiles of dikes at Wormsloe. The lower dike as measured on terrestrial laser scanning-derived DEM (A); the upper dike as measured from the airborne LiDAR-derived DEM (B).

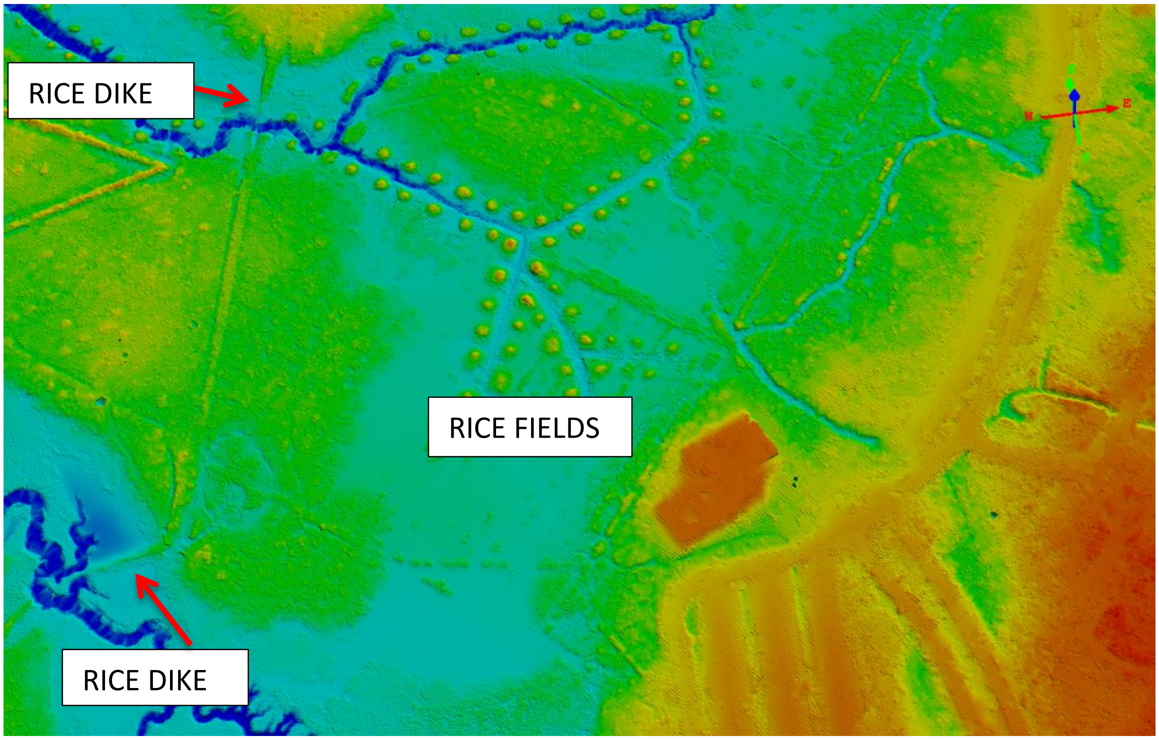

Figure 3.17. Airborne LiDAR DEM of former rice fields at Skidaway Island.

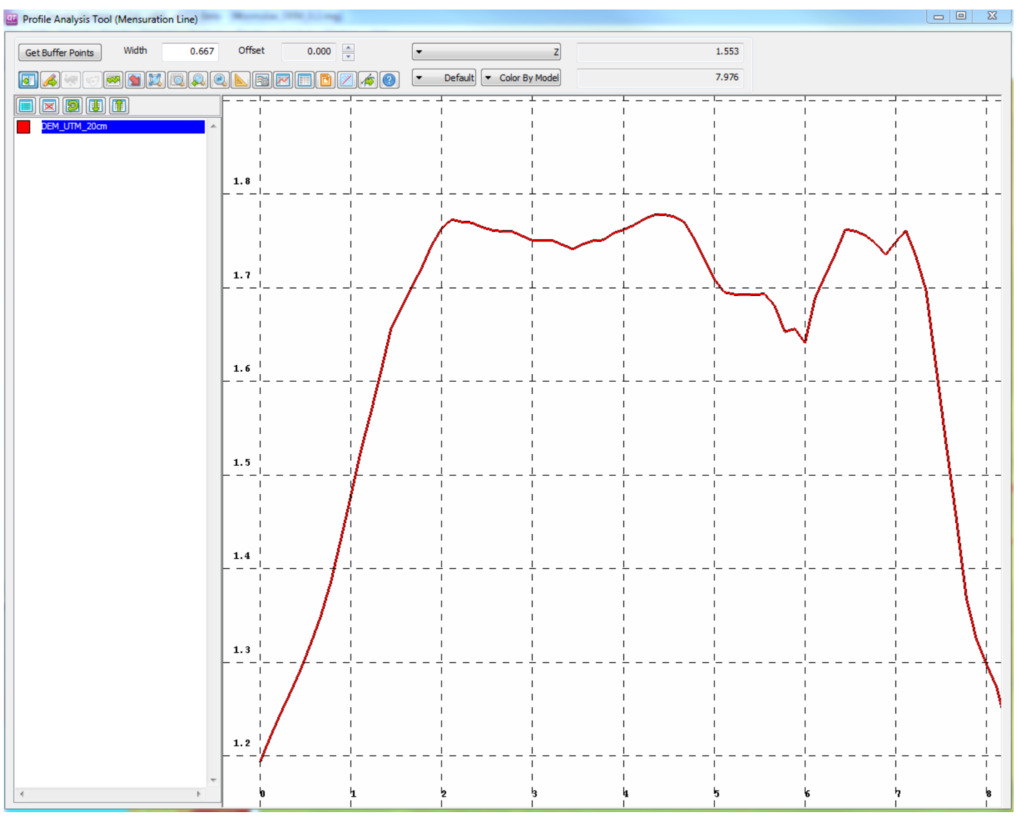

Figure 3.18. Elevation profile of a rice dike on Skidaway Island from airborne LiDAR.

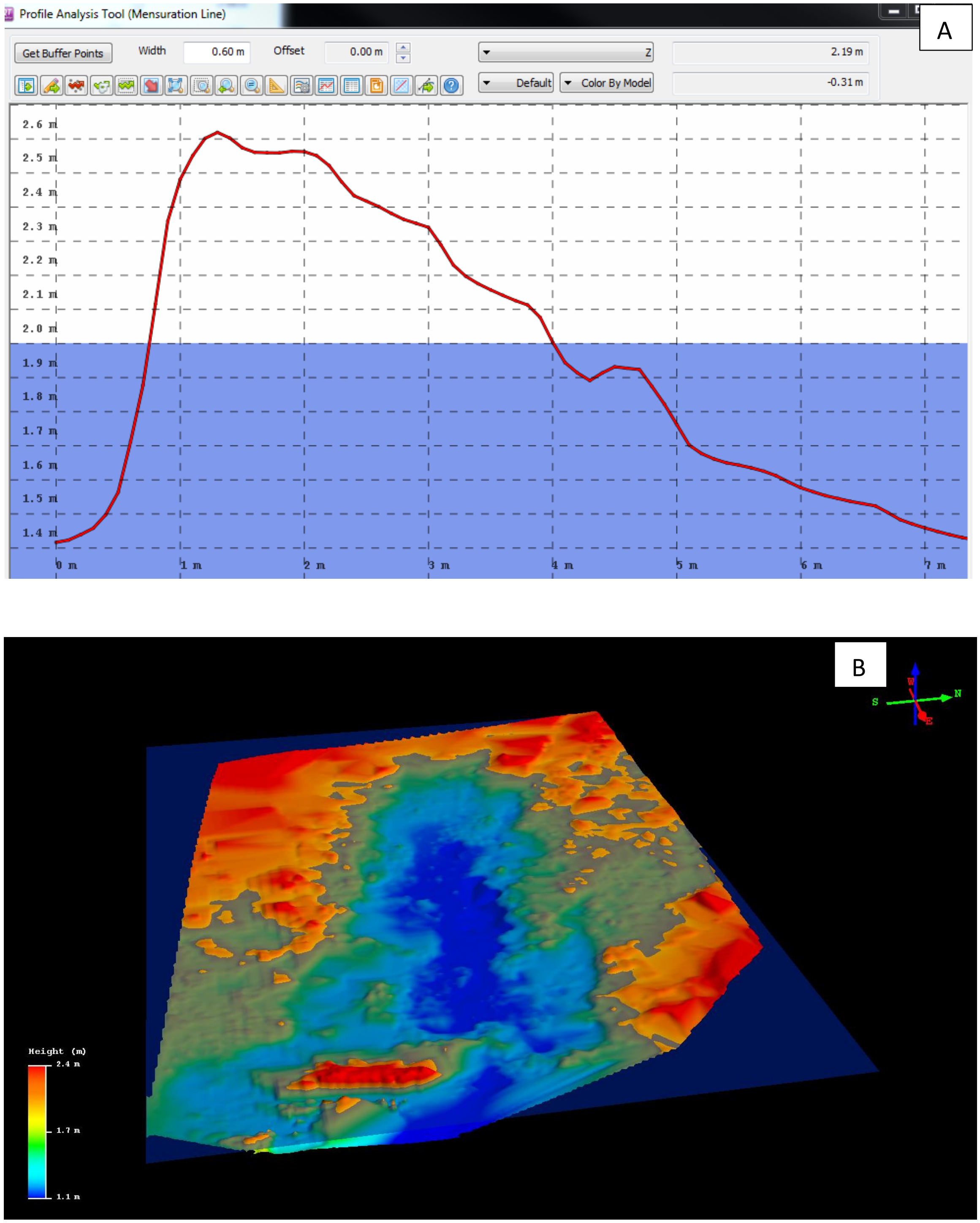

Figure 3.19. Dike at 2 m high tide at Wormsloe (A). DEM showing a view of the dike and of the study area during a 2 m high tide surge (B). Upland area with elevations above 2 m are shown in orange and red.

Figure 3.20. Elevation profile across the marsh at Wormsloe from terrestrial laser scanning DEM.

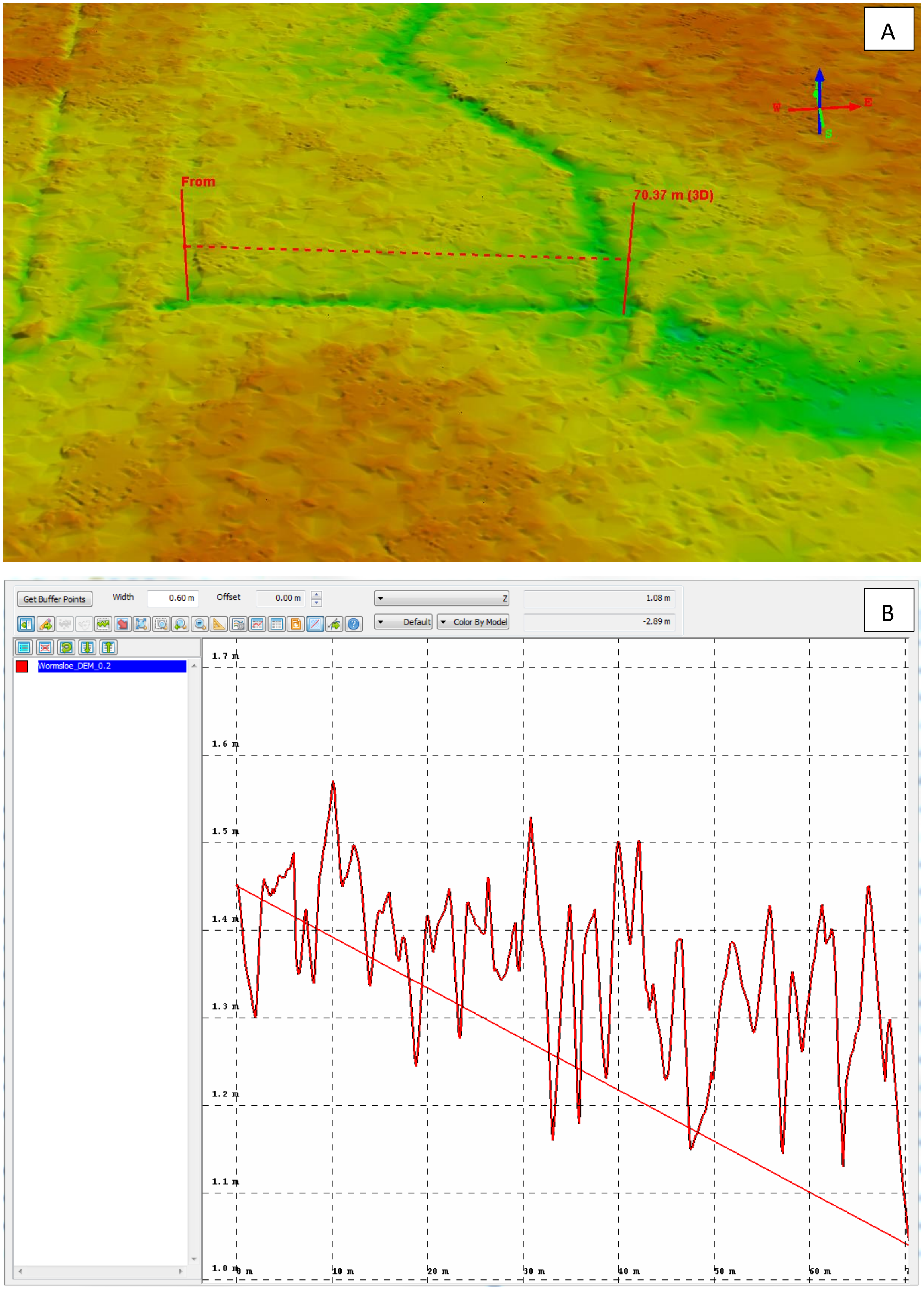

Figure 3.21. Slope analysis at Wormsloe. Measurements on the airborne LiDAR-derived DEM (A); elevation profile with slope (B).

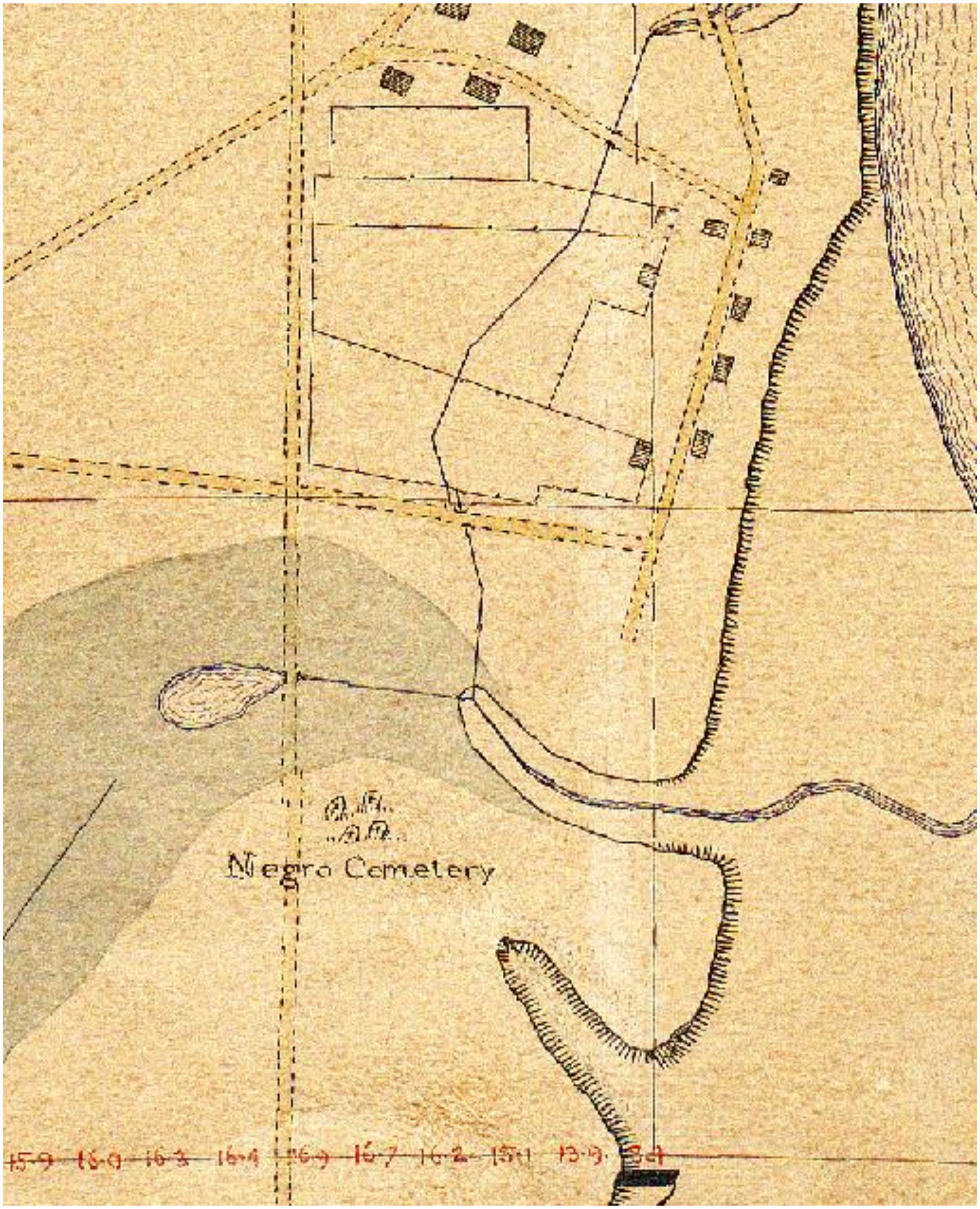

Figure 3.22. Blanford historical map, 1890. Note the water reservoir connected to the salt marsh area through the ditch (still existing). Map available from the WIEH database served by the Center for Geospatial research at the University of Georgia.

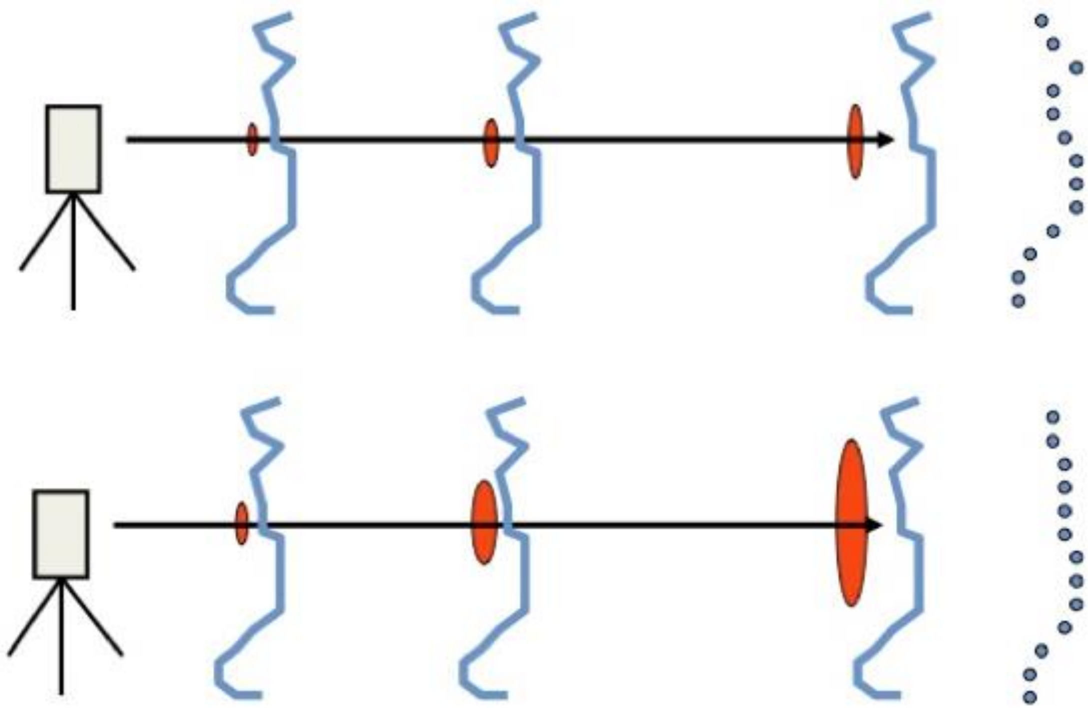

Figure 3.23. A more narrow beam divergence (top) results in a finer resolution point cloud than a broader beam divergence (bottom).

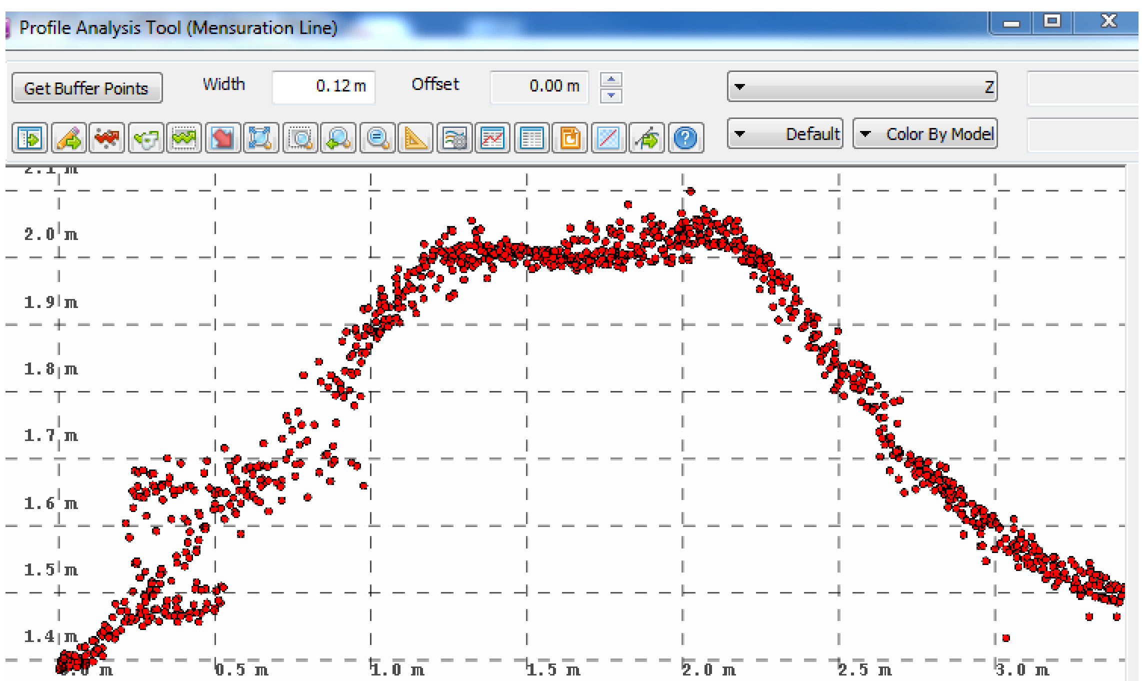

Figure 3.24. Elevation profile of the lower dike as measured on the low tide dense point cloud obtained from SfM of images acquired by UAS.

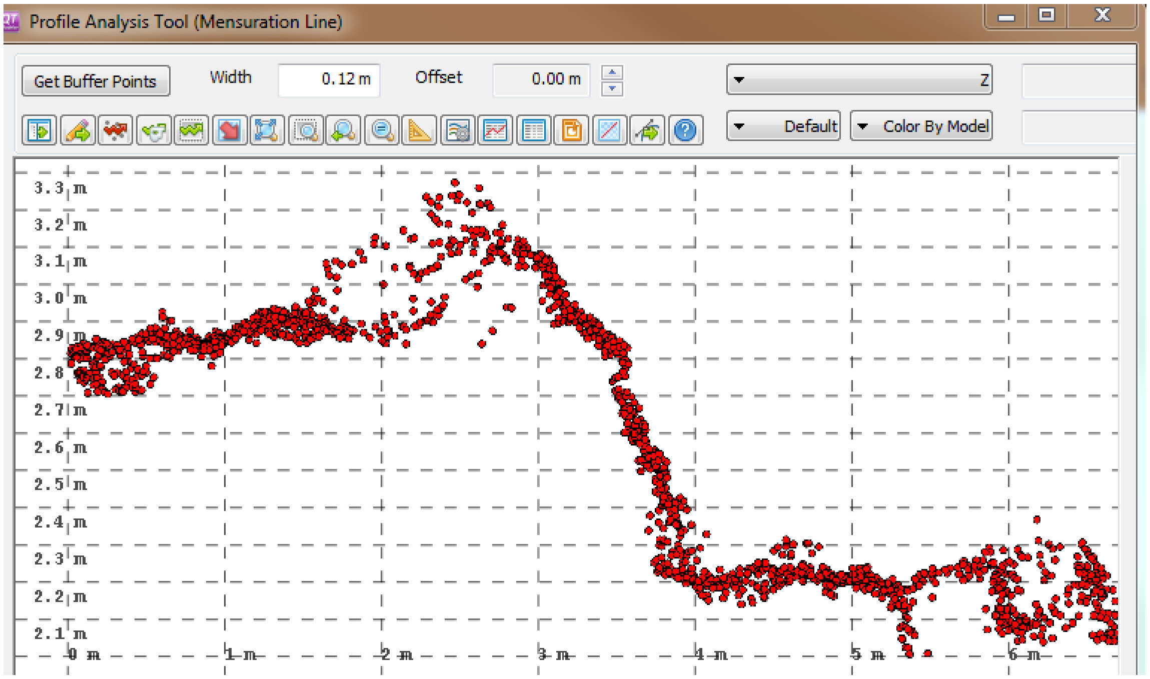

Figure 3.25. Elevation profile of the upper dike measured on the low tide point cloud obtained from the quadcopter.

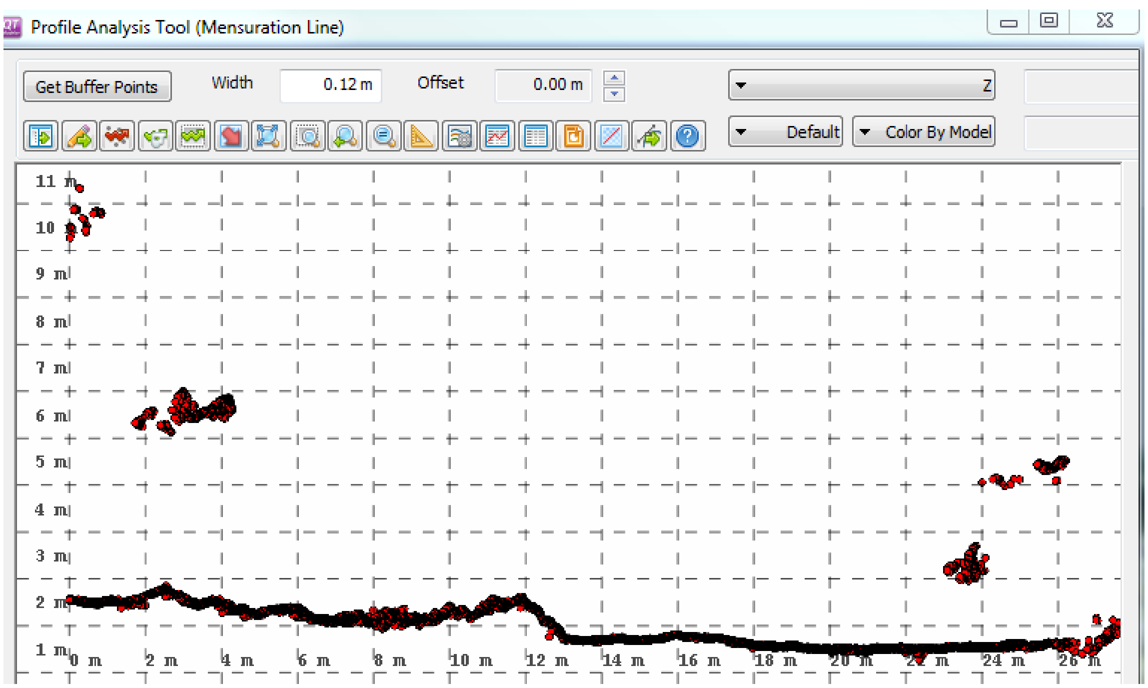

Figure 3.26. Elevation profile across the marsh measured on the low tide point cloud obtained from the quadcopter.

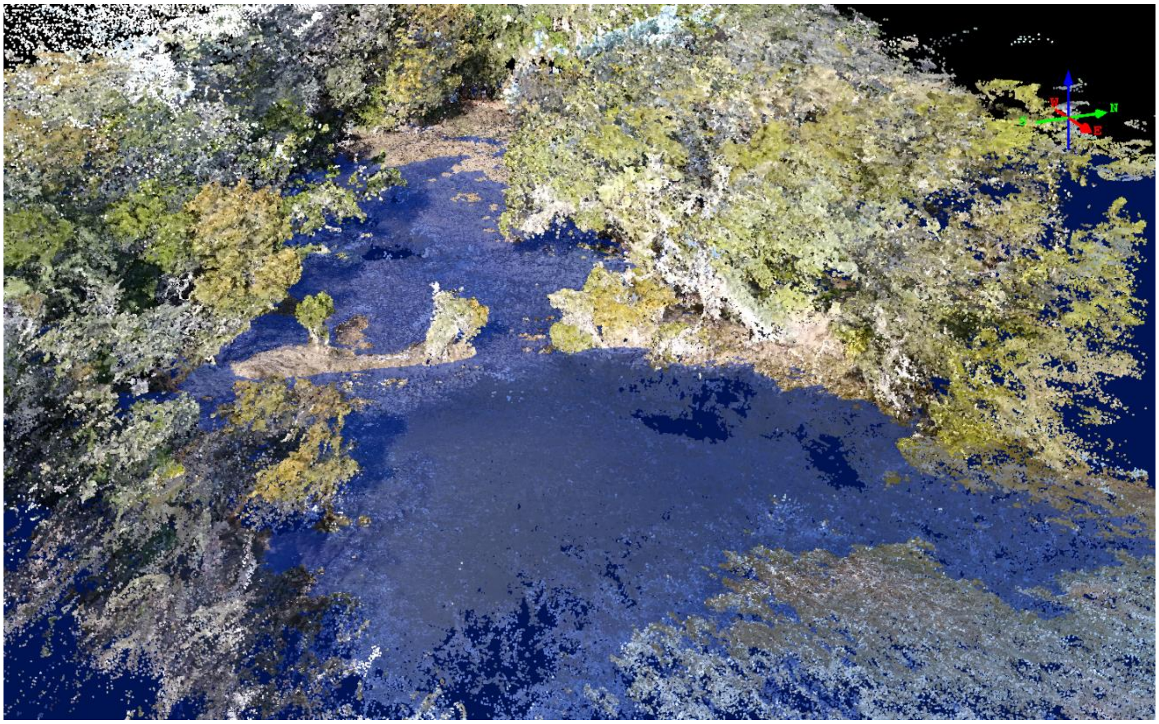

Figure 3.27. Simulation of a 2 m high tide at Wormsloe using 3D point cloud data retrieved from using unmanned aerial systems.

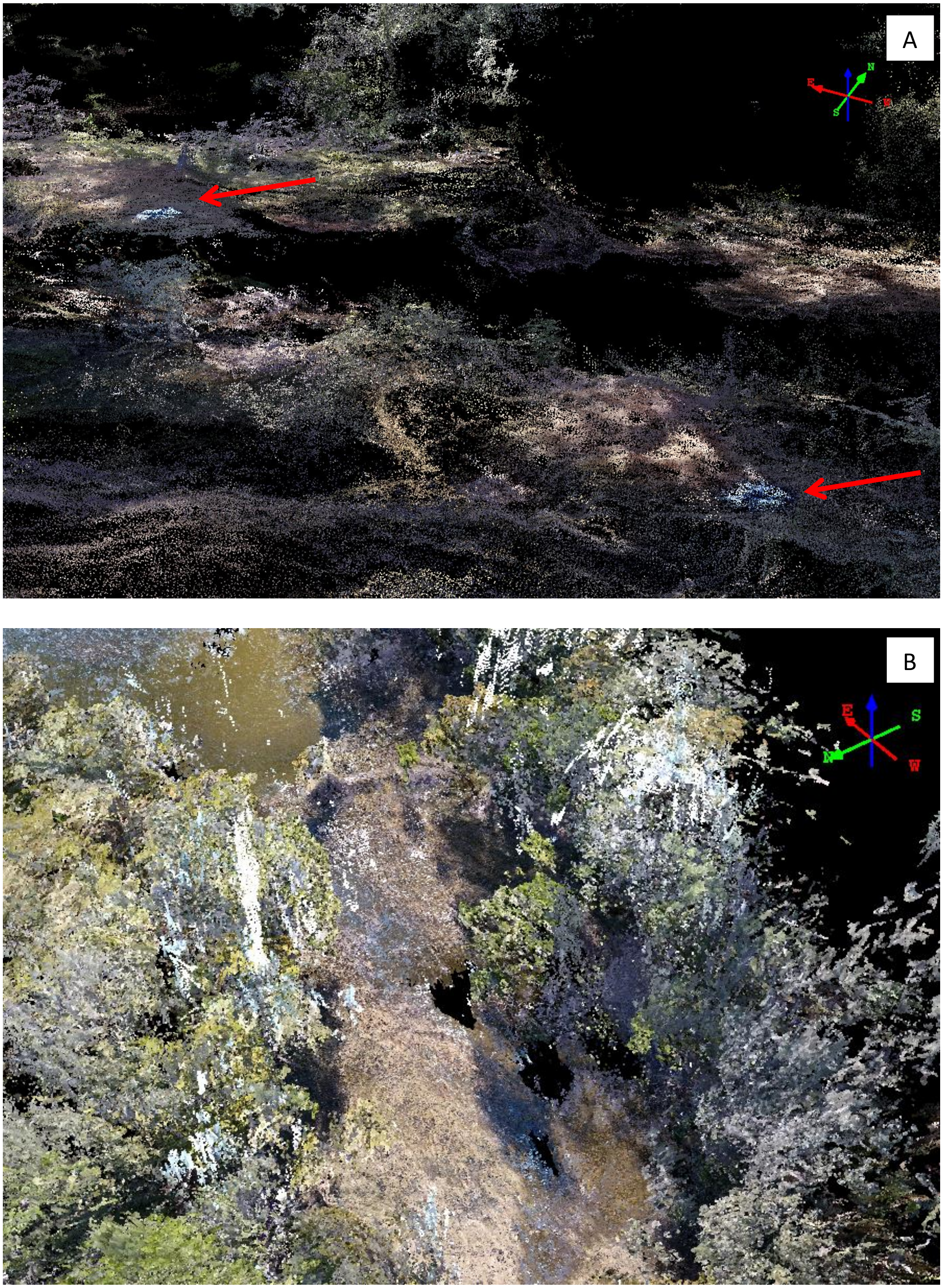

Figure 3.28. Data inaccuracies resulted from 3D reconstruction of quadcopter aerial images: reprojection errors (A); data gaps (B).

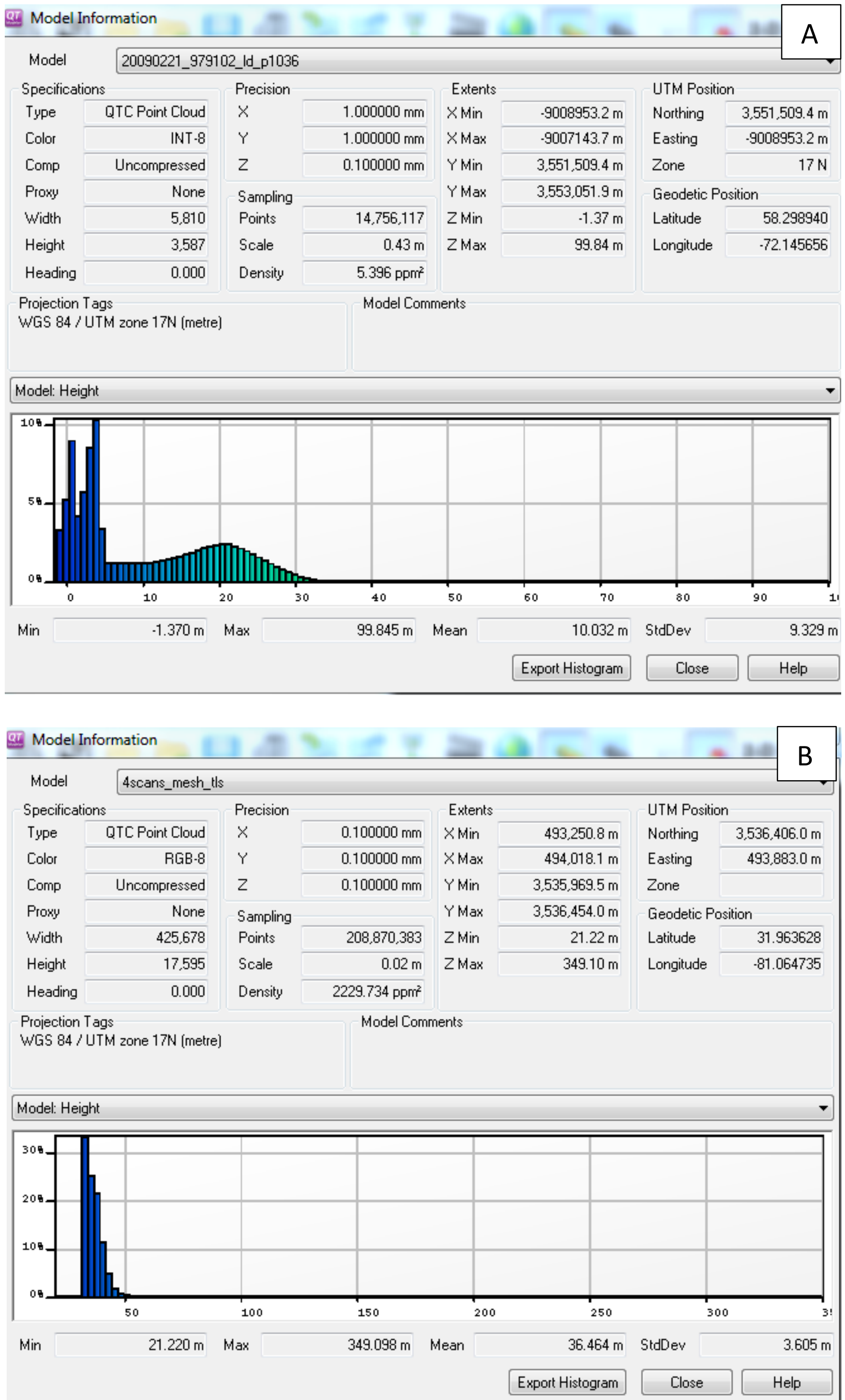

Figure 3.29. Point density info for airborne LiDAR data (A) and terrestrial LiDAR data (B).

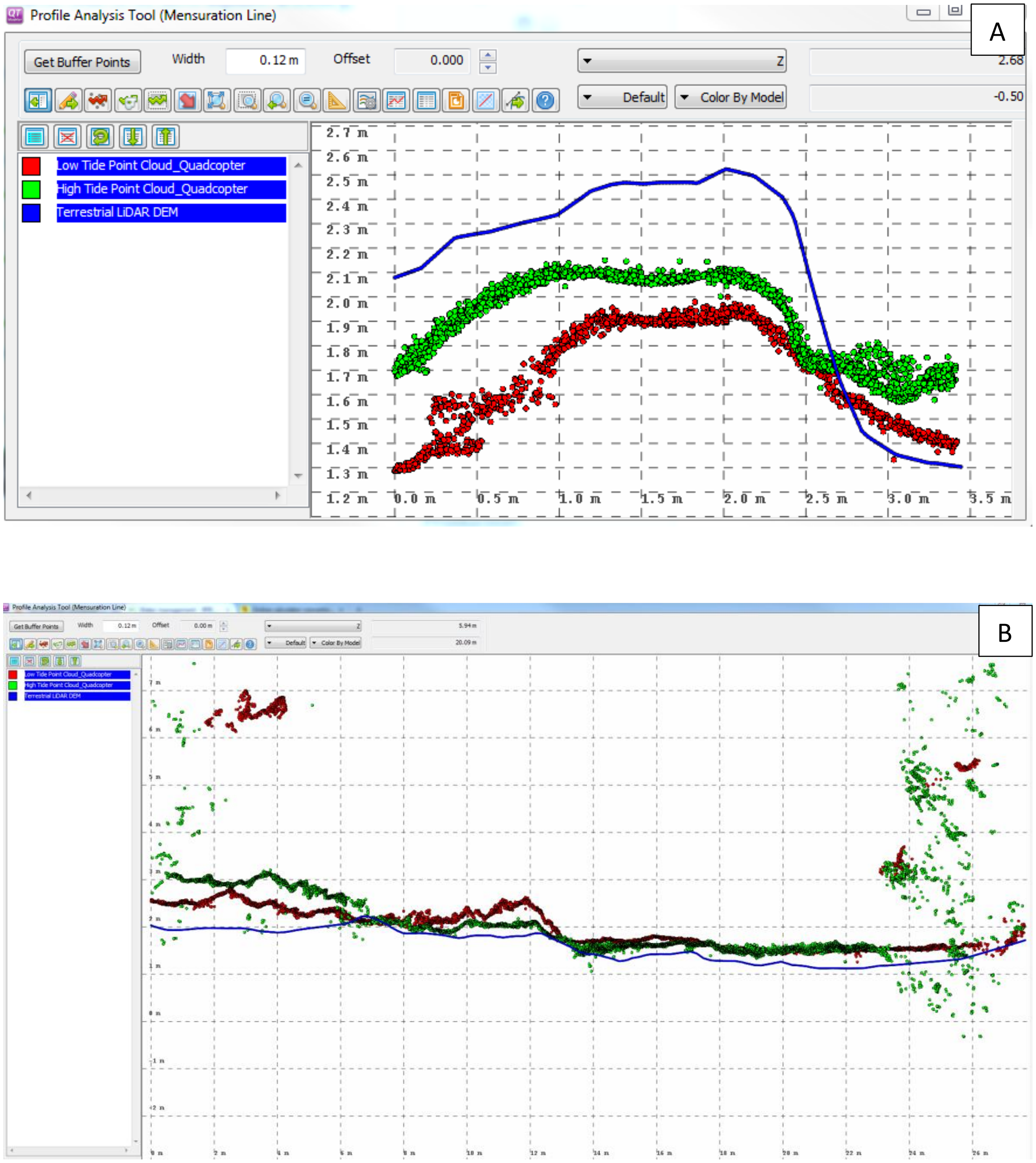

Figure 3.30. Comparing measurements and elevation profiles between SfM-derived point clouds and terrestrial LiDAR: the lower dike profile (A) and the topography across the marsh (B).

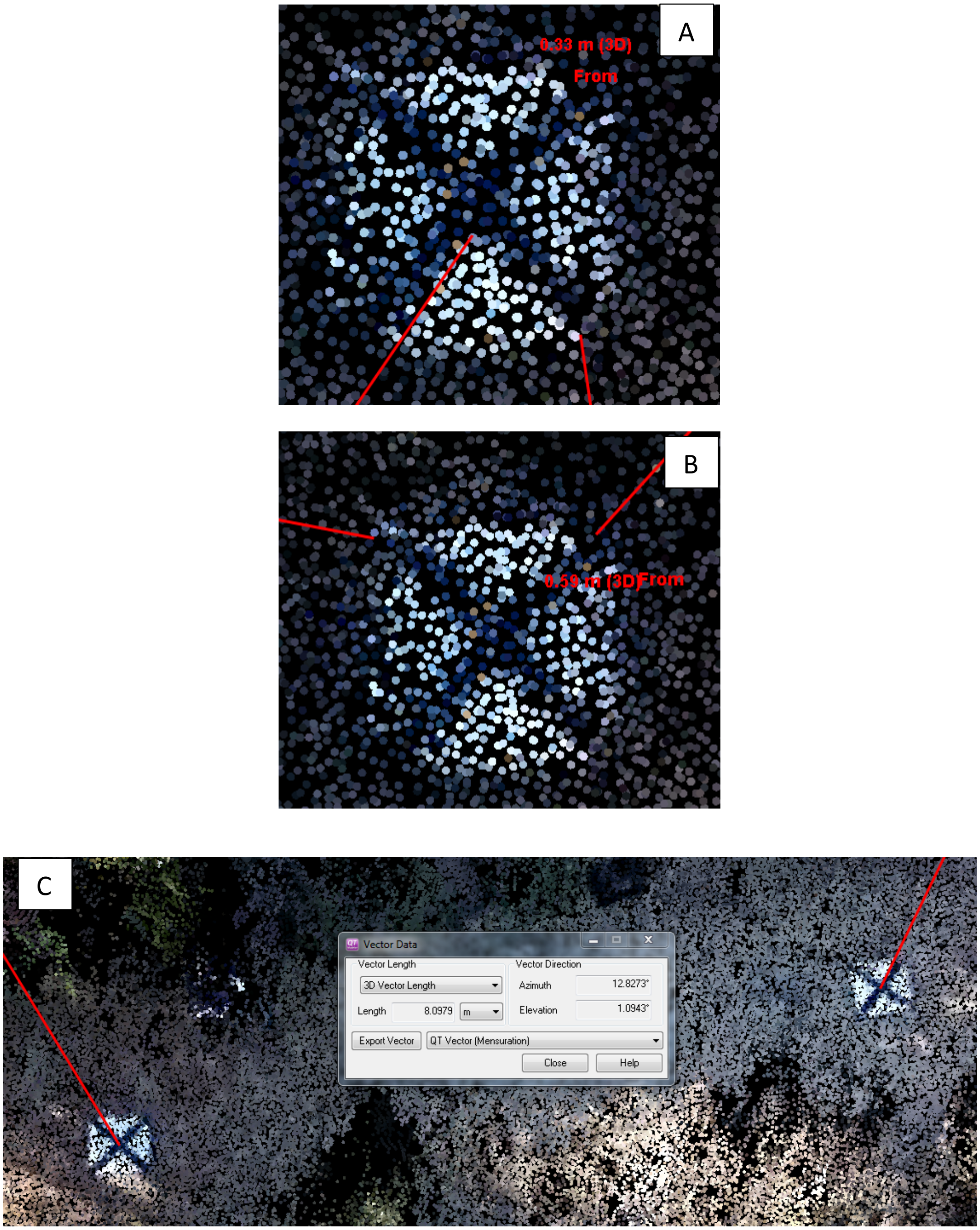

Figure 3.31. Measurements of targets (A, B) and between targets (C) on the low tide point cloud.

CHAPTER 4

PHYTOLITH EVIDENCE OF HISTORICAL RICE CULTIVATION AT WORMSLOE HISTORIC SITE[3]

[3] Pasqua, A., L. M. da Costa, and E. Garrison. To be submitted to *Journal of Archaeological Science*

ABSTRACT

The employment of phytolith analysis in archaeobotany has helped in the archaeological investigation of many studies aimed at finding evidence of past agricultural practices. Phytoliths are microscopic silica bodies that are produced by plants and grasses, and provide a reliable method to identify micro-botanical remains in the soil, where they can be preserved for long periods of time after plant decay. Phytolith analysis was performed at Wormsloe Historic Site to investigate historical rice cultivation on site, as this aspect of its environmental history had not been defined. Evidence related to rice cultivation at Wormsloe would increase its current archaeological, cultural, and historical significance. Rice, among other crops, produces three main phytolith types, i.e., double-peaked, bulliforms, and bilobates. These types can be diagnostic at the genus level and, sometimes, even at the species level, thus allowing analyst to distinguish between domesticated and wild rice species. Furthermore, rice phytoliths can also be diagnostic of the plant part within which they were formed, i.e., double-peaked form in the rice husk, while bulliforms and bilobates form in the stem and the leaves of rice plants. At Wormsloe, examination of soil samples collected in the area where rice cultivation is suggested revealed the presence of phytoliths belonging to the rice genus, and some suggested a domesticated nature. Radionuclide analysis performed on soil samples suggests soil may be older than 100 years. The results of this study indicate that rice was somewhat present in the area under investigation, and that it was probably cultivated for a short period of time in the second half of the 19th century.

Keywords: Rice cultivation, Archaeobotany, Phytolith analysis, Wormsloe

4.1. INTRODUCTION

The term “phytoliths” – from Greek literally ‘plant stones’ – refers to microscopic, inorganic particles of “*hydrated silica formed in the cells of living plants that are liberated from the cells upon death and decay of the plants*” (Piperno, 1988). Although other terms such as “plant opals” (Zheng, 2000), “opal phytoliths”, or “opaline silica” (Garrison, 2003; Piperno, 1988) have been employed over the years to indicate the silica bodies present in plants, the term “phytoliths” has undoubtedly been the most commonly used in the literature, and the one employed in this study. Soluble silica, present in soils in the form of monosilicic acid $Si(OH)_4$, is absorbed by plants and then deposited as opaline silica in and between their cells, thus taking different morphologies depending upon which plant or which part of the plant it is deposited into, e.g., stems, leaves, or inflorescences (Garrison, 2003; Harvey and Fuller, 2005). Despite the fact that absorption of silica is common to many plants, some taxa have the ability to store more silica and produce more phytoliths than others; this is the case, for example, of the Cyperaceae and Gramineae families of the plant kingdom (Piperno, 1988). After plants die and decompose, they release their silica deposits in the ground. Sometimes, phytoliths can be transported elsewhere from their original deposition through wind, fire, water runoff, and animal droppings (Dunn, 1983; Piperno, 1988). Nevertheless, phytoliths are primarily deposited *in situ*, unlike pollen grains which are usually dispersed by wind over wide areas in the form of “pollen rain” (Garrison, 2003). Once deposited in the ground, phytoliths become part of the local soil, where they can be preserved for a long time, depending on the local environmental conditions. For instance, phytoliths preserve better in soils with a pH ranging between 3 and 9 as well as in tropical and poorly drained soils

(Piperno, 1988); other variables such as the presence of salt, and a pH value around 3 may also aid the preservation process of phytoliths (Costa, pers. comm.). On the other hand, environmental conditions such as soils with pH values around 9 may seriously compromise the preservation of phytoliths (Piperno, 1988). Phytoliths have also a relatively high vertical stability, meaning that their location along the soil profile usually does not change over time after they get deposited (Piperno, 1988). Vertical displacement of phytoliths may sometimes occur in case of well-drained and sandy soils, as water fluctuation up and down the profile may play a role in the vertical movement of phytoliths across soil horizons (Costa *et al.*, 2010). Nevertheless, as Rovner affirms, "*vertical movement cannot be ignored, but it is a non-issue warranting no special attention. It is certainly no invalidation of phytolith analysis in archaeology*" (Piperno, 1988). In terms of physical characteristics, phytoliths may range in color from transparent to dark brown, depending on the presence of impurities such as iron or carbon; their edges are smoother than those of quartz grains, so that they are more easily identified at the optical microscope when quartz grains are mixed with phytoliths (Costa, pers. comm.). Generally, phytoliths vary in size from around 1 to 1000 μm (Rovner, 1983), although most of them are usually found in the silt and very fine sand fractions of the soil, i.e., 2-125 μm (Costa, pers. comm.). With regard to their specific gravity, phytoliths range from 1.5 to 2.3 (Piperno, 1988).

Over the last decades, many studies have demonstrated the value of phytoliths in the archaeological identification of plants, thus allowing the reconstruction of past agricultural environments (Ball *et al.*, 2015; Harvey and Fuller, 2005; Piperno, 1988). The ideal case when using phytoliths as a tool for palaeoecological reconstruction is when there is a one-to-one correspondence between phytoliths and plants that produce them, so that a certain phytolith morphology can be related to one plant only, and vice versa. Unfortunately, this is generally not the case in nature, as often times problems of multiplicity and redundancy occur (Lu *et al.*, 2006; Lu and Liu, 2003b; Rovner, 1983). In particular, multiplicity occurs when the same plant produces more than one phytolith shape, such as the genus *Oryza sativa*, i.e., rice. On the other hand, redundancy involves the production of the same phytolith shape by different plant species, such as in the case of bilobate phytoliths, which are common to many grass subfamilies of the Gramineae family (Lu and Liu, 2003b). As an aid in the interpretation of phytoliths recovered in archaeological settings, various classification systems have been proposed over the last decades. Some of these systems, in fact, have identified general correspondences between certain grass subfamilies and phytolith morphologies, thus providing archaeologists and palaeobotanists with general guidelines on relating phytoliths to the grasses that produce them. In the study conducted by Twiss *et al.* (1969), for instance, a morphological classification of grass phytoliths of North America was developed, and grasses were grouped into three broad taxonomic subfamilies known as panicoid, festucoid, and chloridoid. In particular, it was noted that phytolith morphologies such as crosses and dumbbells – the latter also known as bilobates – are produced by panicoid grasses, which grow in warm and moist environments, such as the southeastern United States (Lu and Liu, 2003a); rectangular, circular, elliptical, and oblong phytolith morphologies, instead, are produced by festucoid grasses, which grow in humid conditions; finally, saddle morphologies are produced by chloridoid grasses, which include short grasses that develop in dry and warm conditions. Therefore, the presence of certain phytolith assemblages rather than others at archaeological sites may also provide useful insights for better understanding changes in the paleoclimate of one particular area (Huang and Zhang, 2000).

Phytoliths have provided evidence of historical rice cultivation in several archaeological areas (Cao *et al.*, 2006; Chun-Hai *et al.*, 2007; Fujiwara and Kaner, 1993; Huang and Zhang, 2000; Itzstein-Davey *et al.*, 2007; Jiang and Liu, 2006; Jiang and Piperno, 1994; Jiang, 1995; Jin *et al.*, 2014; Lu *et al.*, 2006; Lu *et al.*, 2002; Qiu *et al.*, 2014; Watanabe, 1968; Zhang *et al.*, 2010; Zhao *et al.*, 1998; Zhao and Piperno, 2000; Zheng *et al.*, 2003b; Zheng and Jiang, 2007). As Huang and Zhang (2000) argue, in fact, phytolith analysis represents "*an indirect but reliable method for detecting rice cultivation at archaeological sites*". In particular, many studies focused on the use of phytoliths to investigate the origin and the domestication of rice in Asia (Fuller *et al.*, 2007; Fuller *et al.*, 2010; Fuller and Weisskopf, 2011). Others, instead, have employed phytoliths to infer rice processing stages (Harvey and Fuller, 2005).

Rice represents one of the most important crops in the world, and can grow in a wide range of ecological systems ranging from the uplands, where it is cultivated as a dry crop, to bottomlands, where it is cultivated as a wet crop (Weisskopf *et al.*, 2013). Rice is a grass belonging to the *Oryzoideae* tribe of the *Poaceae* (Gramineae) family, with about 23 species at the genus level *Oryza* (Gu *et al.*, 2013). Oryza species include domesticated varieties such as *Oryza sativa* as well as wild species such as *Oryza minuta* and *Oryza officinalis* (Gu *et al.*, 2013). In general, rice plants produce three distinctive phytolith morphologies, which are produced by distinct parts of the plant: the husk produces double-peaked phytoliths, while the leaves and stem produce fan-shaped bulliforms and bilobates phytoliths (Figure 4.1) (Gu *et al.,* 2013; Zhang *et al.*, 2010). These three phytolith types can have different taxonomic values. For instance, it is generally assumed that, among the three types, rice double-peaked phytoliths have the highest taxonomic value, for it has been demonstrated that double-peaked phytoliths are unique to the genus *Oryza* (Gu *et al.*, 2013; Pearsall *et al.*, 1995; Zhao *et al.*, 1998). Therefore, double-peaked phytoliths have been used to distinguish between domesticated and wild rice species (Gu *et al.*, 2013; Pearsall *et al.*, 1995; Zhao, 1998; Zhao *et al.*, 1998). In particular, in the study conducted by Zhao *et al.* (1998), a method based on discriminant analysis was devised in order to classify double-peaked phytoliths into three groups, i.e. domesticated, wild, and indeterminate rice. The variables used in this method were five morphological measurements of double-peaked cells, i.e., top width (TW), middle width (MW), depth of the curve (CD), and heights of the peaks (H1 and H2) (Figure 4.2). This method has been used to distinguish between domesticated and wild rice species in a number of studies (Itzstein-Davey *et al.*, 2007; Wu *et al.*, 2014; Zhao, 1998; Zhao *et al.*, 1998).

With regard to the taxonomic value of fan-shaped bulliforms, instead, it can be affected by the fact that bulliforms are common to many grass taxa in the *Poaceae* family (Lu *et al.*, 1997; Lu *et al.*, 2002). Fan-shaped bulliform cells in rice – also known as keystone, cuneiform bulliform, or motor cells – are characterized by shallow scale-like decorations around the base, and by two lateral protrusions located on the half-round side of the cell (Fujiwara and Kaner, 1993; Lu *et al.*, 2002; Wu *et al.*, 2014). As demonstrated by Lu *et al.* (2002) – who analyzed bulliform phytoliths from 16 grass species – the presence of scale-like decorations in bulliform cells represents a distinctive characteristic of the genus *Oryza*, thus providing a reliable way to discriminate between domesticated and wild rice species. it was demonstrated fact, that bulliform cells from domesticated rice statistically present a number of 9 decorations or higher, while those from wild rice usually have less than 9 decorations (Figure 4.3); therefore, this criteria has been used to infer rice domestication in a number of studies (Lu *et al.*, 2002; Wu *et al.*, 2014). Furthermore, by measuring morphological parameters such as vertical length (VL), horizontal length (HL), lateral length (LL), the vertical length of the base portion (b), and the vertical length of the non-base portion (a) (Figure 4.4), bulliform cells have been employed to discriminate rice at the species and sub-species level (Fujiwara and Kaner, 1993; Huang and Zhang, 2000; Zheng *et al.*, 2003a; Zheng *et al.*, 2003b). According to Pearsall *et al.* (1995) and Zhao *et al.* (1998), however, these methods are not sufficient to distinguish between domesticated and wild rice species when they overlap geographically. Finally, Huang and Zhang (2000) infer domestication from bulliform cells by employing the mean ratio of the length of the non-base portion (a) to the length of the base portion (b) in bulliform cells, suggesting that domesticated rice bulliform cells have generally a mean ratio of less than 1.

As Lu and Liu (2003b) demonstrated, bilobate phytoliths is a very common phytolith morphology in grass taxa, as it is produced by at least 85 species belonging to the Panicoideae, Oryzoideae, Chloridoideae, and the Arundinoideae grass subfamilies. From the morphological classification system developed in the study conducted by Lu and Liu (2003b), it was found that bilobates with truncated margins at both ends were somewhat diagnostic of the Oryzoideae tribe or subfamily. Other studies (Gu *et al.*, 2013; Huang and Zhang, 2000; Wu *et al.*, 2014) also noted that bilobates in the Oryzoideae subfamily are arranged in a parallel fashion along the plant stem or leaves. However, a

3D analysis of the morphological parameters of rice bilobates suggested that bilobates cannot be diagnostic at the species level (Gu *et al.*, 2013). However, Costa (2010) suggests that bilobates are not stable in soils, therefore are not commonly found in soils despite the presence of grasses that produce them; furthermore, bilobates tend to dissolve more easily when processed with sodium hydroxide in the lab than other types of grass phytoliths (Costa, pers. comm.).

As suggested by Lu and Liu (2003b), when single phytolith morphologies cannot be diagnostic of specific grass species, a more holistic approach based on phytolith assemblages should be used to infer grass species instead. The range of phytolith shapes can, in fact, be limited for the vast genetic differences occurring in nature. As a result, many studies have employed this approach to infer the presence of domesticated rice species – thus cultivation – at archaeological sites (Zhang *et al.*, 2010). Other studies have also employed a combination of phytolith assemblages and contextual features to infer rice cultivation, such as the presence of agricultural tools (Zheng and Jiang, 2007), rice grains and location in inhabited areas (Huang and Zhang, 2000; Zheng *et al.*, 2003b), or the absence of wild rice in the area (Jiang and Piperno, 1994).

To date, there is not a complete understanding of whether rice was ever cultivated at Wormsloe Historic Site, let alone the areas where cultivation might have been performed. Previous research on site, in fact, did not fully investigate the potential for onsite rice cultivation, and therefore did not explore the use of archaeobotanical analysis and thorough landscape inspection to locate areas where rice could have been cultivated. As part of the ongoing investigation of Wormsloe's environmental history and historical development supported by the Wormsloe Foundation and the Wormsloe Institute for

Environmental History, this study aims at providing more conclusive evidence related to historical rice cultivation at Wormsloe. Should evidence related to rice cultivation be revealed, Wormsloe would fill a gap in its environmental history, and would increase its current archaeological, cultural, and historical significance both within Georgia and the southeastern United States. The main goal of this study, therefore, is to perform an archaeobotanical analysis in one particular area of Wormsloe Historic Site on the Isle of Hope, Georgia, where micro-topographic features are indicative of rice cultivation. In particular, phytoliths from soil samples will be analyzed to investigate the presence of rice phytolihs, which might indicate that rice was being grown in the area.

4.2. STUDY AREA

Wormsloe State Historic Site is located on the Isle of Hope, just south of Savannah, Georgia, and represents one of the most significant historical, cultural, and natural sites in the southeastern United States. Since its establishment in 1736 by Noble Jones, Wormsloe has served many purposes, such as a military outpost during the first years of the Georgia colony, an agricultural plantation producing sea island cotton in the 1800s, and a farm and tourist attraction in the 1900s. Today, the Barrow family still lives onsite and, through the Wormsloe Foundation and the Wormsloe Institute for Environmental History, promotes academic research in order to increase the current understanding of Wormsloe's land use change and historical development.

In order to locate areas at Wormsloe where rice cultivation may have been performed, a careful observation and inspection of the Wormsloe landscape and topography was performed by means of LiDAR elevation data and historical maps –

available at the UGA Center for Geospatial Research – as well as ground reconnaissance. Eventually, three main areas were selected as being suggestive of rice cultivation at Wormsloe and, therefore, worthy of further investigation (Figure 4.5). Given the limited time and resources, only one area designated Area 1, was chosen for the purpose of this study because it represented the most promising for revealing evidence of rice cultivation. First, the area presents what appears to be a manmade dike, which could indicate a structure put in place for controlling and preventing salt water influx. Second, two drainage ditches converge and discharge their waters in the marsh; these could have served as canals to bring freshwater to the cultivated field located in the marsh. Third, from the analysis of historical maps it was noted that one of the two ditches was connected to a water pond, which could have served as reservoir for irrigating the field. Fourth, the poorly drained soil of the marsh may have provided the right type of soil for the wet cultivation of rice. Finally, the area is located approximately 173 m south of the only surviving 19th century slave cabin at Wormsloe. The cabin was part of the so-called "slave quarters" which was built in the second half of the 1800s to accommodate enslaved laborers working on the sea island cotton crop cultivated and harvested at Wormsloe. Being in close proximity to the slave settlement, the area might have been chosen for subsistence agricultural purposes by the African-American population.

The study area (Figure 4.6) is a small tidal salt marsh inlet within the Wormsloe State Historic site of approximately 1416 m^2 in size (0.34 acres). The area is located on the eastern side of the Isle of Hope along the Skidaway River, and has roughly a rectangular shape measuring approximately 70 x 20 m. The site is characterized mostly by *Juncus roemerianus* (black needlerush) and *Spartina alterniflora* vegetation in the marsh, and by saw palmetto and maritime forest in the immediate surroundings.

4.3. METHODS

In order to investigate historical rice cultivation at Wormsloe by means of archaeobotanical analysis, soil samples were collected from the study area where rice cultivation is suggested, and were later processed for phytolith extraction, analysis, and interpretation in the Geomorphology lab and the Environmental Change lab of the Department of Geography at the University of Georgia.

Soil data collection

Between September 2-5, 2014 ten soil cores were collected from the study area at low tide conditions. These dates were chosen for their low tide conditions in the morning, thus allowing enough time during the day to recover the samples. In order to ensure true representation of the area and avoid biases in the collection of samples, the GPS coordinates of 10 random points were generated within the study area boundaries in ArcMap 10.2 of the ArcGIS software package. Soil cores were collected with a 3-inch diameter hand auger to a maximum depth of approximately 1.5 meters (Figure 4.7). Upon extraction, each core was placed on a metal gutter for further analysis, i.e. estimating the number of horizons, color, texture, and other physical characteristics such as the presence of organic matter. A Munsell Color Chart was used to estimate soil color. Samples were collected from each horizon of each core for a total of 43 samples, and were later stored in sealed plastic bags. Samples were then air dried to let moisture evaporate. Within the scope of this study, three of the ten cores were selected for phytolith extraction and analysis (Figure 4.8). In particular, cores retrieved at points 1, 3, and 6 were chosen in order to cover as much of the study area as possible, i.e., west, center, and east. In total, 12 samples were retrieved from the three cores, as described in Table 4.1.

Phytolith extraction

Phytolith extraction was performed in the Geomorphology Lab of the Department of Geography at UGA. The method used to prepare and process the samples for phytolith analysis follows the procedures of Piperno (1988) and, in particular, methods described by Costa during his visit to the Department of Geography in September 2014. David Leigh, head of the Geomorphology Lab at UGA, also served as logistical and theoretical support in the extraction procedure. A total of 10 grams of each sample were put in a muffle furnace for 4 hours at 500°C to remove organic matter, and were then homogenized with a pestle and mortar; later, they were processed with 50 mL of 10% HCl (hydrochloric acid) for an hour to remove carbonates, and finally treated with 50 mL of 0.5N NaOH (sodium hydroxide) for 8 hours to deflocculate the soil particles. Samples were then divided into three soil fractions, i.e., very fine sand (0.105 – 0.053 mm), coarse silt (0.053 – 0.015 mm), and fine silt (0.015 – 0.002 mm) through wet sieving and gravity sedimentation for a total of 36 samples (Piperno, 1988). Each sample was then oven dried and weighed in order to analyze how much phytolith content was in the sample (Table 4.2). Sodium polytungstate was used for heavy liquid separation (density 2.30 g/mL). Samples were put in test tubes with 10 mL of heavy liquid solution, and then centrifuged 3 times at approximately 2250 rpm for 10 minutes to allow phytolith separation. To retrieve the phytolith residue from each sample, a suction device provided with a 0.45 µm diameter filter was used. Phytolith extract from each sample was oven dried, weighed, and part of it was mounted on slides with Entellan mounting medium for analysis.

Phytolith analysis and interpretation

Microscope analysis was performed at the Environmental Change Lab in the Department of Geography at UGA led by David Porinchu, who also provided technical suggestions. Slides were scanned at 200x and 400x magnification using a Zeiss Axio Imager A2 microscope provided with Axio MRc5 digital camera and AxioVision LE64 software. Phytoliths of interest were photographed, and then measured as described in Figures 4.2 and 4.3. All slides were scanned entirely to allow the identification of any Oryza-type phytolith. When possible, at least 300 phytoliths were counted on each slide, and classified morphologically as described in Table 4.3. The classification system used in this study follows Jiang and Piperno (1994) and Huang and Zhang (2000).

In order to achieve higher confidence in the prediction of rice domestication, phytoliths extracted from domesticated rice varieties from Brazil and the United States were employed as keys against which the Wormsloe samples were compared. In particular, the domesticated rice samples from the United States included Carolina Gold plants privately cultivated in the Athens, Georgia area[4], as well as Carolina Gold grains from Sapelo Island[5], while the Brazilian samples included the five different rice varieties

[4] Before being transplanted in a private garden in Hull, Georgia, the Carolina Gold rice grains were planted in a nursery at the Southern Seed Legacy Lab, a local lab linked to the UGA Anthropology Program which fosters the cultivation of local seeds and plants. Originally, the grains are believed to come from Anson Mills, an heirloom grain company (Chapman, pers. comm.).

[5] Rice grains were obtained from the Carolina Farm Stewardship Association, an organization involved in the preservation of heirloom southeastern vegetables, grains, and flowers (Walker, pers. comm.).

of Ouro Minas, Predileta, Rio Grande, Rubelita, and Seleta. Phytoliths were extracted by employing the following procedure (Costa, pers. comm.). Plant samples were washed with distilled water, and then put in a muffle furnace at 300ºC for two hours. Then, the furnace was let open for about 15 minutes in order to allow some air in, thus facilitating the process of ashing the sample. The temperature in the furnace was then raised at 500º C. After two hours, the samples were extracted and treated with 10% HCl for an hour to remove carbonates. After washing them with distilled water until no carbonate residue was present, samples were then dried in the oven at 105º C, and finally mounted on slides for microscope analysis.

Statistical analysis

Domesticated bulliform and double-peaked phytoliths from Wormsloe were statistically analyzed and compared to phytoliths from known domesticated rice species from Brazil, Sapelo Island, China, and Athens, Georgia to determine whether and to what extent the Wormsloe phytoliths differ from known rice samples. The reference samples were chosen in order to achieve as much a geographic diversity as possible, with samples coming from Asia, South America, and North America. A multivariate analysis of variance (MANOVA) was performed to investigate the overall difference between samples. In particular, the null hypothesis for the statistical analyses was that no significant difference between samples could be appreciated, while the alternative hypothesis reflected significant differences between samples. Since for both analyses of bulliforms and double-peaked phytoliths the assumption for homogeneity of covariance matrices was not met, Pillai's trace results are presented instead of Wilks' lambda.

Furthermore, post hoc tests were performed to analyze which specific morphological parameters differ among samples. The dependent variables used for statistical analysis were HL, VL, and L/W for bulliforms, while for double-peaked TW, MW, H, and CD were used. For post hoc tests, Tukey's HSD (Honestly Significant Difference) was used, while Games- Howell was used when the samples' variance was unequal. In order to graphically show similarities and differences among samples, a discriminant function analysis (DFA) was also performed, and a plot showing the multidimensional space occupied by each sample was created. The statistical analyses were conducted using the SPSS 20.0 software package, with a p-value of significance equal to 0.05.

4.4. RESULTS

The results of phytolith analysis are presented in Table 4.3. Among all samples, the most abundant phytolith types were square/rectangular, and others – which included mostly amorphous, epidermis cells, and oddly-shaped phytoliths. Other abundant types included bulliform, elongate, and round/elliptical phytoliths (Figure 4.9). Diatoms, saddles, sponge spicules, and bilobates were very poorly represented in the samples. No cross phytoliths were encountered in the 36 samples analyzed. In a few cases, the phytolith content was so small that it was not possible to reach the count of 300. In total, 1507 bulliforms were counted across all samples. Of these, 99 were chosen for further investigation due to their close resemblance to *Oryza*-type bulliform phytoliths. Similarly, 33 double-peaked husks were selected for further investigation. No *Oryza*-type bilobates were found.

From the statistical analysis on bulliforms, both the MANOVA (Pillai's Trace = 1.01, $F_{(9, 363)}$= 20.50; p-value < 0.001; η^2=0.34) and the DFA (Chi-square = 285.39; p-value < 0.001) results show that the Wormsloe and the control samples differ significantly among each other. However, as shown by the plot generated by discriminant function analysis (Figure 4.10), overall the domesticated bulliform phytoliths from Wormsloe are close to domesticated bulliforms from China and Brazil, while the Athens samples are well separated from the other three groups. In particular, 38.5 % of Wormsloe domesticated bulliforms are misclassified as China bulliforms, and 25 % of China bulliforms are misclassified as Wormsloe bulliforms (See table under Figure 4.10). Furthermore, from the post hoc analyses on bulliforms, it is evident that: 1) the Wormsloe samples differ significantly with the other samples with respect to VL; 2) the HL parameter from Wormsloe does not differ significantly to the HL parameter from China (p-value = 0.077); 3) the L/W ratio from Wormsloe is significantly different only from the L/W ratio of the Athens sample (p = 0.001), while it is significant similar to the Brazil (p-value = 0.14) and China (p-value = 1.0) specimens (See appendix A.1 for complete results).

The double-peaked statistical analysis revealed that the Wormsloe phytoliths are significantly different from the other samples from Sapelo Island, Athens, and China (MANOVA: Pillai's Trace = 1.49, $F_{(12, 264)}$= 21.60; p-value < 0.001; η^2=0.49; DFA: Chi-square = 251.08; p-value < 0.001). As shown in the plot generated by discriminant function analysis (Figure 4.11), Wormsloe is clearly separated from the other samples, with 100% of cases well classified. These results were also consistent with the post hoc analyses following the MANOVA, which shows that the TW, MW, CD, and H morphological parameters from Wormsloe double-peaked are significantly different from the same parameters measured on the other samples (See Appendix A.2 for complete results).

4.5. ANALYSIS AND DISCUSSION

When using phytoliths to investigate rice cultivation in Georgia and generally in the Southeastern United States, care should be taken in distinguishing between domesticated and wild varieties of the *Oryzoideae* tribe. In fact, as Lu and Liu (2003a) affirm, wild relatives of domesticated rice such as *Leersia oryzoides* (rice cutgrass) and *Zizaniopsis miliacea* (giant cutgrass) may be present in the area. Therefore, this may cause limitations in both the identification of phytoliths and the prediction of domestication, particularly when using bulliform phytoliths to perform species distinction (Pearsall *et al.*, 1995; Zhao *et al.*, 1998). Reference rice specimens from domesticated plants in addition to the Wormsloe samples were also analyzed in order to ensure a higher confidence in the identification of Oryza-type phytoliths as well as in the prediction of domestication. Wormlsoe bulliform phytoliths were compared against bulliforms extracted from domesticated varieties from the United States and Brazil, as well as the domesticated bulliforms from China specimens that were observed in the study conducted by Gu *et al*. (2013).

Bulliform phytoliths

As shown in Table 4.4., *Oryza*-type bulliforms were classified as domesticated by employing the following procedure: 1) the presence of at least 9 scale-like decorations as suggested by Lu *et al.* (2002); 2) as argued by Huang and Zhang (2000), the ratio a/b should be <1 in domesticated rice bulliforms; 3) the VL/HL (L/W) ratio was compared to the reference specimens from Brazil, China, and the United States; and 4) VL and HL values were compared to mean values of the reference specimens from Brazil, China, and the United States. The decision to consider all of the mentioned criteria rather than just a few was intended to achieve higher confidence in the prediction of phytoliths, given the above mentioned limitations.

The presence of at least 9 scale-like decorations on bulliform phytoliths was the main criteria with which the 99 bulliforms from the Wormsloe samples were selected, photographed, and measured while being analyzed at the microscope. However, after taking into consideration all of the other criteria, only 26 bulliforms remained, all having a number of scales ranging between 9 and 13, and a mean value of 10.65 (Table 4.4.). Some of them (Figure 4.14. d, e, k, m, o, p, u) also display one or two lateral protrusions which are typical of rice bulliforms (Lu *et al.*, 2002). However, the analysis of 30 known domesticated Carolina Gold bulliforms from the United States revealed that 5 bulliforms (16.66%) presented less than 9 scales in spite of being of domesticated type, i.e., 7 and 8 scales. Nevertheless, the other 25 Carolina Gold bulliforms (83.33%) presented between 9 and 17 scales, with a mean value of 10.56, which closely resembles that of Wormsloe bulliforms. As a matter of fact, this criteria has been already used in the literature to infer domestication in bulliform cells (Lu *et al.*, 2002; Wu *et al.*, 2014).

The a/b ratio was the second criteria used to infer domestication on Wormsloe bulliforms. As suggested by Huang and Zhang (2000), in fact, this ratio should be less than 1, thus giving domesticated rice bulliforms a rather proportioned and symmetrical appearance. The mean value of the a/b ratio for the Wormsloe bulliforms is 0.83. It should be noted, however, that this criteria may not be met by every domesticated rice bulliform as demonstrated by the analysis of Carolina Gold specimens, in which 22 out of 30 bulliforms (73.33%) met this condition, with a mean value of 0.81. The China specimens were not included in this comparative analysis due to differences in how measurements of these two values were taken, while a and b values were not measured on Brazil samples.

With regard to the third criteria, from the analysis of domesticated bulliforms (Figure 4.12) extracted from five Brazilian rice varieties, it was apparent that the L/W ratio falls within the 0.85-1.15 range in 70% of the cases (17/24 bulliforms) for Ouro Minas, 81% (18/22 bulliforms) for Predileta, 84% (21/25 bulliforms) for Rio Grande, 84% (21/25 bulliforms) for Rubelita, and 65% (17/26 bulliforms) for Seleta varieties (Costa, pers. comm.) (Figure 4.13). The analysis of United States specimens revealed that 20/30 (66.6%) bulliforms fall in this range, while 18/20 (90%) domesticated bulliforms from China display the same characteristic. The mean L/W value for the Wormsloe bulliforms corresponds to 0.97 (Table 4.5.) which is exactly the mean value of the 20 domesticated bulliforms from China studied by Gu *et al.* (2013), thus showing very close resemblance as also revealed by post hoc tests. The mean L/W values of 49 specimens from Brazil and 30 specimens from the United States appear slightly different, i.e., 1.03 and 1.09, respectively, although still within the 0.85/1.15 range proposed in this study. More specifically, the varieties from Brazil display mean values of 1.06 (Ouro Minas), 1.02 (Predileta), 0.99 (Rio Grande), and 1.03 (Rubelita and Seleta) (Figure 4.13).

Therefore, this criterion may help in the identification of domesticated rice bulliforms (Costa, pers. comm.).

Finally, the VL and HL values of the Wormsloe bulliforms were compared against mean values of reference specimens in order to appreciate similarities and differences concerning their size. As shown in Table 4.5., it was noted that Wormsloe bulliforms present VL values between 35.03 µm and 70.93 µm, with a mean value of 44.37 µm; on the other hand, HL values range between 35.3 µm and 80.19 µm, with a mean value of 45.41 µm. As also demonstrated by post hoc analysis, it is apparent that the Wormsloe HL values are statistically closer to those from China, while they are significantly different than those from Brazil and the Athens area. In particular, the mean VL and HL values of 49 Brazilian specimens are 29.09 µm and 28.16 µm, while those from 30 Carolina Gold samples corresponded to 78.33 µm and 71.45 µm. The analysis of these values suggests a closer resemblance of the Wormsloe bulliforms with those from China, rather than with the local Carolina Gold variety or the Brazilian varieties.

Double-peaked phytoliths

In addition to employing bulliform cells to investigate rice domestication at Wormsloe, this study also employed double-peaked phytoliths. As Pearsall *et al.* (1995) and Zhao *et al.* (1998) suggest, these cells are unique to the genus Oryza and thus are the most promising to successfully distinguish domesticated and wild species when they overlap geographically, such as in this case. The selection of this type of phytoliths under the microscope, however, proved more challenging than for bulliform cells, due to their smaller size and sometimes ambiguous shape. Reference specimens for this phytolith type included Carolina Gold plants from the Athens, Georgia area, Carolina Gold grains from Sapelo Island, Georgia, and the samples from China analyzed by Gu *et al.* (2013). Overall, 33 Oryza-type double-peaked cells were selected and measured.

Following the discriminant function method proposed by Zhao *et al.* (1998) and employed by Wu *et al.* (2014), double-peaked measurements were used to discriminate between domesticated, wild, and indeterminate rice double-peaked bulliforms. The method includes four formulas, two for predicting domesticated rice, and two for predicting wild rice (below):

<u>Formulas for predicting domesticated rice</u>

Eq(1) *Prediction of domesticated rice*: = - 19.027 – 0.129(TW) + 0.116(MW) + 0.676(H1) + 3.101(H2) + 0.921(CD) – 0.028($H1^2$) – 0.079($H2^2$) – 0.047(CD^2)

Eq(2) *Prediction of wild rice*: = - 14.124 – 0.085(TW) + 0.113(MW) + 0.7(H1) + 2.288(H2) + 1.338(CD) – 0.021($H1^2$) – 0.066($H2^2$) – 0.067(CD^2)

When inserting the measurements of double-peaked cells in the above formulas, if the score from the first formula is larger in absolute value than that from the second formula, the cell is likely from domesticated rice; if the score from the first formula is lower, the origin remains unclear.

<u>Formulas for predicting wild rice</u>

Eq(3) *Prediction of wild rice*: = -14.617 – 0.085(TW) + 0.113(MW) + 0.7(H1) + 2.288(H2) + 1.338(CD) – 0.021($H1^2$) – 0.066($H2^2$) – 0.067(CD^2)

Eq(4) *Prediction of domesticated rice*: $- 18.334 - 0.129(TW) + 0.116(MW) + 0.676(H1) + 3.101(H2) + 0.921(CD) - 0.028(H1^2) - 0.079(H2^2) - 0.047(CD^2)$

In this case, if the score from the first formula is larger in absolute value than that from the second formula, the cell is likely from wild rice; if the score from the second formula is larger, the origin of the cell remains unclear.

The decision to assign each double-peaked phytolith to one of the three groups is made after its measurements are put into both sets of formulas. If the phytolith is predicted as domesticated using the first set of formulas, and fails to be predicted as wild using the second set of formulas, then it is likely domesticated; if the opposite occurs, then it is likely wild. If it is neither predicted as domesticated nor as wild using both sets of formulas, the phytolith is of undetermined origin (Zhao *et al*., 1998). Of the 33 double-peaked phytoliths that were analyzed, 13 (39.39%) were predicted as domesticated, 18 (54.54%) as wild, and 2 (4.54%) as indeterminate.

In addition to using the Zhao *et al.* discriminant analysis method, the measurements – TW, MW, CD, and H (mean of H1 and H2) – of double-peaked phytoliths from Wormsloe were also compared against the mean values of reference specimens (Table 4.6). As also revealed by statistical analysis, the Wormsloe values are significantly different from those of reference specimens, which all display larger values. From the analysis of wild double-peaked phytoliths in Gu *et al.* (2013), it is apparent that the Wormsloe measurements strongly resemble those of *Oryza ridleyi*, a wild rice species; however, this type is not present in the Southeastern United States, thus the Wormsloe husk phytoliths may simply belong to another domesticated variety.

Nevertheless, this does not exclude the possibility that the Wormsloe double-peaked phytoliths classified as domesticated may belong to another wild species, which does not exclude cultivation though; local wild rice, in fact, might have been simply cultivated for a short period of time, similarly to what Native Americans used to do. Therefore, given the difference in size between the Wormsloe double-peaked phytoliths and the reference samples, the analysis of this type of phytoliths provides less substantial and conclusive evidence towards assuming rice domestication at Wormsloe than bulliform phytoliths analysis.

When tested on known domesticated Carolina Gold specimens, the discriminant analysis method successfully predicted domestication for only 6 of the 30 samples from Athens (20%), and 13 of the 30 samples from Sapelo Island (43.33%). The method assigned the rest of the reference specimens to the indeterminate class, thus no domesticated rice double-peaked phytolith was assigned to the wild group. This may limit the validity of the method for successfully separating double-peaked phytoliths between domesticated and wild species, although this method has been widely used in the literature for this purpose (Wu *et al.*, 2014; Zhao, 1998; Zhao *et al.*, 1998).

A comprehensive scheme showing the results of phytolith analyses is described in Table 4.7, where the relationship between domesticated bulliforms and double-peaked is presented. The mixed presence of wild and domesticated double-peaked cells may indicate the current presence of wild rice relatives in the area such as *Leersia oryzoides* (rice cutgrass) and *Zizaniopsis miliacea* (giant cutgrass). Also, the presence of wild rice may represent one of the successive ecological stages occurring after rice cultivation, characterized by the development of wild or volunteer rice in former rice fields. The presence of domesticated phytoliths in the top layers of the three cores may be explained by internal contamination both within the same layer, and between samples from different depths of the same core. Despite the best efforts in cleaning the coring auger after each sample extraction, in fact, it is possible that small quantities of sediments from other depths or even locations were still present.

It is also interesting to note the geographic distribution of domesticated phytoliths across the study area. In general, Core 6 presents the fewest number of domesticated phytoliths between bulliforms and double-peaked (6 in total), while Core 1 presents the majority of them (22). The stratigraphy of the cores across the study area, in fact, may differ from one site to another so that 60 cm of depth on one profile may not correspond to the same depth – and thus horizon – on another core a few meters apart, i.e., it follows an elevation gradient. It is also difficult to understand what layers could correspond to the old rice field that is suggested by the presence of phytoliths. Rice cultivation may, in fact, have been performed for only short periods of time, as well as in different agricultural seasons which could have taken place even years apart from each other. The latter aspect may also explain the relatively low amount of rice phytoliths that were found; some studies, in fact, suggested the presence of at least 5000 rice phytoliths to infer cultivation (Cao *et al.*, 2006). Nevertheless, given the geographic location (close to the slave settlement), and the presence of topographic features related to rice cultivation such as dikes and ditches (see Chapter 3), the presence of some domesticated rice phytoliths, especially bulliform, is to be considered indicative of cultivation. In general, wet rice cultivation requires poorly drained soils with a high quantity of clay to retain water, so that a clay horizon may correspond to the level at which the old rice field was located.

From the analysis of the samples collected at Wormsloe, it is apparent that most of the samples present a rather slow permeability given by the presence of clayey and loamy sands (Table 4.1). This indicates the natural predisposition of the soil to the wet cultivation of rice, although it is quite difficult to pinpoint specific layers corresponding to agricultural practices. The vertical distribution of domesticated phytoliths, in fact, presents some unexpected results such as the presence of domesticated phytoliths in the top layers of the cores. It is very likely that the particularly unconsolidated and liquid sediments recovered from the marsh, as well as the use of an open bucket auger that was employed for the extraction of the soil cores, affected the stratigraphic order of phytoliths, thus limiting their accurate interpretation.

Radionuclide analysis

In order to approximate the historical time period during which rice phytoliths were produced at Wormsloe, a radionuclide analysis was performed on the four samples of Core 1. Radionuclides are radioactive elements in the Earth's atmosphere, crust, and water, which have been used in geoscience studies as a dating tool (Arnaud *et al.*, 2006). The use of radionuclides for dating sediments is based upon the decay times of these radioactive elements, i.e., their half-life, which is the time half of the atoms in each element takes to decay to another substance of its radioactive cycle. The fact that these elements are in radioactive disequilibrium with their relatives in the sediments allows us to estimate ages by measuring the excess fallout coming from the atmosphere that gets deposited in the sediments. Among the most commonly used elements used for this type of dating are Caesium-137 (^{137}Cs) and Lead-210 (^{210}Pb), which have a half-life of 30.3

years, and 22.3 years, respectively (Microanalytica.com, 2015). In particular, Caesium-137 is an artificial radionuclide that was emitted in the atmosphere during the atomic experiments of the 1950s and 1960s. Any presence of this element in sediments indicates that the sample is younger than 1954, when the first significant amounts of the elements entered the atmosphere (Alexander, pers. comm.). Therefore, the use of Caesium-137 is limited for samples dating around 60 years. The use of Lead-210 on the other hand, can be extended to samples dating 100-150 years. Lead-210 is part of the Uranium-238 decay series, and is a direct relative of Radon-222, which escapes into the atmosphere until it produces excess Lead-210.

The radionuclide analysis on the Wormsloe samples involved the use of both Caesium-137 and Lead-210 for age estimates. Approximately 40 gr. of each of the four samples was sent to Dr. Clark Alexander at the Skidaway Institute of Oceanography, where the analysis was performed using a gamma spectrometer. The results are shown in Table 4.8. The activities of both Caesium-137 and Lead-210 are very low (0.00 – 0.06 dpm/g for Caesium-137, and 0.11 – 0.44 dpm/g for Lead-210). As suggested by Alexander (pers. comm.), in fact, the amount of Caesium-137 is just above the detection limit of the machine used for processing the samples, while a normal detection activity for Lead-210 is 2, 3, or 4 dpm/g. Furthermore, a normal detection curve for Lead-210 should decrease constantly with depth, while results from Wormsloe show an increase in the amount at the deepest layer. This may be due to contamination occurred during core extraction, as the auger may have pushed down sediments from the top while being reinserted deep into the ground for additional sampling. The presence of some Caesium-137 in the top layer suggests that the top layer is younger than 1954; however, its low activity may be explained by the fact that the top layer includes a mix of sediments from the first 25 cm of the core, thus the Caesium might come from the very surface of the core in direct contact with the atmosphere. If this is the case, then the lower horizons should be around 100 years old or more, as suggested by the similar activities of Lead-210 in most of the profile as well as by the low amounts of the element in the sample. The unusual behavior of Lead-210 at the very bottom may be explained by contamination during sampling. If this interpretation is correct, the rice phytoliths found at Wormsloe suggest the presence of cultivation around the turn of the 20th century.

4.6. CONCLUSIONS AND FUTURE STUDIES

The main goal of this study was the archaeobotanical investigation of Georgia coastal soils in order to locate archaeological evidence related to rice cultivation at Wormsloe Historic Site. From the analysis of soil samples recovered from the salt marsh, 26 bulliform cells and 13 double-peaked cells were predicted as domesticated. Multiple criteria were used to predict domestication in bulliform cells: 1) the presence of scale-like decorations; 2) the a/b ratio; 3) the L/W ratio; 4) VL and HL measurements. The main criteria used to predict domestication in double-peaked cells was the discriminant analysis method developed by Zhao *et al.* (1998) which has been used to infer domestication in similar studies (Wu *et al*., 2014; Zhao, 1998; Zhao *et al*., 1998). Statistical analysis performed on domesticated bulliform and double-peaked phytoliths from Wormsloe and reference specimens revealed that: 1) Wormsloe bulliforms are very close to China bulliforms, e.g., 38.5% of Wormsloe bulliforms is misclassified as China specimens; 2) the L/W ratio from Wormsloe bulliforms is significantly similar to Brazil (p-value = 0.14) and China (p-value = 1.0) specimens; 3) Wormsloe double-peaked phytoliths are significantly different from all the reference specimens. The presence of domesticated bulliform in particular, and double-peaked phytoliths is indicative of rice cultivation at Wormsloe. The presence of wild rice phytoliths may also indicate the presence of wild rice relatives in the area as well as the cultivation, rather than domestication, of local wild rice. This interpretation is also supported by the presence of earthworks such as dikes and ditches as well as by the close proximity of the study area to the former slave settlement; furthermore, the poorly drained salt marsh soil would have been an appropriate environment for the wet cultivation of rice, as clayey and loamy soils were used for rice fields due to their soil moisture retention abilities.

Given the unconsolidated nature of the marsh sediment at Wormsloe – which might have affected the stratigraphic order of phytoliths – future research might benefit from the use of more sophisticated core extraction techniques than an open bucket auger, such as that of freeze corers; through the use of liquid nitrogen, frozen soil cores present the advantage of maintaining the stratigraphy intact, thus improving interpretation. A preliminary radionuclide analysis analyzing the amounts of Caesium-137 and Lead-210 was performed on one core, and suggests that the core samples, thus the phytoliths, may be around 100 years or older. Future studies might improve these age estimates by employing a finer sampling resolution along the soil core. Furthermore, future research at Wormsloe could investigate the remaining two areas on the property where rice cultivation is suggested by employing the methodology developed in this study, so as to increase the understanding of the extent of rice cultivation practices at Wormsloe.

In conclusion, the results of this study met the proposed objective of locating archaeobotanical remains of rice phytoliths in the area under investigation. The presence of domesticated rice phytoliths suggests that rice was cultivated at Wormsloe Historic Site for a short period of time in the second half of the 1800s. The results of this study provide more conclusive evidence towards the understanding of this aspect of Wormsloe's environmental history.

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Table 4.1. Physical characteristics of the cores and samples processed for phytolith analysis.

1(581) Core				
Horizon	**Depth (cm)**	**Color**	**Texture**	**Notes**
1	0-25	2.5 YR 2.5/1 (black)	sandy clay	considerable organic matter, quite plastic to the touch, brownish color
2	40-60	5BP 2.5 (bluish black)	sandy clay	considerable organic matter, greyish color
3a*	80-100	N 2.5 gley (black/gley)	clay	very clayey, less organic matter. Color is more greyish*
3b	130-150	N 2.5 gley (black/gley)	clay	very clayey, less organic matter. Color is more greyish
				* two samples were taken from the same horizon
3(583) Core				
Horizon	**Depth (cm)**	**Color**	**Texture**	**Notes**
1	0-10	5YR 2.5/1 (black)	clayey	small roots, darker
2	10-60	10 YR 3/1 (very dark gray)	sandy	organic matter
3	60-80	10 YR 4/1 (dark gray)	sandy	brownish/reddish color/soil quite brittle
4	80-110	10 YR 3/1 (very dark gray)	loamy sand	moist, plastic, easy to mould
5	110-down	10 YR 4/1 (dark gray)	sandy	very little organic matter
6(586) Core				
Horizon	**Depth (cm)**	**Color**	**Texture**	**Notes**
1	0-30	10 YR 2/1 (black)	clayey	dark color, organic matter
2	30-60	7.5 YR 4/1 (dark gray)	sandy clay	moist, more gray in color
3	60-110	10 YR 5/1 (gray)	sandy clay	color is light gray with light brown

Table 4.2. Weights of samples by soil fractions and phytolith content. Very fine sand (0.105 – 0.053 mm); coarse silt (0.053 – 0.015 mm); fine silt (0.015 – 0.002 mm).

Sample (core and horizon)	Net Weight of soil fraction (grams)	Net Weight phytolith content (grams/percentage of total)
1-1 Very fine sand (VFS)	0.875	0.006 0.68%
1-2 VFS	0.911	0.006 0.65%
1-3a VFS	1.212	0.013 1.07%
1-3b VFS	1.33	0.018 1.35%
1-1 Coarse silt	0.506	0.025 4.94%
1-2 Coarse silt	0.492	0.015 3.04%
1-3a Coarse silt	0.519	0.027 5.2%
1-3b Coarse silt	0.531	0.038 7.15%
1-1 Fine silt	0.066	0.003 4.54%
1-2 Fine silt	0.103	0.005 4.85%
1-3a Fine silt	0.121	0.033 27.27%
1-3b Fine silt	0.087	0.015 17.24%
3-1 VFS	0.726	0.003 0.41%
3-2 VFS	0.796	0.006 0.75%
3-3 VFS	0.812	0.005 0.61%
3-4 VFS	0.914	0.004 0.43%
3-5 VFS	0.9	0.006 0.66%
3-1 Coarse silt	0.541	0.034 6.28%
3-2 Coarse silt	0.475	0.171 36%
3-3 Coarse silt	0.398	0.023 5.77%
3-4 Coarse silt	0.391	0.023 5.88%
3-5 Coarse silt	0.342	0.03 8.77%
3-1 Fine silt	0.112	0.002 1.78%
3-2 Fine silt	0.09	0.004 4.44%
3-3 Fine silt	0.069	0.002 2.89%
3-4 Fine silt	0.064	0.003 4.68%
3-5 Fine silt	0.043	0.001 2.32%
6-1 VFS	0.852	0.004 0.46%
6-2 VFS	0.899	0.003 0.33%
6-3 VFS	1.056	0.003 0.28%
6-1 Coarse silt	0.2	0.027 13.49%
6-2 Coarse silt	0.226	0.022 9.73%
6-3 Coarse silt	0.172	0.013 7.55%
6-1 Fine silt	0.053	0.001 1.88%
6-2 Fine silt	0.061	0.003 4.91%
6-3 Fine silt	0.054	0.001 1.85%

Table 4.3. Phytolith counts per sample. B: bulliform; S/R: square/recatangular; E: elongate; R/E: round/elliptical; O: others (including amorphous, epidermis, polylobate); D: diatoms; S: saddle; BI: bilobates; C: cross; SS: sponge spicules; OB: Oryza-type bulliform; OH: Oryza-type husk. * Total number of phytoliths counted on the slide.

Sample (core and horizon)	Phytolith types											
	B	S/R	E	R/E	O	D	S	BI	C	SS	OB	OH	TOT*
1-1 VFS	53	139	19	9	76	1	2	0	0	1	2	0	300
1-2 VFS	58	117	16	12	97	0	0	0	0	0	0	1	300
1-3a VFS	43	115	26	36	78	0	1	1	0	0	2	1	300
1-3b VFS	56	109	25	29	73	0	8	0	0	0	4	1	300
1-1 Coarse	83	133	19	24	40	1	0	0	0	0	11	2	300
1-2 Coarse	91	111	26	25	46	0	0	0	0	1	8	2	300
1-3a Coarse	64	121	30	35	47	1	1	0	0	1	10	0	300
1-3b Coarse	54	88	26	38	91	0	3	0	0	0	12	4	300
1-1 Fine silt	15	48	25	72	129	6	4	0	0	1	0	0	300
1-2 Fine silt	19	58	29	65	124	1	4	0	0	0	0	3	300
1-3a Fine silt	23	43	31	73	122	1	5	2	0	0	5	1	300
1-3b Fine silt	10	58	34	73	119	0	5	0	0	1	0	2	300
3-1 VFS	55	106	25	36	75	2	0	0	0	1	1	1	300
3-2 VFS	71	113	35	42	38	0	0	1	0	0	0	1	300
3-3 VFS	63	143	20	28	45	0	0	0	0	1	0	0	300
3-4 VFS	67	120	38	23	46	0	0	0	0	6	1	2	300
3-5 VFS	47	115	28	39	71	0	0	0	0	0	2	1	300
3-1 Coarse	62	128	7	36	65	2	0	0	0	0	6	1	300
3-2 Coarse	37	105	26	37	93	0	2	0	0	0	4	2	300
3-3 Coarse	53	137	20	34	56	0	0	0	0	0	3	0	300
3-4 Coarse	52	115	19	38	76	0	0	0	0	0	7	2	300
3-5 Coarse	46	95	13	32	113	0	1	0	0	0	5	1	300
3-1 Fine silt	12	56	32	51	142	4	3	0	0	0	1	1	300
3-2 Fine silt	14	77	33	47	121	8	0	0	0	0	0	2	300
3-3 Fine silt	11	70	21	59	135	0	4	0	0	0	0	0	300
3-4 Fine silt	24	61	28	62	122	0	3	0	0	0	0	0	300
3-5 Fine silt	8	37	7	20	87	0	1	1	0	0	0	0	161
6-1 VFS	45	97	24	45	83	5	1	0	0	0	3	1	300
6-2 VFS	54	98	17	18	111	1	1	0	0	0	0	0	300
6-3 VFS	59	97	19	53	69	0	1	0	0	2	1	1	300
6-1 Coarse	51	113	20	34	78	3	1	0	0	0	5	0	300
6-2 Coarse	59	124	12	45	59	0	1	0	0	0	3	0	300
6-3 Coarse	34	101	14	29	122	0	0	0	0	0	3	0	300
6-1 Fine silt	10	73	17	69	117	11	3	0	0	0	0	0	300
6-2 Fine silt	2	10	12	20	28	0	1	0	0	0	0	0	72
6-3 Fine silt	2	8	1	4	3	0	2	0	0	0	0	0	20

Table 4.4. Measurements and criteria of Wormsloe domesticated rice bulliforms.

Soil core and horizon	Depth (cm)	Scales	VL (a+b)	HL (d)	LL (e)	a	b	c	a/b ratio	L/W ratio	ID
1-1 VFS	0-25	9	41.3	44.82	9.49	17.05	24.25	22.53	0.703092784	0.921463632	a
1-1 COARSE SILT	0-25	9	36.64	42.24	9.13	16.04	20.6	19.93	0.778640777	0.867424242	b
1-2 COARSE SILT	40-60	10	39	42.87	5.95	18.19	20.81	19.09	0.874098991	0.909727082	c
1-3a COARSE SILT	80-110	12	52.05	50.03	7.37	18.61	33.44	20.53	0.556519139	1.040375775	d
1-3a COARSE SILT	80-110	9	35.03	41.17	8.16	17.36	17.67	18.11	0.98245614	0.850862278	e
1-3a COARSE SILT	80-110	12	46.22	44.16	6.98	22.59	23.63	17.75	0.955988151	1.046648551	f
1-3a COARSE SILT	80-110	10	45.2	41.96	7.85	20.92	24.28	25.33	0.861614498	1.077216397	g
1-3a COARSE SILT	80-110	10	38.52	40.91	6.71	14.79	23.73	16.4	0.623261694	0.941579076	h
1-3a FINE SILT	80-110	12	35.74	35.3	2.51	17.28	18.46	11.46	0.936078007	1.012464589	i
1-3b COARSE SILT	130-150	10	41.09	42.52	7.55	16.11	24.98	19.49	0.644915933	0.966368768	j
1-3b COARSE SILT	130-150	14	44.66	49.42	8.55	18.9	25.76	26.22	0.733695652	0.90368272	k
1-3b COARSE SILT	130-150	11	38.91	39.29	5.96	18.91	20	17.86	0.9455	0.990328328	l
1-3b COARSE SILT	130-150	11	48.95	48.07	8.37	21.08	27.87	24.92	0.756368855	1.018306636	m
3-1 COARSE SILT	0-10	13	47.28	44.33	8.04	22.07	25.21	18.97	0.875446251	1.066546357	n
3-1 COARSE SILT	0-10	14	37.45	38.67	6.7	18.61	18.84	17.84	0.987791932	0.968450996	o
3-1 COARSE SILT	0-10	9	40.35	39.25	9.7	18.88	21.47	16.75	0.879366558	1.028025478	p
3-2 COARSE SILT	10-60	10	41.48	43.4	6.92	19.76	21.72	18.55	0.909760589	0.955760369	q
3-2 COARSE SILT	10-60	10	44.68	46.33	7.66	20.44	24.24	22.34	0.843234323	0.964385927	r
3-4 COARSE SILT	80-110	11	43.89	46.38	9.21	19.8	24.09	23.44	0.821917808	0.946313066	s
3-4 COARSE SILT	80-110	10	55.59	48.29	8.76	24.37	31.22	15.62	0.780589366	1.151170014	t
6-1 VFS	0-30	9	70.93	80.19	11.23	33.35	37.58	32.86	0.887440128	0.884524255	u
6-1 COARSE SILT	0-30	10	47.13	50.41	10.18	23.2	23.93	11.79	0.969494359	0.934933545	v

6-1 COARSE SILT	0-30	10	38.09	42.87	6.69	17.59	20.5	19.2	0.85804878	0.8885 00117	w
6-1 COARSE SILT	0-30	9	47.76	45.1	10.8 7	20.49	27.27	18.36	0.751375138	1.0589 80044	x
6-2 COARSE SILT	30-60	10	47.83	45.62	7.51	22.04	25.79	17.48	0.854594804	1.0484 43665	y
6-3 COARSE SILT	60-110	13	47.91	47.12	9.89	18.81	29.1	22.75	0.646391753	1.0167 65705	z

Table 4.5. A subset of Table 2.4 is presented here to compare measurements of Wormsloe bulliforms VL and HL values against reference samples.

Soil horizon and fraction	Depth (cm)	ID	VL (a+b)	HL (d)	a	b	a/b ratio	L/W ratio
1-1 VFS	0-25	a	41.3	44.82	17.05	24.25	0.703093	0.921464
1-1 COARSE SILT	0-25	b	36.64	42.24	16.04	20.6	0.778641	0.867424
1-2 COARSE SILT	40-60	c	39	42.87	18.19	20.81	0.874099	0.909727
1-3a COARSE SILT	80-110	d	52.05	50.03	18.61	33.44	0.556519	1.040376
1-3a COARSE SILT	80-110	e	35.03	41.17	17.36	17.67	0.982456	0.850862
1-3a COARSE SILT	80-110	f	46.22	44.16	22.59	23.63	0.955988	1.046649
1-3a COARSE SILT	80-110	g	45.2	41.96	20.92	24.28	0.861614	1.077216
1-3a COARSE SILT	80-110	h	38.52	40.91	14.79	23.73	0.623262	0.941579
1-3a FINE SILT	80-110	i	35.74	35.3	17.28	18.46	0.936078	1.012465
1-3b COARSE SILT	130-150	j	41.09	42.52	16.11	24.98	0.644916	0.966369
1-3b COARSE SILT	130-150	k	44.66	49.42	18.9	25.76	0.733696	0.903683
1-3b COARSE SILT	130-150	l	38.91	39.29	18.91	20	0.9455	0.990328
1-3b COARSE SILT	130-150	m	48.95	48.07	21.08	27.87	0.756369	1.018307
3-1 COARSE SILT	0-10	n	47.28	44.33	22.07	25.21	0.875446	1.066546
3-1 COARSE SILT	0-10	o	37.45	38.67	18.61	18.84	0.987792	0.968451
3-1 COARSE SILT	0-10	p	40.35	39.25	18.88	21.47	0.879367	1.028025
3-2 COARSE SILT	10-60	q	41.48	43.4	19.76	21.72	0.909761	0.95576
3-2 COARSE SILT	10-60	r	44.68	46.33	20.44	24.24	0.843234	0.964386
3-4 COARSE SILT	80-110	s	43.89	46.38	19.8	24.09	0.821918	0.946313
3-4 COARSE SILT	80-110	t	55.59	48.29	24.37	31.22	0.780589	1.15117
6-1 VFS	0-30	u	70.93	80.19	33.35	37.58	0.88744	0.884524
6-1 COARSE SILT	0-30	v	47.13	50.41	23.2	23.93	0.969494	0.934934
6-1 COARSE SILT	0-30	w	38.09	42.87	17.59	20.5	0.858049	0.8885
6-1 COARSE SILT	0-30	x	47.76	45.1	20.49	27.27	0.751375	1.05898
6-2 COARSE SILT	30-60	y	47.83	45.62	22.04	25.79	0.854595	1.048444
6-3 COARSE SILT	60-110	z	47.91	47.12	18.81	29.1	0.646392	1.016766
MEAN			44.37231	45.41231				0.979202
CGold (30)			78.33	71.45				1.09
Brazil (49)			29.09	28.16				1.03
China (20)			38.4	40				0.97

Table 4.6. Mean values (μm) of double-peaked phytoliths from Wormsloe and reference specimens.

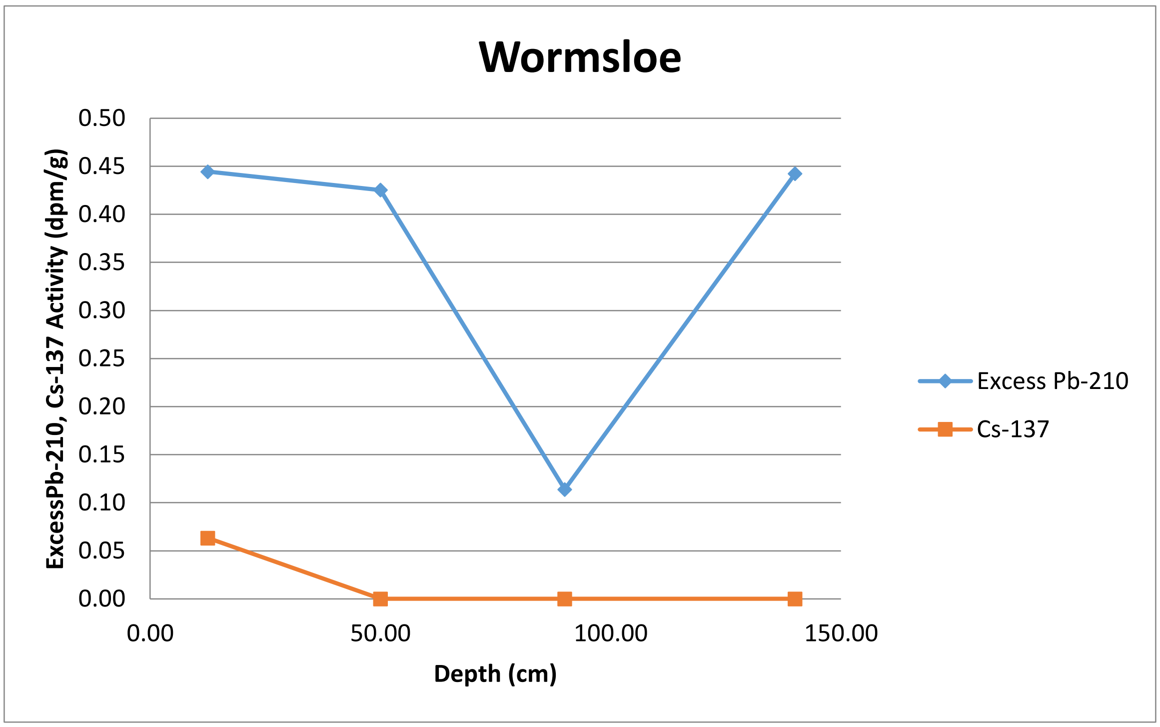
Specimens	Double-peaked measurements (μm)			
	TW	MW	CD	H
Wormsloe	11.9	16.03	2.02	8.19
Sapelo	57.24	92.66	5.88	29.79
Athens	49.64	79.39	5.07	31.16
China	29.1	44	5.2	33.6

Table 4.7. Distribution of domesticated bulliforms and double-peaked Wormsloe phytoliths. Wild double-peaked are also present for comparison.

Sample	Dom. Bull.	Dom. Husks	Wild Husks	Indeterminate Husks	Depth (cm)
1-1	2	1	1	0	0-25
1-2	1	4	2	0	40-60
1-3a	6	1	0	1	80-110
1-3b	4	3	3	1	130-150
3-1	3	1	2	0	0-10
3-2	2	1	4	0	10-60
3-3	0	0	0	0	60-80
3-4	2	1	3	0	80-110
3-5	0	1	1	0	110-down
6-1	4	0	1	0	0-30
6-2	1	0	0	0	30-60
6-3	1	0	1	0	60-110
TOT	26	13	18	2	

Table 4.8. Radionuclide analysis and graph on the Wormsloe samples (Alexander, pers. comm.).

Interval (cm)	Depth (cm)	Pb_{tot} (dpm/g)	Pb_{tot} error	Pb_{xs} (dpm/g)	Pb_{xs} error	Ra-226 (dpm/g)	Ra-226 error	Cs-137 (dpm/g)	Cs-137 error
0-25	12.50	1.26	0.06	0.44	0.08	0.81	0.05	0.06	0.01
40-60	50.00	1.23	0.06	0.43	0.09	0.80	0.06	0.00	0.00
80-100	90.00	1.04	0.04	0.11	0.06	0.92	0.04	0.00	0.00
130-150	140.00	1.35	0.07	0.44	0.09	0.91	0.06	0.00	0.00



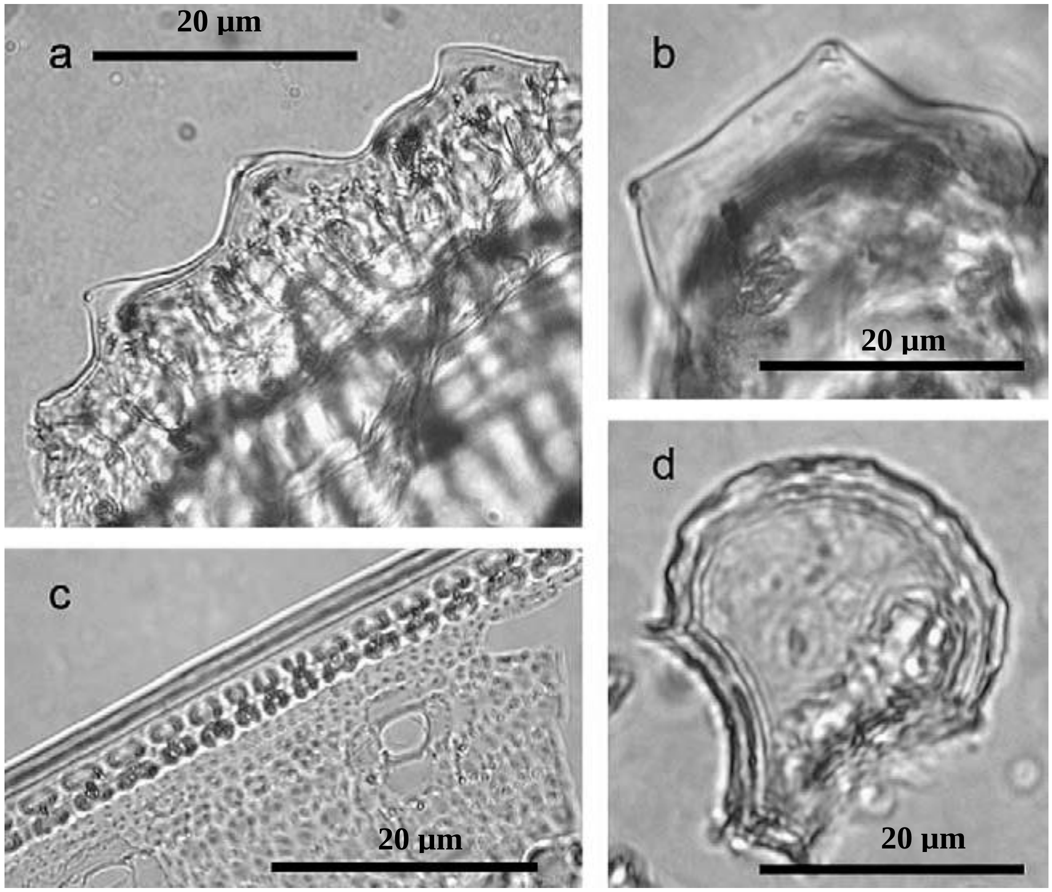


Figure 4.1. Rice phytoliths. (a) phytoliths from the husk; (b) double-peaked phytolith from the husk; (c) parallel bilobates from the leaf and stem; (d) bulliform from the leaf and stem. Scale bar is 20 µm. (adapted from Harvey and Fuller, 2005).

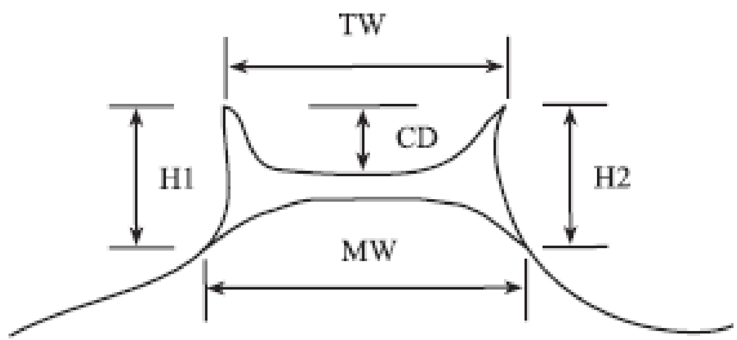


Figure 4.2. Double-peaked phytolith measurements (Itzstein-Davey *et al.*, 2007).

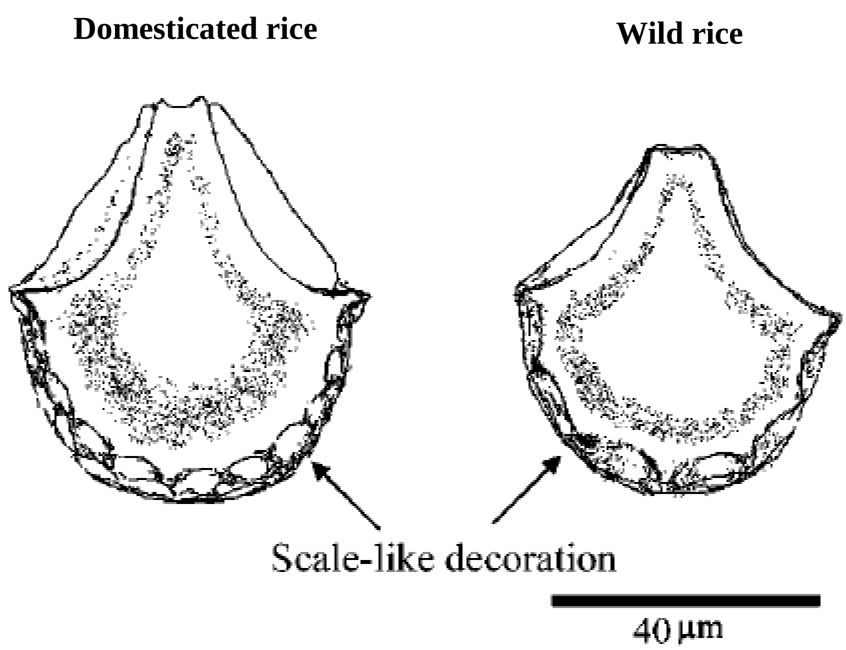


Figure 4.3. Rice bulliforms from domesticated and wild species showing the difference in the number of scale-like decorations (Lu *et al.*, 2002).

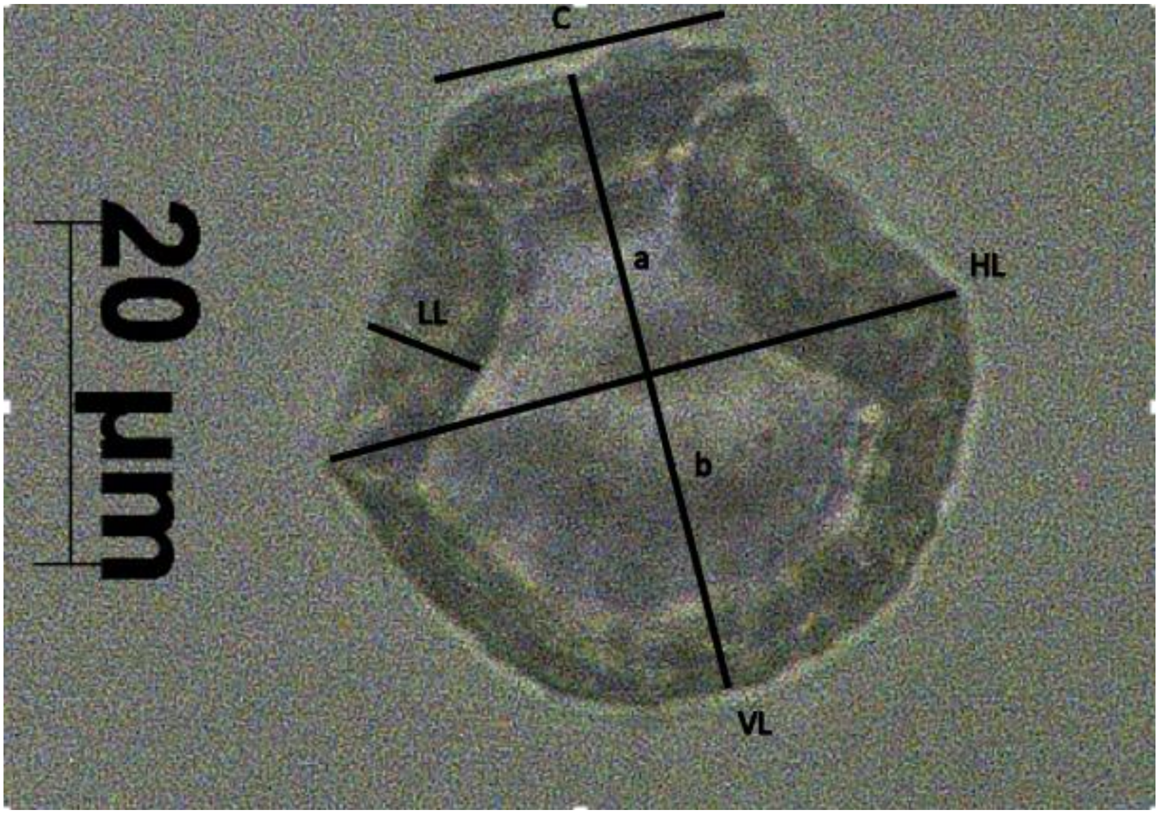


Figure 4.4. Bulliform phytolith measurements.

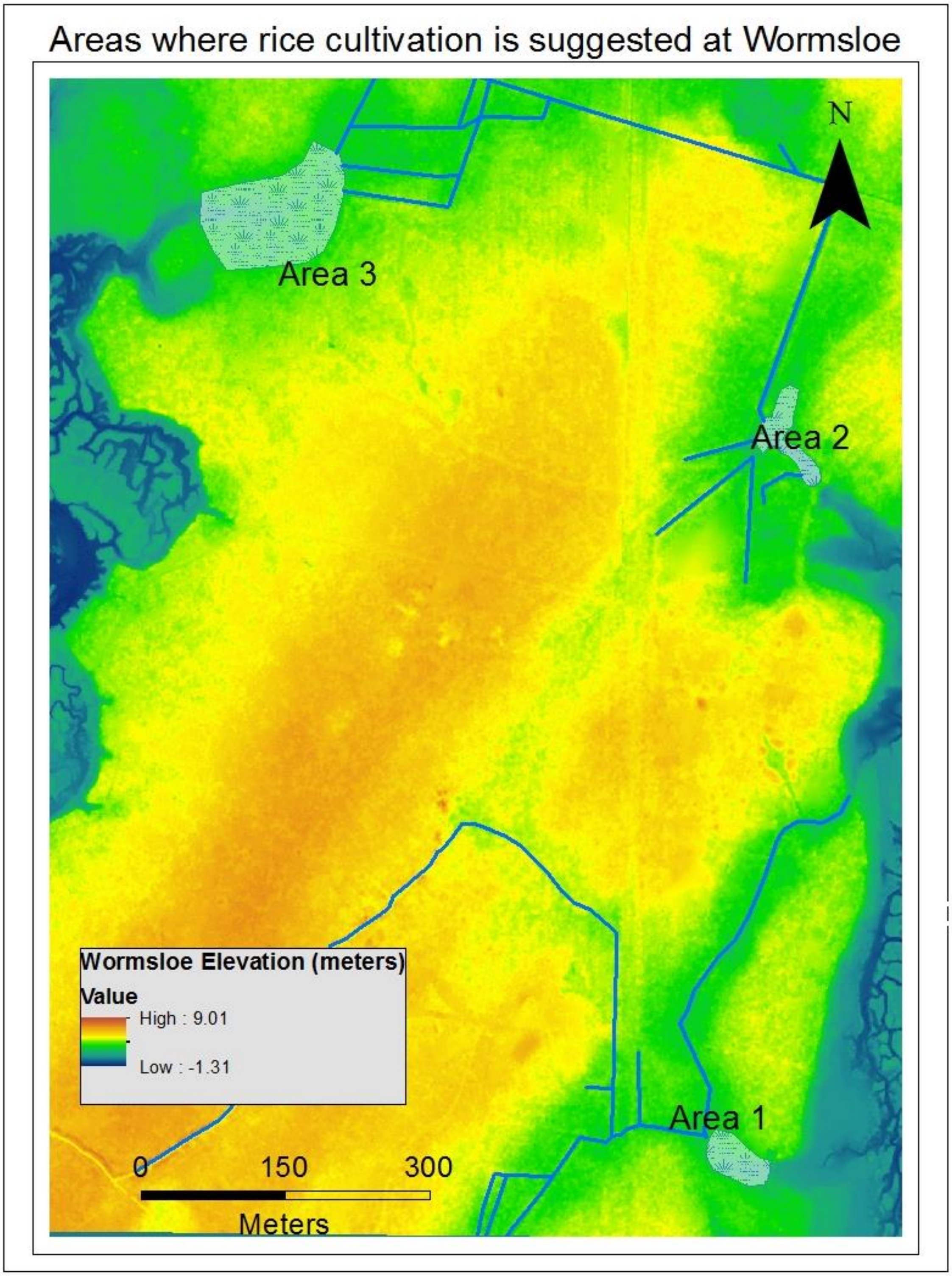


Figure 4.5. LiDAR elevation map of Wormsloe showing the areas deemed suitable for rice cultivation.

Figure 4.6. Study area looking east.

Figure 4.7. Soil core extraction at Wormsloe: soil core on a metal gutter (A); the unconsolidated marsh sediment of one of the cores (B).

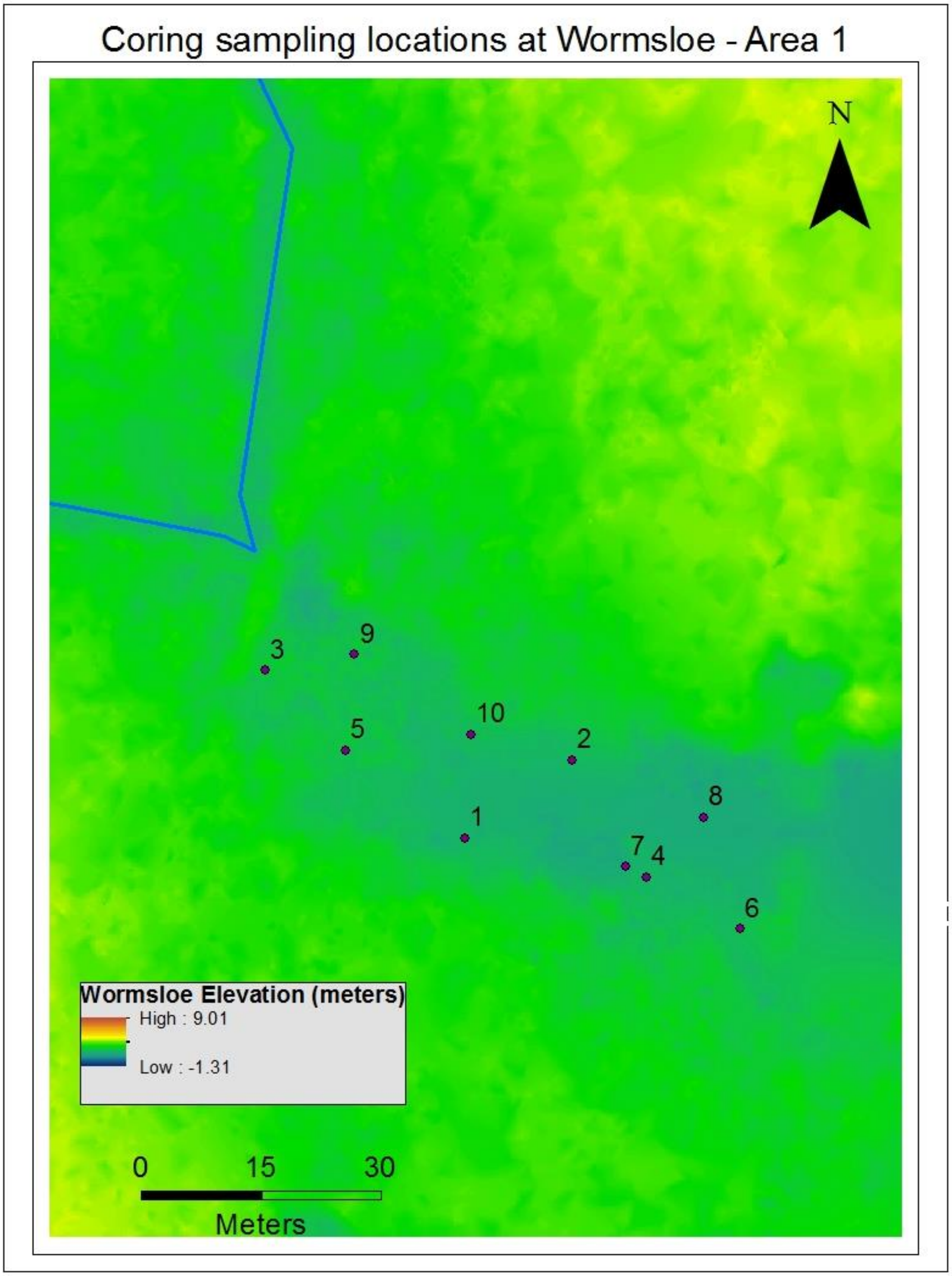


Figure 4.8. Coring sampling locations in the study area at Wormsloe.

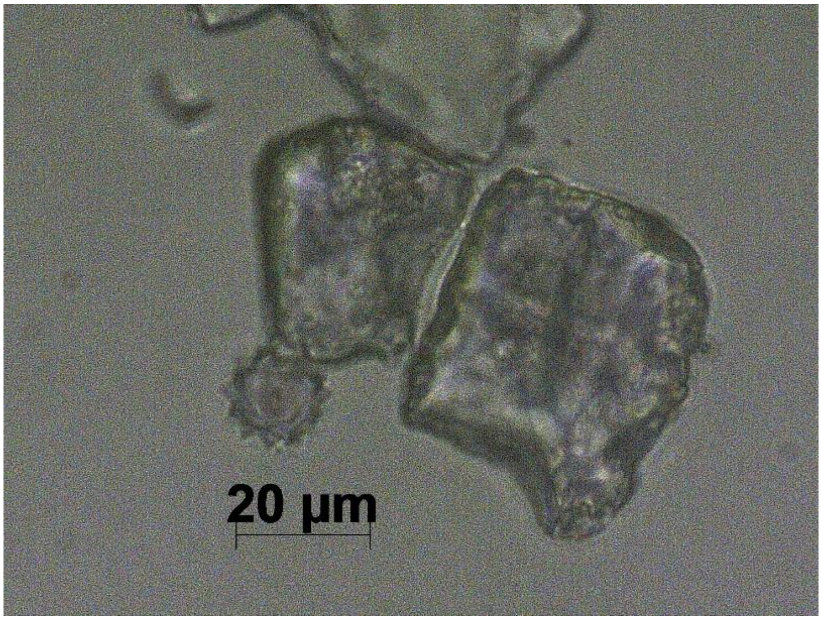
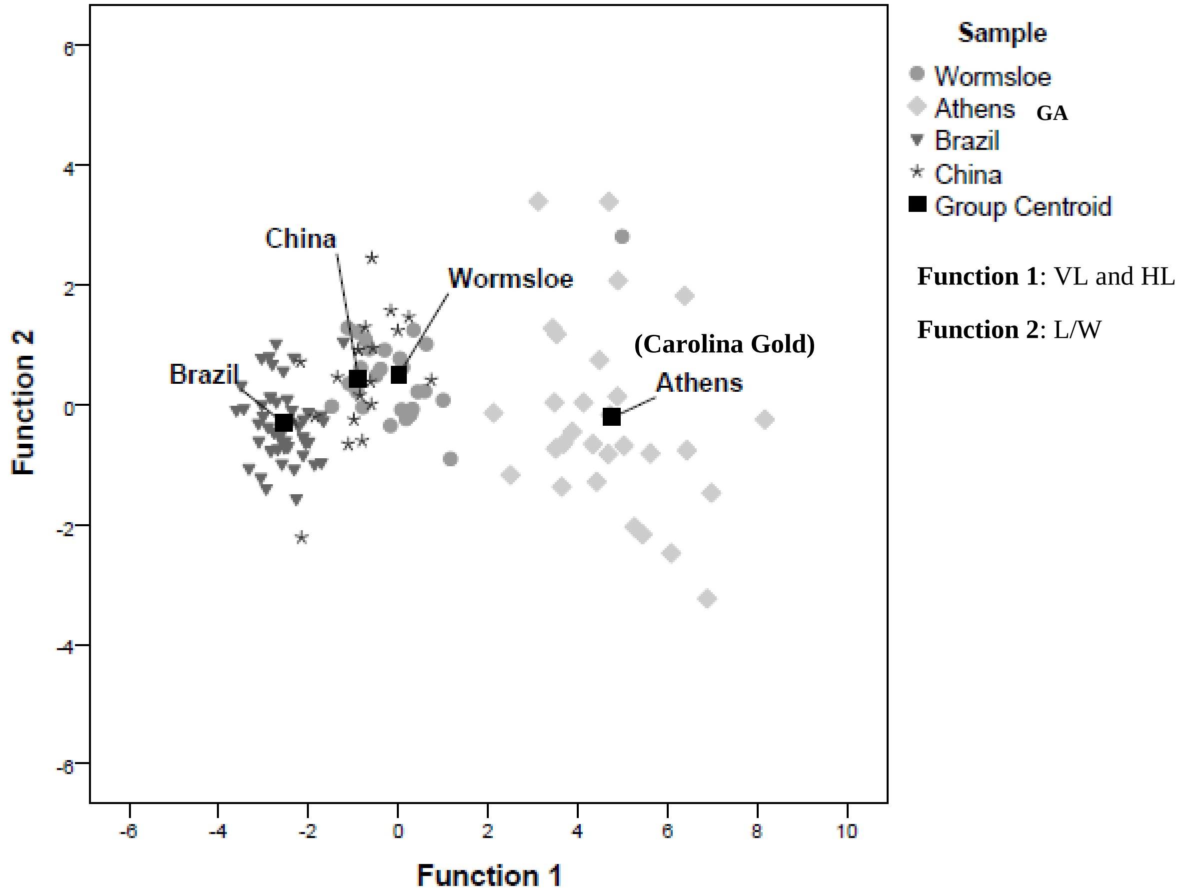
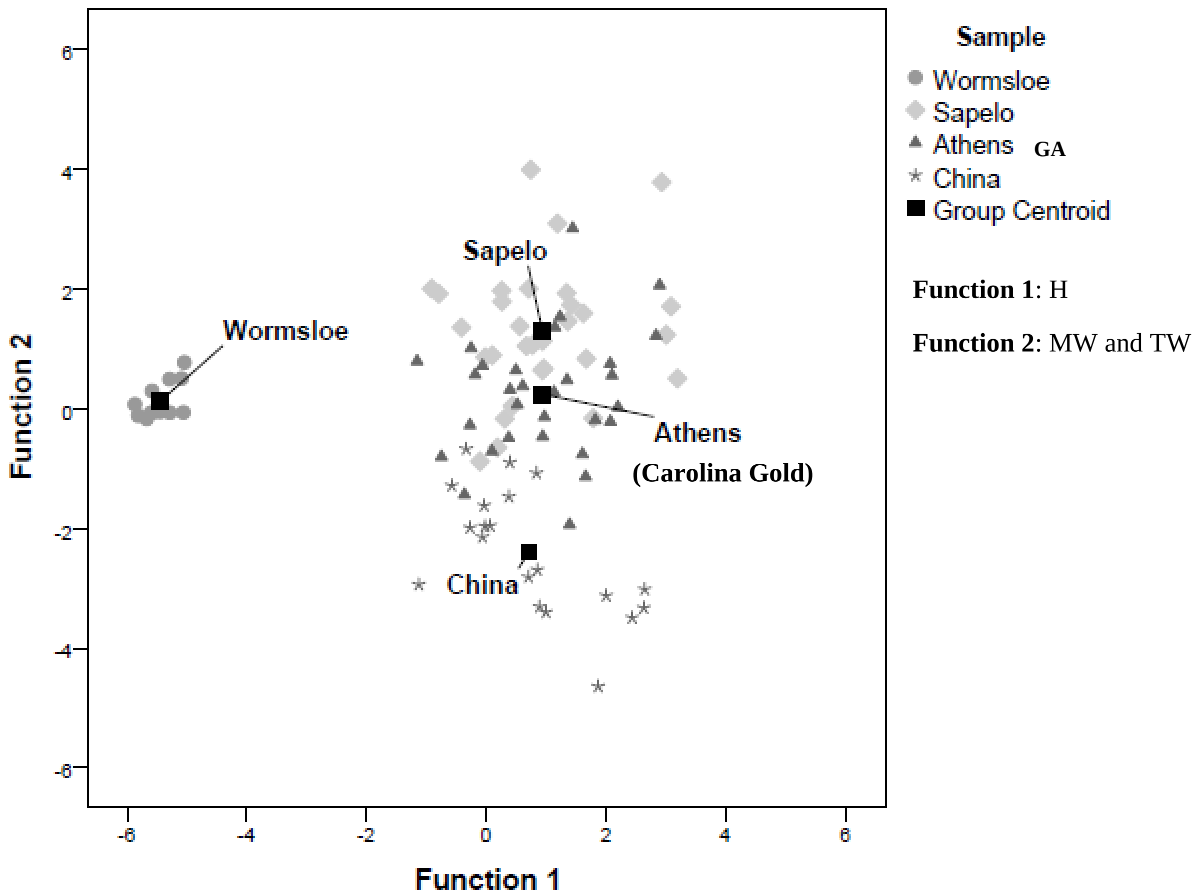


Figure 4.9. Phytolith assemblage from sample 3-1 coarse silt. The round, spiked phytolith corresponds to *Sabal minor* (saw palmetto).



	Predicted Group Membership			
	Wormsloe	Athens	Brazil	China
Wormsloe	57.7	3.8	0.0	38.5
Athens, GA	6.7	93.3	0.0	0.0
Brazil	0.0	0.0	98.0	2.0
China	25.0	0.0	20.0	55.0

Figure 4.10. Discriminant function analysis plot showing the overall relationship between domesticated bulliform phytoliths (top); cross validation matrix showing percentages of predicted group membership between bulliform samples (bottom).



	Predicted Group Membership			
	Wormsloe	Sapelo	Athens	China
Wormsloe	100.0	0.0	0.0	0.0
Sapelo	0.0	70.0	30.0	0.0
Athens, GA	0.0	33.3	56.7	10.0
China	0.0	0.0	15.0	85.0

Figure 4.11. Discriminant function analysis plot showing the overall relationship between domesticated double-peaked phytoliths (top); cross validation matrix showing percentages of predicted group membership between double-peaked samples (bottom).

Figure 4.12. Brazilian rice bulliforms. Scale bar is 50 µm.

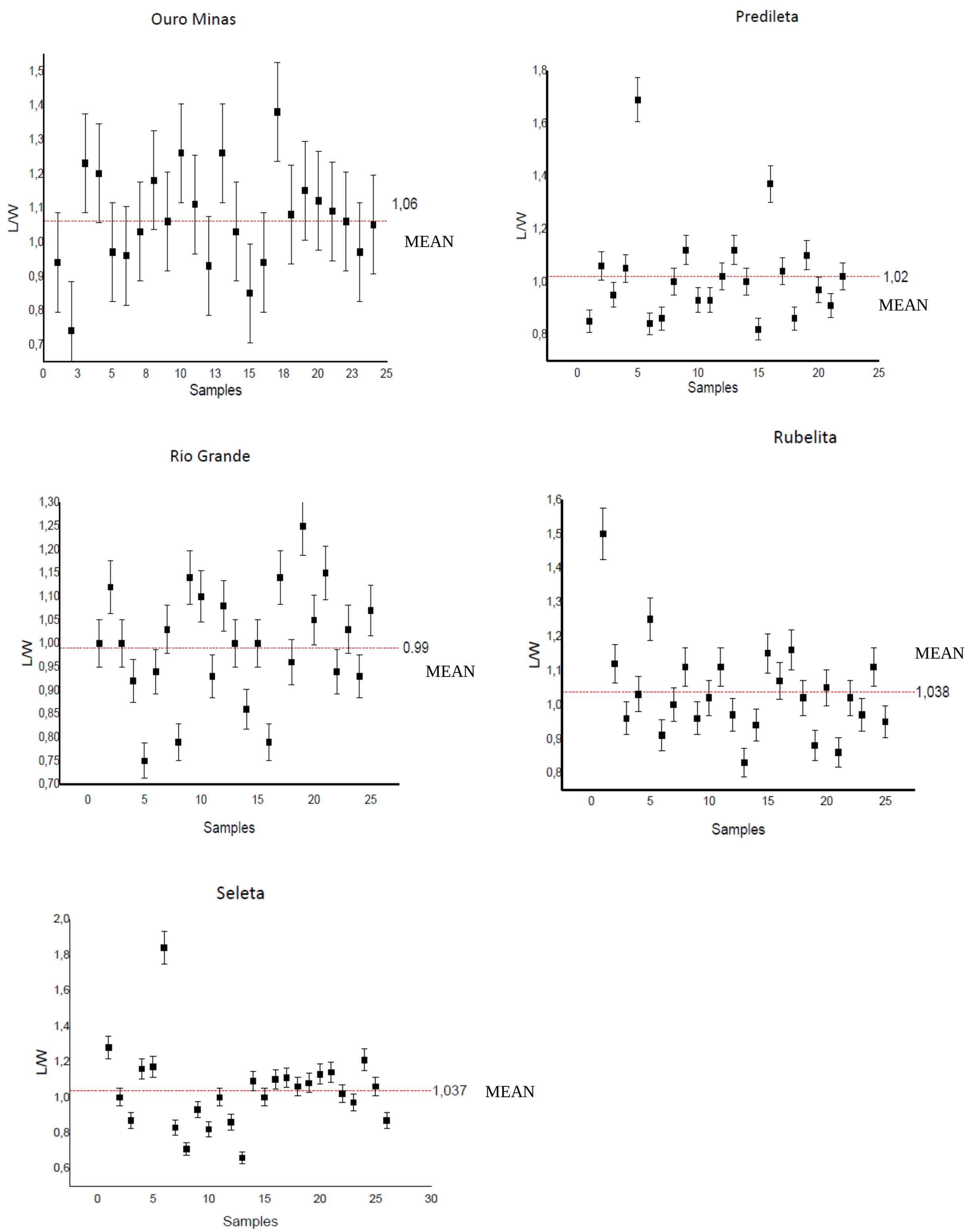


Figure 4.13. L/W ratio for Brazilian rice bulliforms, and mean L/W values.

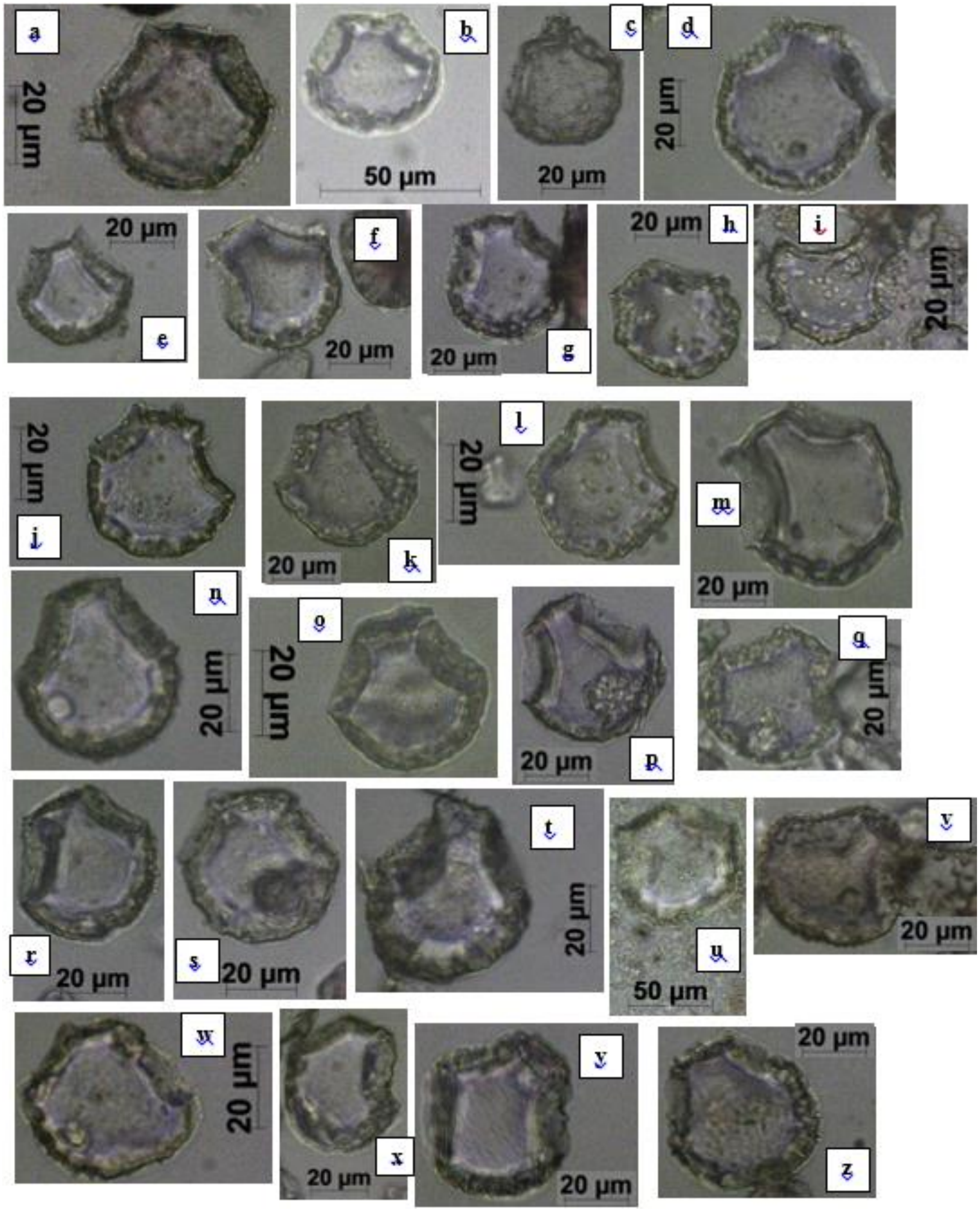


Figure 4.14. Domesticated bulliforms from Wormsloe.

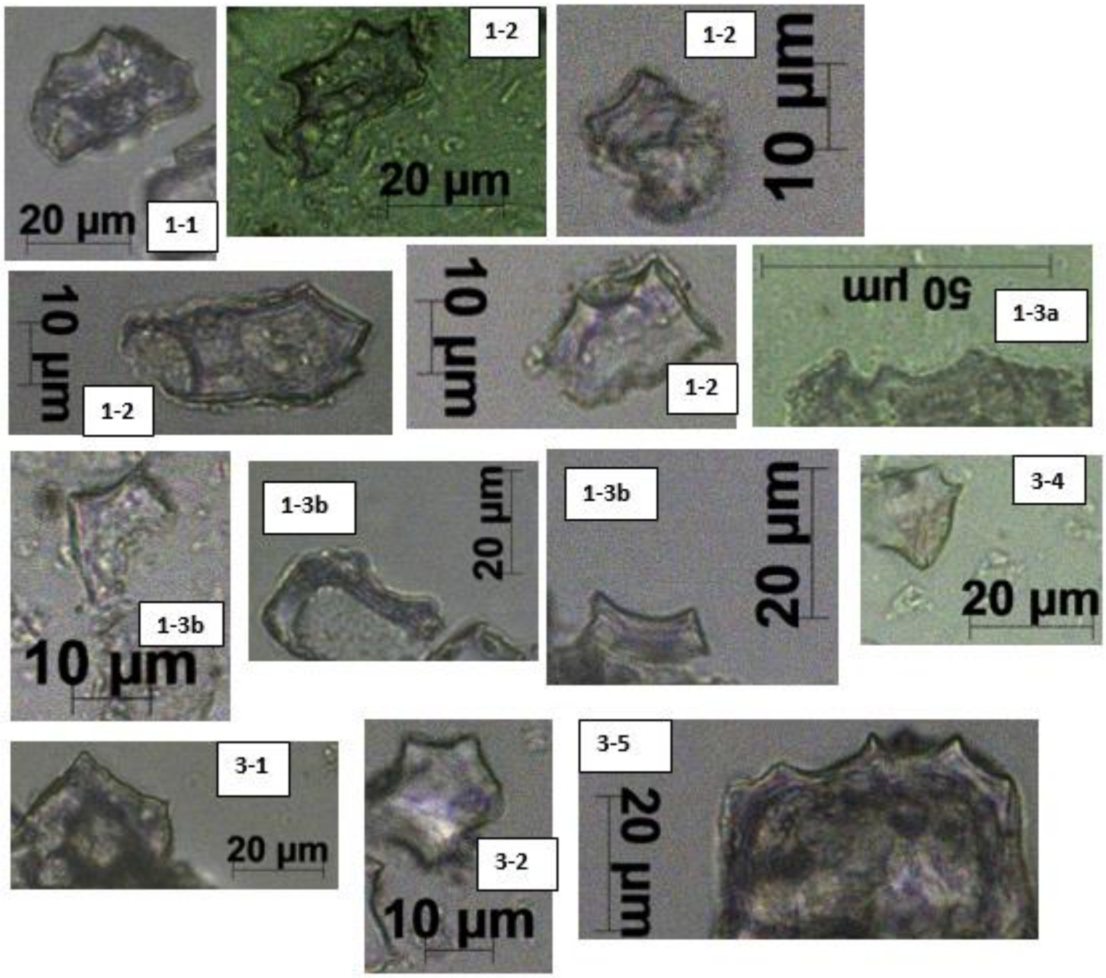


Figure 4.15. Domesticated double-peaked phytoliths from Wormsloe.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 SUMMARY OF FINDINGS

The main purpose of this study was to perform a multiscalar investigation of Wormsloe Historic Site in order to understand whether rice was historically cultivated on site, as this represented one aspect of Wormsloe's environmental history which needed to be clarified. A multidisciplinary and multiscalar approach proved crucial for the successful completion of this study, as it allowed us to understand the problem from a variety of perspectives as well as different approaches of analysis. In particular, this study benefited from fields such as environmental history, geoarchaeology, geography, archaeobotany, and archaeology, as well as scales of analyses from microscopic to local to regional. In particular, the present study had the following objectives:

1. Increase the current understanding of Wormsloe's environmental history, and improve its cultural, archaeological, and historical significance within the context of known historical South Carolina – Georgia coast rice cultivation.
2. Perform detailed topographic mapping and 3D reconstruction of the area where rice cultivation is suggested.
3. Investigate the presence of archaeological remains of rice in the soil.

The first objective approached the problem from a regional perspective through the analysis of former rice fields across South Carolina and Georgia. In particular, many different types of known historical rice fields and environmental settings were inspected so as to better place the experience of rice cultivation at Wormsloe in terms of historical, cultural, and environmental contexts. The presence of similarities between Wormsloe and historical rice fields in terms of sites chosen for cultivation, scales of agricultural efforts, and historical context suggests the presence of subsistence rice agriculture at Wormsloe.

The second objective involved the investigation of the area at the local scale by means of terrestrial laser scanning and imagery acquired by unmanned aerial systems (UAS). Despite some limitations, the creation of a high resolution digital elevation model (DEM) of 20 cm post spacing using terrestrial LiDAR allowed us to obtain a fairly good understanding of the micro topography of the salt marsh. However, the 3D data obtained from the use of UAS and Structure from Motion (SfM) photogrammetry provided higher spatial detail (a point cloud of 3-4 mm point spacing), and allowed the measurement of the topography of the site with higher detail. Furthermore, the use of UAS permitted a 3D reconstruction of the salt marsh at high and low tide conditions, as well as a geovisualization of the area flooding during tidal surges. The comparison between topographic measurements taken from the study area and those taken from known former rice fields revealed the compatibility of Wormsloe with rice cultivation. Finally, UAS revealed a greater reliability and flexibility than terrestrial laser scanning in obtaining high resolution topographic measurements, as the employment of terrestrial laser scanning displayed some limitations in mapping the bare earth as well as topographic features.

Finally, the third objective involved the microscopic analysis of the area using an archaeobotanical approach aimed at investigating the presence of persistent rice remains in the soil. The results indicate that 38.5% of bulliform phytoliths from Wormsloe can be misclassified with the China domesticated rice bulliform phytoliths taken as reference samples in this study; the results also indicate that the L/W ratio from Wormsloe bulliforms is significantly similar to Brazil and China rice speciments. These results suggest that the area was used for the cultivation of rice, probably for a short period of time. The results for the double-peaked phytoliths from Wormsloe, on the other hand, indicate that they differ significantly from double-peaked phytoliths from known domesticated rice specimens. The presence of wild rice phytoliths also suggests that the area has been characterized by the presence of rice relatives, such as rice cutgrass or wild rice, or that local wild rice was cultivated instead. Radionuclide analysis performed on soil samples also seemed to suggest that the soil column might be older than 100 years, thus placing the experience of rice cultivation at Wormsloe around the turn of the 20th century.

As demonstrated in Chapter 2, rice cultivation at Wormsloe was most likely of subsistence nature, and was performed for short periods of time, probably during the 1870s, when sharecroppers cultivated crops on site for themselves and their families. Subsistence rice agriculture, in fact, was a practice common to many former slaves on Sapelo and Daufuskie Islands, who cultivated rice in a variety of environmental settings, sometimes without the need for embankments or canals. Furthermore, the use of salt marshes for rice cultivation was practiced at Drayton Hall and Skidaway Island, so that the salt marsh at Wormsloe might have been used in a similar fashion to cultivate the crop. The rice field at Wormsloe would have been delimited by two dikes (still existing), and would have been flooded with freshwater coming from a reservoir through the still existing ditch, as shown in a historical map from 1890. The presence of rice cultivation at Wormsloe, therefore, increases the current cultural, historical, and archaeological significance of the site, and provides more conclusive evidence towards understanding this particular aspect of Wormsloe's environmental history.

5.2 SCIENTIFIC SIGNIFICANCE

As mentioned above, this study provides more conclusive evidence related to the presence of historical rice cultivation at Wormsloe. Up until now, historical rice cultivation at Wormsloe has always been dismissed due to a number of factors, such as the presence of freshwater sources, embankments, and records detailing its cultivation. With regard to the presence of freshwater, for instance, historical maps of the Isle of Hope indicate that freshwater would have been available in the forms of artesian wells, and natural depressions collecting rainfall. Similarly to what other subsistence rice farmers did on other sea islands along the Georgia and South Carolina coast, therefore, rice farmers at Wormsloe would have used those freshwater sources to cultivate the crop following the inland cultivation system. Furthermore, up until now, the information related to rice cultivation at Wormsloe included the fact that it might have happened in the form of upland cultivation (Swanson, 2012), and that someone in 1879 cultivated 510 pounds of rice, although no additional information on where, how, and for how long he cultivated the crop was included. This study, therefore, provides further evidence on where and how rice cultivation was performed at Wormsloe through archaeobotanical analysis, accurate topographic mapping, and ground reconnaissance of former rice fields across the Low Country. This study has contributed to identifying not only the area where

Peter Campbell (and perhaps other farmers in different years) cultivated the crop, but also the technology and the method of cultivation involved in rice production at Wormsloe. Ultimately, this study both augments Wormsloe's current cultural landscape resources, and improves Wormsloe's understanding of its environmental history, thus increasing the site's current cultural, historical, and archaeological significance.

5.3 FUTURE RESEARCH

Initially, the assessment of what areas might be indicative of rice cultivation at Wormsloe included three areas (Figure 5.1). However, given the limited resources available for this study, only one area, Area 1, was investigated, and evidence of rice cultivation was found. Therefore, given the presence of similar topographies and landscape features, future research endeavors should focus on investigating the other two areas on the property as being promising to reveal additional evidence related to rice cultivation at Wormsloe. This interpretation is supported by the fact that the other two areas are low lying wetlands with drainage ditches that connect them to freshwater sources – such as natural depressions located at higher altitudes (Figure 5.2). These areas could have been used in a similar fashion to cultivate rice according to the inland cultivation system. In particular, these two areas could have been used by sharecroppers living on site in the second half of the 1800s in addition to the one analyzed in this study, so as to sustain more families and/or obtain more rice to sell it to the local markets in Savannah.

Future studies should also benefit from the use of advanced soil coring extraction techniques, such as freeze corers, which employ liquid nitrogen to extract frozen soil cores in which the stratigraphy is being maintained, thus improving interpretation. Furthermore, the addition in the comparative analysis of phytoliths of wild rice species would improve the interpretation of the rice phytoliths found at Wormsloe.

It is hoped that the methods and approaches used in this study will assist researchers in the future who seek further evidence of rice cultivation on the coastal islands and aim to complete our understanding of the historical importance of rice in our nation's history. The increasing number and frequency of extreme events such as floods, hurricanes, and tornadoes, calls for an even greater attention to the identification, documentation, and preservation of cultural resources such as historical rice fields located in legacy landscapes along the South Carolina and Georgia coasts, before they will be lost forever.

5.4. REFERENCES

Swanson, D.A., 2012. *Remaking Wormsloe Plantation: The Environmental History of a Lowcountry Landscape,* University of Georgia Press,

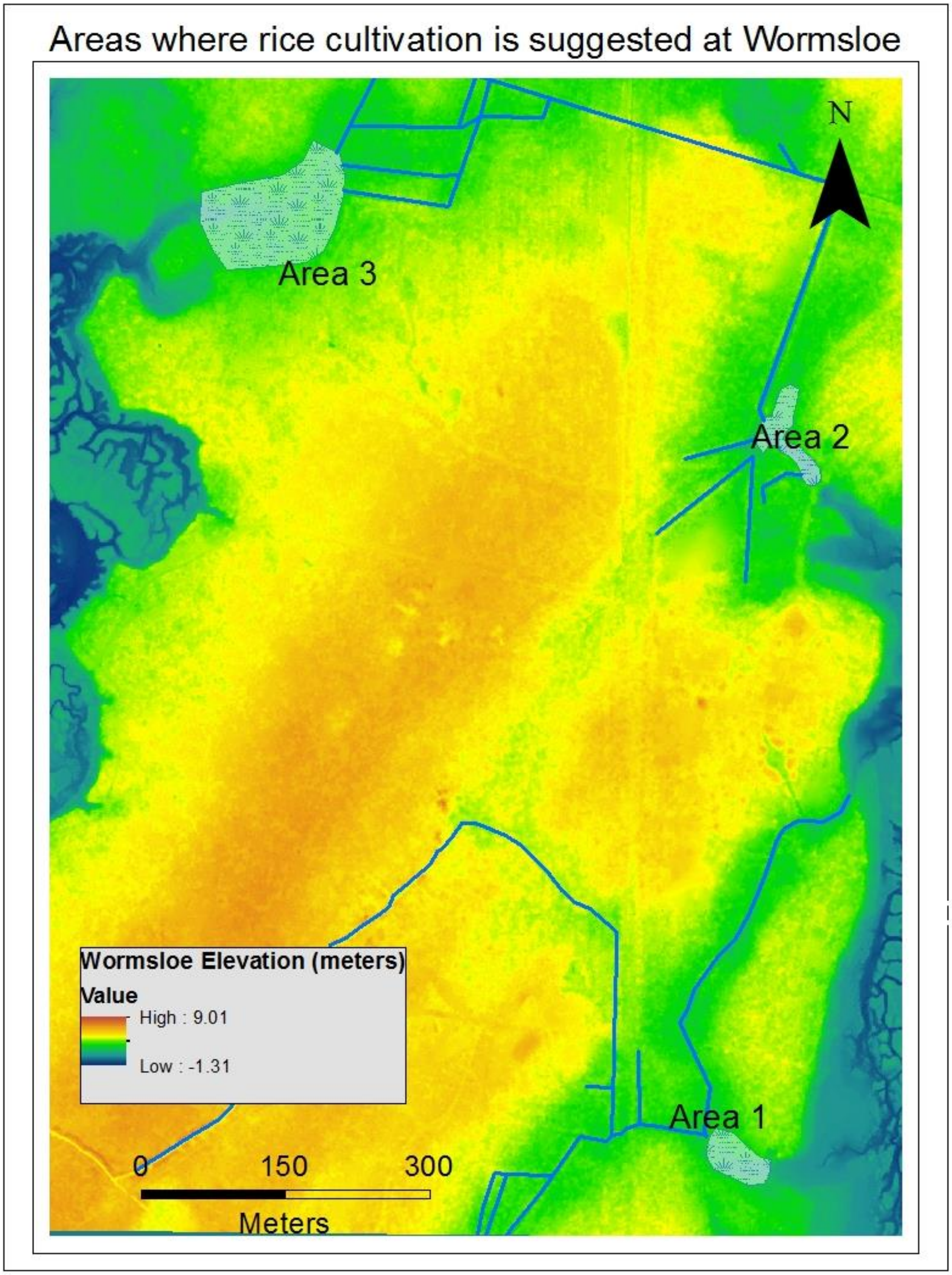


Figure 5.1. LiDAR map showing areas indicative of rice cultivation at Wormsloe.

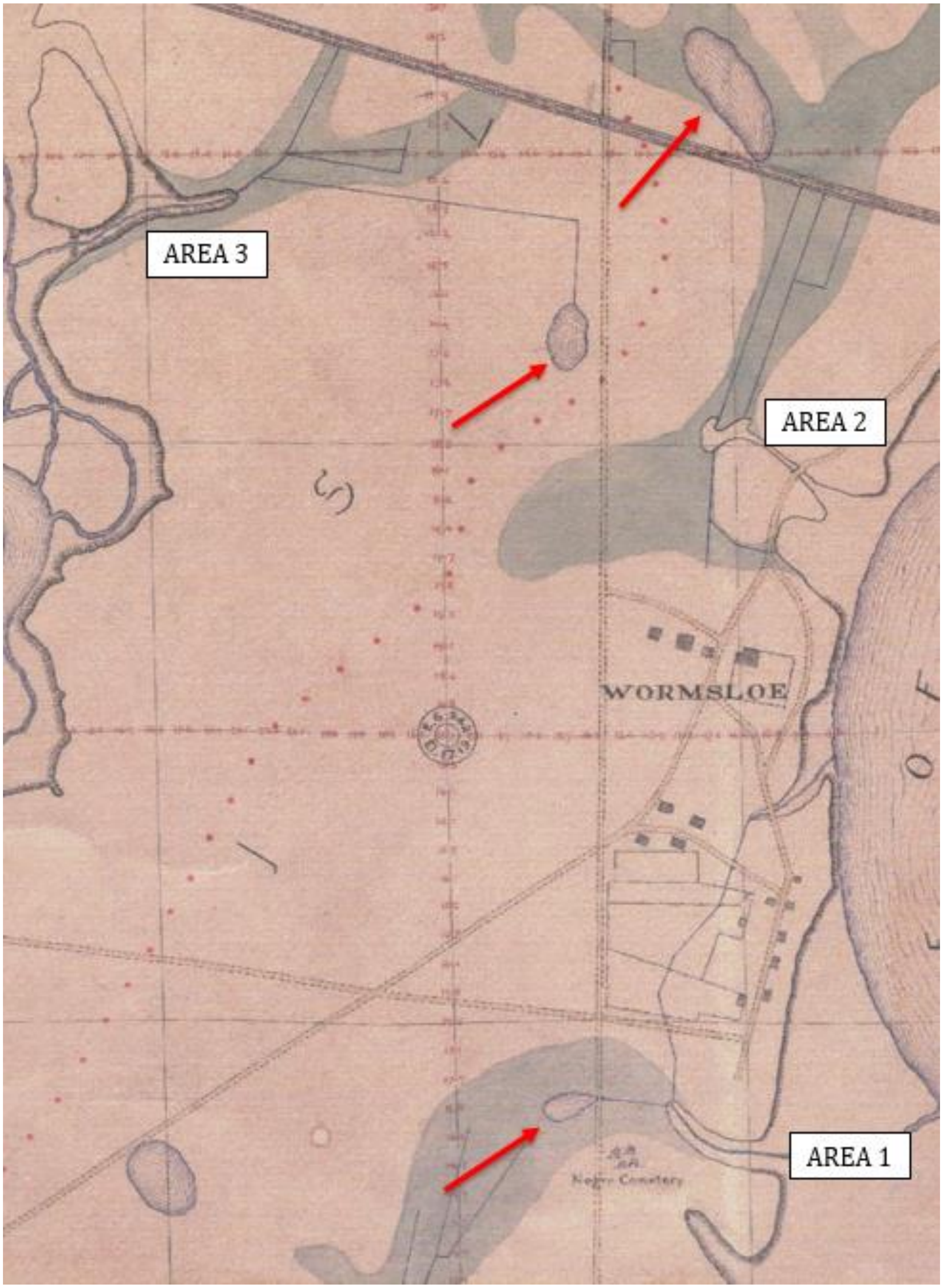


Figure 5.2. 1890 Blanford map showing freshwater reservoirs for rice cultivation at Wormsloe.

APPENDIX A

PHYTOLITH MANOVA STATISTICAL ANALYSIS

1. BULLIFORM PHYTOLITHS

a. Multivariate Analysis

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[d]
Intercept	Pillai's Trace	.998	20488.108[b]	3.000	119.000	.000	.998	61464.323	1.000
	Wilks' Lambda	.002	20488.108[b]	3.000	119.000	.000	.998	61464.323	1.000
	Hotelling's Trace	516.507	20488.108[b]	3.000	119.000	.000	.998	61464.323	1.000
	Roy's Largest Root	516.507	20488.108[b]	3.000	119.000	.000	.998	61464.323	1.000
Sample	Pillai's Trace	1.011	20.500	9.000	363.000	.000	.337	184.503	1.000
	Wilks' Lambda	.094	53.002	9.000	289.765	.000	.546	348.352	1.000
	Hotelling's Trace	8.563	111.952	9.000	353.000	.000	.741	1007.567	1.000
	Roy's Largest Root	8.430	340.028[c]	3.000	121.000	.000	.894	1020.085	1.000

a. Design: Intercept + Sample
b. Exact statistic
c. The statistic is an upper bound on F that yields a lower bound on the significance level.
d. Computed using alpha = .05

b. Post Hoc Analysis

Since the assumption of equal variance was only met for L/W, the used Games-Howell Post Hoc for VL and HL, while we used Tukey HSD for L/W

Dependent Variable			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
VL							
Games-Howell	Wormsloe	Athens, GA	-33.9596923*	2.58732521	.000	-40.8349794	-27.0844052
		Brazil	15.2763893*	1.56054328	.000	11.0416420	19.5111367
		China	5.9223077*	1.78988154	.010	1.1339733	10.7106421
	Athens, GA	Wormsloe	33.9596923*	2.58732521	.000	27.0844052	40.8349794
		Brazil	49.2360816*	2.18587222	.000	43.3173340	55.1548292
		China	39.8820000*	2.35508342	.000	33.5727045	46.1912955
	Brazil	Wormsloe	-15.2763893*	1.56054328	.000	-19.5111367	-11.0416420
		Athens, GA	-49.2360816*	2.18587222	.000	-55.1548292	-43.3173340
		China	-9.3540816*	1.13466362	.000	-12.4450253	-6.2631380
	China	Wormsloe	-5.9223077*	1.78988154	.010	-10.7106421	-1.1339733
		Athens, GA	-39.8820000*	2.35508342	.000	-46.1912955	-33.5727045
		Brazil	9.3540816*	1.13466362	.000	6.2631380	12.4450253
HL							
Games-Howell	Wormsloe	Athens, GA	-26.0430256*	2.19059058	.000	-31.8519461	-20.2341052
		Brazil	17.2449608*	1.64612326	.000	12.7689563	21.7209652
		China	5.4223077	2.18703965	.077	-.4196337	11.2642491
	Athens, GA	Wormsloe	26.0430256*	2.19059058	.000	20.2341052	31.8519461
		Brazil	43.2879864*	1.60417476	.000	38.9623498	47.6136230
		China	31.4653333*	2.15564313	.000	25.7193829	37.2112838
	Brazil	Wormsloe	-17.2449608*	1.64612326	.000	-21.7209652	-12.7689563
		Athens, GA	-43.2879864*	1.60417476	.000	-47.6136230	-38.9623498
		China	-11.8226531*	1.59932235	.000	-16.2472690	-7.3980371
	China	Wormsloe	-5.4223077	2.18703965	.077	-11.2642491	.4196337
		Athens, GA	-31.4653333*	2.15564313	.000	-37.2112838	-25.7193829
		Brazil	11.8226531*	1.59932235	.000	7.3980371	16.2472690
L/W							
Tukey HSD	Wormsloe	Athens, GA	-.1193168*	.03068520	.001	-.1992546	-.0393789
		Brazil	-.0598196	.02778614	.143	-.1322051	.0125659

		China	.0002568	.03406117	1.000	-.0884757	.0889894
	Athens, GA	Wormsloe	.1193168*	.03068520	.001	.0393789	.1992546
		Brazil	.0594972	.02654833	.118	-.0096637	.1286581
		China	.1195736*	.03305915	.002	.0334514	.2056958
	Brazil	Wormsloe	.0598196	.02778614	.143	-.0125659	.1322051
		Athens, GA	-.0594972	.02654833	.118	-.1286581	.0096637
		China	.0600764	.03038742	.202	-.0190857	.1392385
	China	Wormsloe	-.0002568	.03406117	1.000	-.0889894	.0884757
		Athens, GA	-.1195736*	.03305915	.002	-.2056958	-.0334514
		Brazil	-.0600764	.03038742	.202	-.1392385	.0190857

Based on observed means.
The error term is Mean Square (Error) = .013.
*. The mean difference is significant at the .05 level.

2. DOUBLE-PEAKED PHYTOLITHS

a. Multivariate Analysis

Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[d]
Intercept	Pillai's Trace	.972	740.648[b]	4.000	86.000	.000	.972	2962.592	1.000
	Wilks' Lambda	.028	740.648[b]	4.000	86.000	.000	.972	2962.592	1.000
	Hotelling's Trace	34.449	740.648[b]	4.000	86.000	.000	.972	2962.592	1.000
	Roy's Largest Root	34.449	740.648[b]	4.000	86.000	.000	.972	2962.592	1.000
Sample	Pillai's Trace	1.486	21.599	12.000	264.000	.000	.495	259.188	1.000
	Wilks' Lambda	.058	36.832	12.000	227.826	.000	.614	361.893	1.000
	Hotelling's Trace	6.912	48.765	12.000	254.000	.000	.697	585.180	1.000
	Roy's Largest Root	5.041	110.895[c]	4.000	88.000	.000	.834	443.582	1.000

a. Design: Intercept + Sample
b. Exact Statistic
c. The statistic is an upper bound on F that yields a lower bound on the significance level.
d. Computed using alpha = .05

b. Post Hoc Analysis

Since none of the samples met the assumption of equal variance, we used Games-Howell for all parameters.

Multiple Comparisons

Games-Howell

Dependent Variable			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
TW	Wormsloe	Sapelo	-45.3429487*	2.81919817	.000	-52.9178205	-37.7680769
		Athens, GA	-37.7412821*	2.51039040	.000	-44.4737944	-31.0087697
		China	-17.1696154*	2.20207883	.000	-23.1670295	-11.1722013
	Sapelo	Wormsloe	45.3429487*	2.81919817	.000	37.7680769	52.9178205
		Athens, GA	7.6016667	3.41708427	.129	-1.4421743	16.6455077
		China	28.1733333*	3.19742961	.000	19.6609381	36.6857286
	Athens, GA	Wormsloe	37.7412821*	2.51039040	.000	31.0087697	44.4737944
		Sapelo	-7.6016667	3.41708427	.129	-16.6455077	1.4421743
		China	20.5716667*	2.92877752	.000	12.7766591	28.3666743
	China	Wormsloe	17.1696154*	2.20207883	.000	11.1722013	23.1670295
		Sapelo	-28.1733333*	3.19742961	.000	-36.6857286	-19.6609381
		Athens, GA	-20.5716667*	2.92877752	.000	-28.3666743	-12.7766591
MW	Wormsloe	Sapelo	-76.6291538*	3.94253617	.000	-87.2096625	-66.0486451
		Athens, GA	-63.3644872*	3.66713003	.000	-73.1953325	-53.5336419
		China	-27.9911538*	3.01977706	.000	-36.1960829	-19.7862248
	Sapelo	Wormsloe	76.6291538*	3.94253617	.000	66.0486451	87.2096625
		Athens, GA	13.2646667*	4.81476329	.038	.5260308	26.0033026
		China	48.6380000*	4.34202215	.000	37.0747163	60.2012837
	Athens, GA	Wormsloe	63.3644872*	3.66713003	.000	53.5336419	73.1953325
		Sapelo	-13.2646667*	4.81476329	.038	-26.0033026	-.5260308
		China	35.3733333*	4.09358127	.000	24.4777762	46.2688905
	China	Wormsloe	27.9911538*	3.01977706	.000	19.7862248	36.1960829
		Sapelo	-48.6380000*	4.34202215	.000	-60.2012837	-37.0747163

		Athens, GA	-35.3733333*	4.09358127	.000	-46.2688905	-24.4777762
CD	Wormsloe	Sapelo	-3.8557436*	.50591882	.000	-5.2132646	-2.4982226
		Athens, GA	-3.6770769*	.38512573	.000	-4.7085664	-2.6455874
		China	-3.1930769*	.39375132	.000	-4.2630710	-2.1230828
	Sapelo	Wormsloe	3.8557436*	.50591882	.000	2.4982226	5.2132646
		Athens, GA	.1786667	.55388171	.988	-1.2917234	1.6490567
		China	.6626667	.55991359	.640	-.8281872	2.1535206
	Athens, GA	Wormsloe	3.6770769*	.38512573	.000	2.6455874	4.7085664
		Sapelo	-.1786667	.55388171	.988	-1.6490567	1.2917234
		China	.4840000	.45373031	.711	-.7261588	1.6941588
	China	Wormsloe	3.1930769*	.39375132	.000	2.1230828	4.2630710
		Sapelo	-.6626667	.55991359	.640	-2.1535206	.8281872
		Athens, GA	-.4840000	.45373031	.711	-1.6941588	.7261588
H	Wormsloe	Sapelo	-25.8772179*	.94148295	.000	-28.4266948	-23.3277411
		Athens, GA	-27.2503846*	.89571213	.000	-29.6745525	-24.8262167
		China	-29.6353846*	1.41355055	.000	-33.5922706	-25.6784986
	Sapelo	Wormsloe	25.8772179*	.94148295	.000	23.3277411	28.4266948
		Athens, GA	-1.3731667	1.26014537	.697	-4.7066641	1.9603307
		China	-3.7581667	1.66846974	.129	-8.2602239	.7438905
	Athens, GA	Wormsloe	27.2503846*	.89571213	.000	24.8262167	29.6745525
		Sapelo	1.3731667	1.26014537	.697	-1.9603307	4.7066641
		China	-2.3850000	1.64307680	.477	-6.8276626	2.0576626
	China	Wormsloe	29.6353846*	1.41355055	.000	25.6784986	33.5922706
		Sapelo	3.7581667	1.66846974	.129	-.7438905	8.2602239
		Athens, GA	2.3850000	1.64307680	.477	-2.0576626	6.8276626

Based on observed means.
The error term is Mean Square (Error) = 23.927.

*. The mean difference is significant at the .05 level.

LIST OF ACRONYMS

DEM: Digital Elevation Model

DNR: Department of Natural Resources

DSM: Digital Surface Model

GPS: Global Positioning System

RTK: Real Time Kinematic

SfM: Structure from Motion

TLS: Terrestrial Laser Scanning

UAS: Unmanned Aerial Systems