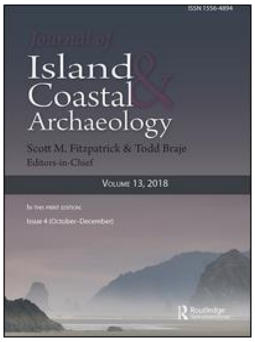

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Colonial rainfed farming strategies in an extremely arid insular environment: Niche construction on Lanzarote, Canary Islands, Spain

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ABSTRACT

The island of Lanzarote in the Canary Islands was first settled by people from northern Africa in the first millennium BC and then colonized by Spain in the late fifteenth century. This colonial legacy reflects an intensive land use driven by a European commodities market that experienced a series of boom-and-bust cycles. Although arid and seemingly resource limited, colonial farmers in the sixteenth to nineteenth centuries copied water capture techniques from the Indigenous population, were strategic in terms of field placement, and engaged in a range of niche construction techniques. An analysis of 420 soil samples for their chemical properties (e.g., pH, electrical conductivity, nutrients) has revealed that sixteenth to nineteenth agricultural infrastructure in the form of open fields, terraces, water capture basins, and mulched fields was constructed on the landscape avoiding areas of high soil salinity and placement was tailored to variations in terrain slope, elevation, and rainfall. These improvements fundamentally changed ecosystem relations resulting in increased agricultural productivity. A series of eolian and volcanic events in the eighteenth century resulted in environmental changes requiring counteractive responses and new processes of niche reconfiguration. Large tracts of land were initially removed from production, but processes of niche construction created new opportunities. These included constructing mulched pits for cultivating sweet potato and tephra mulching for enhanced moisture conservation and accelerated growth of cochineal insect (*Dactylopius coccus*) production on cactus host plants. Cochineal production lasted for a period of sixty years (ca. AD 1825–1885) before a collapse of the market caused by the invention of chemical substitutes.

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Introduction

Studies incorporating a long-term perspective to assess the sustainability of traditional agricultural systems in arid regions provide useful information in the face of current and future environmental challenges in agricultural development and global environmental change (Lancelotti et al. 2019). Some traditional agricultural systems have shown their effectiveness as a means to increase crop production in unfavorable environments while preventing the degradation of soil and water resources (Díaz et al. 2013). Researchers have suggested that combining traditional management techniques with modern agro-ecological practices could be a viable strategy for increasing the productivity, sustainability, and resilience of agricultural production under predicted climate scenarios (Altieri and Nicholls 2017; Kurashima, Fortini, and Ticktin 2019; Singh and Singh 2017). To help meet this goal, this study investigates historical land use in the Canary Islands during a period of colonial expansion lasting from the sixteenth to nineteenth centuries.

We examine the agricultural history of Lanzarote Island, Spain (Figure 1), where colonial agriculture was sustained for centuries by several rain-fed systems that were effective in alleviating environmental constraints on production inherent in arid zones. These constraints included a lack of water, naturally induced salinity-sodicity, and low soil fertility (Díaz 2004). In the following we define the spatial distribution of surface agricultural features. Because of the difficulties in the dating of unmortized stacked stone alignments, terraces, and walls, and the lack of historical maps, constructing a regional developmental chronology can only be done on a general level. We also conducted soil chemical analyses to determine the relative fertility of geological substrates and the ability of colonial Lanzarote farmers to create productive and sustainable landscapes. We consider how agricultural infrastructure was distributed across the landscape in response to the constraints imposed by topography and water availability. We examine how unforeseen natural events may have impacted the productivity of Lanzarote agriculture and how colonial farmers reconfigured the agricultural system. We conclude that Canary Island colonial farmers engaged in various forms of niche construction to maximize productivity in the face of external economic opportunities and constraints, and placed less emphasis on sustainability.

Canary islands human ecodynamics and niche construction

With the advent of improved ocean navigation in the fifteenth century, colonial powers were unleashed upon the world that they considered theirs to exploit for resources to satisfy European markets. Much of the activity originating in the countries of England, Spain, and Portugal centered on the Americas where large agricultural enterprises were established for the production of sugar, molasses, and tobacco. Prior to this, one of the first places to experience colonial expansion was the Canary Islands located 130 kilometers from the coast of Africa (Figure 1).

The Spanish colonists encountered an indigenous population which has been linked through genetic studies to populations in North Africa (Maca-Meyer et al. 2004; Rando et al. 1999) who settled the archipelago in the first millennium BC (Morales et al. 2009). The islanders practiced an integrated agricultural and pastoral economy

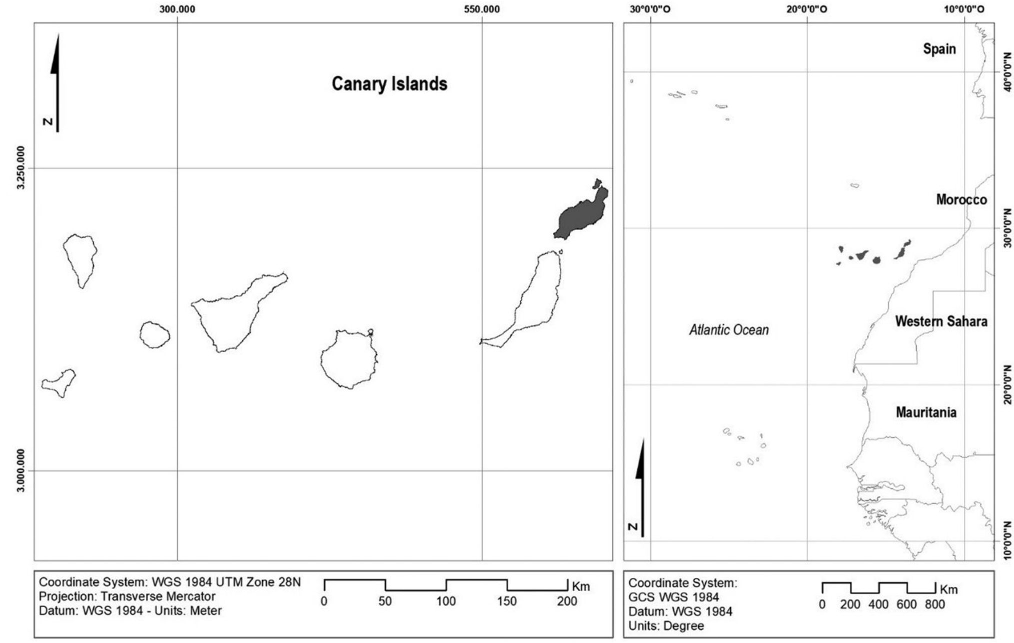

Figure 1. Canary Islands, Spain, and the Lanzarote Island location (shaded).

supplemented by marine resources (Velasco 1999). Domestic cereals, such as barley and wheat, were the main cultivars. Small ruminants (e.g., goats, sheep, Canarian Black pig) were also a core feature of the economy, the latter of which was also genetically traced to western North Africa and supported the assignment of a Berber ancestry (Olalde et al. 2015). This economic base supported a well-established social hierarchy on the larger islands of Tenerife and Gran Canaria (Crosby 1983; Gaspar and González 1987; Pérez 1989). Ethnohistoric research into social organization on the lower elevation islands such as Lanzarote make no mention of a class structure (Pérez et al. 1999).

By the time the first Europeans arrived in the archipelago in the late fifteenth century the landscape had been significantly transformed by pre-colonial activity (Morales et al. 2009). Environmental alterations included partial deforestation on the larger islands such as Tenerife and extensive deforestation on arid islands. Lanzarote experienced the removal of wood resources along with extinction of a small field mouse (*Malpaisomys insularis*) and a land-nesting seabird (*Puffinis olsoni*). A long period of soil degradation (100 BC–AD 1300), possibly caused by sheep and goat overgrazing, has been inferred from soil stratigraphic studies at the El Bebero Site (Morales et al. 2009). Agricultural practices have not been identified as a contributing factor. Prehistoric settlements of this ceramic using society appear to be largely confined to the central El Jable plain, and dryland farming has been characterized as of low intensity and risky as a result of unpredictable rainfall and devastating locust plagues (Pérez et al. 1999).

Colonial entrepreneurs continued to modify the environment and developed their agricultural systems through extensive terracing and field plot architecture. Over the next four centuries they experienced a series of economic cycles with different products (e.g., cereals, barrilla [*Mesembryanthemum crystallinum*], grapes [*Vitis vinifera*], cochinilla [*Dactylopius coccus*]]) that resulted in repeated failure; finally to be almost completely abandoned in the late twentieth century.

Our focus in this paper is on the ecodynamics (Fitzhugh et al. 2019; Kirch 2007; McGlade 1995; Van der Leeuw and McGlad) of colonial agricultural development on the most eastern of the Canary Islands, Lanzarote, one of the more arid places of the world. Fitzhugh et al. (2019, 1079) note the importance of historical contingency when studying ecodynamics and how "…change is the result of unique, complex, and indeterminate historical trajectories of interactions (both human and non-human)." By studying the placed-based history of Lanzarote we are able to understand the complex, non-linear, interdependent, and contingent trajectories of change in this arid, and by some measures, marginal island environment. Lanzarote is an ideal location for investigating the role of human agency in the co-evolution of social and natural subsystems, as the island can be considered a "model system" for human ecodynamics (*sensu* DiNapoli and Leppard 2018; Kirch 2007; Vitousek 2004). Kirch (2007, 9) suggests that within islands, fundamental variables can be identified and the mechanisms of interaction among them investigated. Lanzarote, like other islands, contains high degrees of spatial variation in biogeochemical and climatic factors within relatively short distances, and this makes it possible to investigate how people responded to this variation.

Niche construction is an important process within ecodynamic relationships. We examine niche construction on Lanzarote whereby the activities and choices of organisms, including people, impacted the changing selective environment (Odling-Smee, Laland, and Feldman 2003). By studying the accumulated cultural and environmental changes, or "ecological inheritance" (Quintus and Cochrane 2018) of Lanzarote we can identify the selective pressures that organisms, including people, experienced. Not all change in the Canary Islands, however, contributed to the selective pressures, and it is necessary to carefully document and measure the impact of specific transformations on the evolutionary responses of past populations (see Huebert and Allen 2020; Laland and Sterelny 2006; Matthews et al. 2014).

To achieve this, we follow Odling-Smee, Laland, and Feldman (2003) and Huebert and Allen (2020) who differentiate "inceptive" niche construction from "counteractive" and "proactive" niche construction. Within inceptive niche construction, processes of relocation and perturbation are key. These could involve the relocation of introduced cultigens to new environments (e.g., the introduction of cereal varieties to the Canary Islands by the original inhabitants or later colonial farmers, or the introduction of grapes during the colonial period), or the development and retooling of agricultural or other procurement practices. Inceptive niche construction can also involve perturbations like the firing or removal of vegetation and subsequent soil erosion, which in some contexts has detrimental effects and in others creates productive agricultural zones for economic species (*sensu* Spriggs 1997). Counteractive NC involves responses to ongoing environmental changes and tends to be conservative or stabilizing. This form of NC can restore previously developed food procurement practices, for example when terracing is extended to accumulate sediments for the construction of gardens of existing cultigens. Proactive niche construction involves innovations used to solve emergent or anticipated environmental problems or enhance resources (Huebert and Allen 2020), for example the creation of new gardening infrastructure and planting mediums, or the increased focus on specific productive species.

In the case of Lanzarote, colonial farmers were faced with several climatic and biogeochemical constraints that made farming risky. Yet, farmers learned to identify chemically adverse soils and created water control strategies that drew sediments into their fields and terracing systems. This resulted in the transformation of the Lanzarote landscape into a vast agricultural infrastructure of field and terrace complexes that covered the majority of the island's surface, even on the most rugged of terrains. Natural processes, such as eighteenth century volcanism or storm events, however, abruptly transformed the landscape within a few years and eliminated landscapes once used for subsistence. These events caused immediate and heightened selective pressures on farmers. However, as humans experimented and learned about the new landscapes, these accidents of history provided new materials that allowed for the reconfiguration of niches and expansion of niche boundaries. On Lanzarote, volcanic and eolian events led to the development of tephra mulching and pit planting which transformed the agroecosystems.

Within this context of human-environmental interactions, the historical documents tell us that arid region colonial agriculturalists in the Canary Islands were primarily motivated by external European markets, and thus, they were interested in strategies that sought to maximize commodity returns. In general, people were involved in processes of niche construction that returned marketable products in larger quantities as opposed to sustainable yields over long periods of time. The growth and decline of Lanzarote's agricultural economy from the sixteenth to nineteenth centuries involved patterns of inceptive, counteractive and proactive niche construction in response to internal and external factors.

Colonial agriculture in the Canary Islands

European colonization created a single political unit out of the Canarian archipelago (Gaspar and Vallejo 1992). While the indigenous Canarians originated from the adjacent African coast in the first millennium BC, the islands were settled differentially, at various times by different groups and were, despite this similar origin, not a cohesive unit. European "rediscovery" of the islands in the late fifteenth century, and the subsequent invasion, conquest, and colonization (Mercer 1980, 155) is what serves as the dividing line between colonial history and "prehistory" in the Canary Islands and the formation of a geopolitically important entity. The Spanish kingdoms of Castille and Aragon completed the conquest of the archipelago in AD 1476 (Tejera and Vallejo 1992) and began a long-recorded history of difficult economic sustainability. With respect to the indigenous "Majos," the record is not clear, but some persons regarded as "chiefs" were able to retain property and inter-marriage of these same persons with Europeans is reported (Pérez et al. 1999).

Large scale agricultural enterprises in the Canary Islands were initiated soon after conquest. Intensive farming continued for four centuries in a series of "boom and bust" cycles in which Lanzarote played a varying role. A sequence of commodities was introduced, developed, and exported beginning in the AD 1500s with the harvesting and export of orchil lichen, a purple dyestuff. Concurrently, large scale sugar cane production was introduced to Tenerife (Figure 1). This water-needy plant prompted the development of run-off irrigation systems, conflicts over water rights, and extensive timber harvesting to fuel the production of molasses (Fernández-Armesto 1982). This undertaking was a short-lived endeavor as it was not competitive with cheap Brazilian sugarcane, which expanded greatly in AD 1526–1590 (Van Hook 1949). This initial agricultural experiment was converted to intensive wine production, principally along the north coast of Tenerife between AD 1575 and AD 1725 (Steckley 1980), with vineyards on Lanzarote playing a more minor role. Considered a sweet luxury wine, the high-priced Malvasia-based wine was enormously popular. Tenerife vineyards annually exported between 8000 and 10,000 pipes (∼5000 tons) of wine to European markets even with a century of progressively rising prices. The wine market collapsed in the first quarter of the eighteenth century and the economy of the Canary Islands was seriously depressed for nearly a hundred years.

A third economic boom began around AD 1825 when the cochineal insect (*Dactylopius coccus*) was introduced from Mexico for the production of a deep red dye, brilliant enough to satisfy the demands of the growing English textile mills kept busy by the popularity of dark red fabrics. As a small, parasitic scale insect hosting on the Opuntia cactus (*Opuntia maxima*), cochineal could be produced in large numbers in the arid and semi-arid regions of nearly all of the Canary Islands. After a hesitant start, the investment in this crop rose exponentially and landowners transitioned their crops to capitalize on the potential for massive profits (Hernández 1990; Lemus 2001). Vast tracts of the landscape on Lanzarote and elsewhere were reconfigured with high walls, terraces, leveling, deep plantings, and tephra mulch applications. Water run-off capture techniques were developed for more elevated catchments, and deep drilling and water storage ponds were developed on the higher islands. This expensive investment in infrastructure led to rampant land speculation and soaring land prices that, for a time, could be sustained by the ever-rising price and volume of cochineal.

Production of cochineal peaked in AD 1875 in the Canary Islands—then the largest and most important cochineal producer—with an export that year of 2722 tons (Cardon 2007, 631). The creation of synthetic red dye only a few decades later severely curtailed the commodity's profitability. Synthetic reproduction of crimson was discovered in England and Germany in the mid to late nineteenth century (Greenfield 2005, 221–223). The extraction of the pigment from coal tar (developed in Germany) greatly advanced the mass production and affordability of this color (Greenfield 2005, 227). At this time, cochineal producers began marketing and using the dye for products other than textiles and paint pigments, namely food and cosmetic colorants (Gerber 1978, 31–32) that were already common in Mexico at the time of conquest (Vázquez de Ágredos Pascual 2007, 131).

Each of the three historic agricultural economies represents the implementation of an "extraction-based paradigm" where high profits could be earned by satisfying the needs of developing European economies. Initially, these "get rich quick schemes" of Spain's upper class were awarded trading monopolies (Fernández-Armesto 1982) to compensate for the heavy investments in agricultural infrastructure. These persons, and the labor force they directed, came from semi-arid regions in Spain where they were experienced with intensive agriculture and water control. In their homelands, they practiced agriculture with the intent of avoiding risk and under- productivity. In light of this

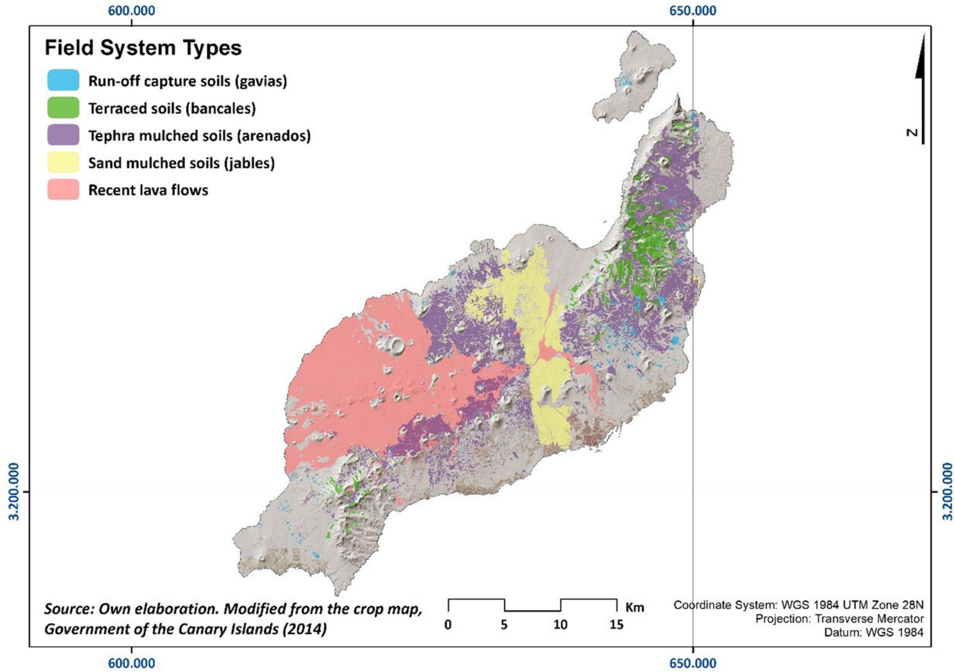

Figure 2. Distribution of agricultural field system types, Lanzarote, Canary Islands, Spain.

background, we ask why did their approaches to agricultural production in the Canary Islands repeatedly fail?

Historical economists examining this pattern of repeat agronomic failures implicate unstable international political relations between the major European powers, unbalanced trade relationships, disproportional monetary exchange rates, lack of exchangeable currency, and scientific inventions. One or more of these factors in each case are considered causes that generated market instability and eventual unprofitability (Steckley 1980). The frequently detailed historical records that describe colonial period trade, exchange, and public litigation provide a broad picture of what happens to the commodities, but comparatively little detail on the strategies of agricultural development or the environmental variables that might have limited productivity. In the historic statistics on wine production, for example, there is evidence for productivity limits demonstrated by the static level of exports for the better part of a century. This broad picture is incomplete and is a simplified assessment of the economic and ecological dynamics that guided colonial producers. Given the diversity of microenvironments within the Canary Islands, as well as the archipelago's small size and varying geological age, the context of production has explanatory value to understanding the sequence of historical events.

Biogeochemical constraints on Lanzarote

Lanzarote, the eastern-most island of the Canarian archipelago, with an area of 862 km^2, is located in the Atlantic Ocean between 29° 14′ 41′′and 28° 50′ 28′′ N latitude and 13° 28′ 06′′and 13° 47′ 46′′ W longitude and approximately 130 km from the west African coast. Most parts of the island receive an average of 150 mm of rainfall per year with no

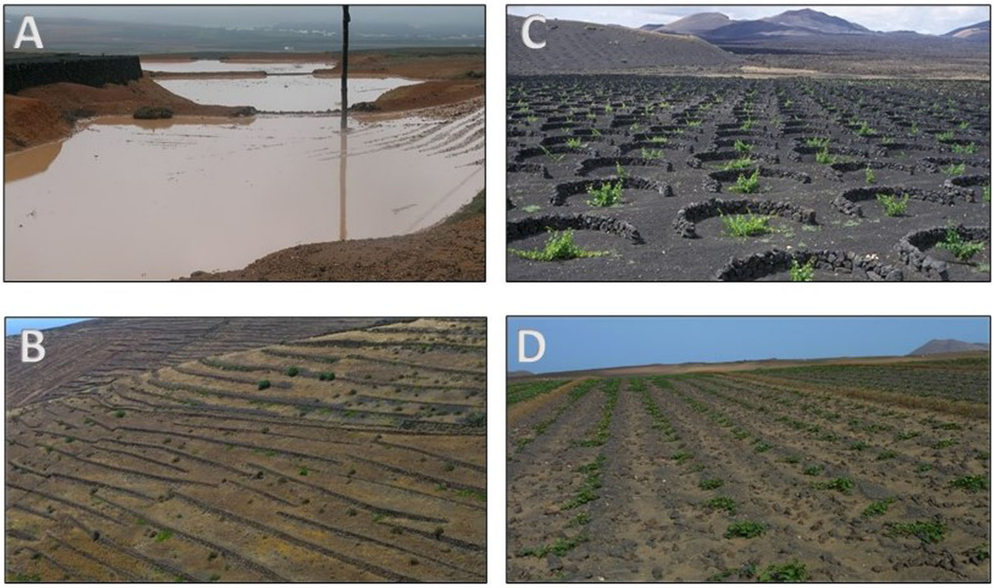

Figure 3. Images showing the typical configuration of (A) runoff-capture plots; (B) terrace complex; (C) tephra mulched plots; and (D) sand mulched plots (Photos: F. DÃaz).

parts receiving more than 250 mm (Supplemental Figure S1). The rainfall is seasonal, from October to March, with high inter-annual variability. While most rainfall events are low intensity, it is common for at least one high intensity event (>10 mm h^{-1}) to occur each year that can cause flash flooding (AEMET 2012).

The mean annual temperature is 20.7 °C on the coast (García-Rodríguez, García-Rodríguez, and Castilla-Gutiérrez 2016) and slightly cooler at higher elevations (Supplemental Figure S2). The high temperatures and elevated solar radiation intensity (annual average ~ 8 h of sunshine per day), combined with moderate to strong winds throughout the year (annual average wind speed ~ 5–7 m s^{-1}), result in high potential evapotranspiration rates (PET ~ 1200–1400 mm yr^{-1}; FAO Penman-Monteith method; PELD 2013). The Aridity Index calculated as the ratio P/PET varies between 0.05 and 0.2 which has led to classification of Lanzarote as arid land (Supplemental Figure S3; Cherlet et al. 2018). The natural vegetation in accordance with the aridity is sparse, and mainly consists of ephemeral grasses and scattered xerophytic shrubs (e.g., *Launaea arborescens, Caroxylon vermiculatum*).

The topography of Lanzarote is characteristic of mature islands [15 million years (ma) old], where most of the original subaerial geological material has been removed by catastrophic mass wasting and gradual erosion (Carracedo and Troll 2016; Troll and Carracedo 2016). At present its landscape is dominated by two deeply eroded volcanic massifs (i.e., los Ajaches in the south and Famara in the north, with numerous U-shape ravines and high vertical cliffs), separated by a wide central plain continuously modified by the addition of differentially accumulating sediments on the landforms (Carracedo and Troll 2016). Maximum highest points are located on the southern Ajaches volcano (~560 masl), and the northern Famara volcano (~670 masl). Most of the territory (~ 70%) represents flat or gently sloping (< 5%) areas, while approximately 40% of the

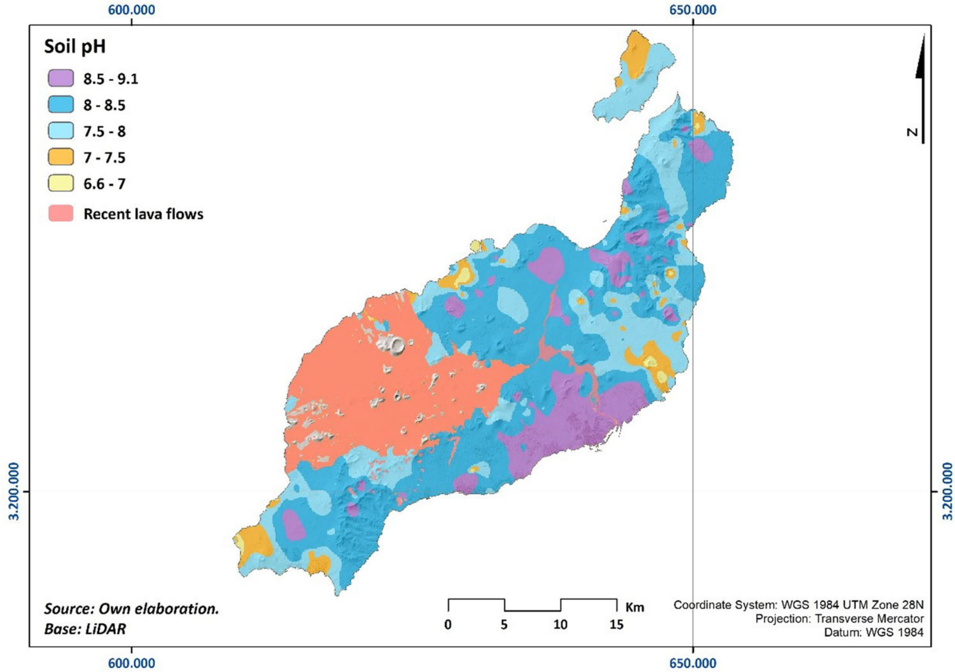

Figure 4. Soil pH distribution on the island of Lanzarote.

terrain, mainly associated to the volcanic massif, has slopes greater than 20% (Supplemental Figure S4).

Four main geological substrates are well separated in time and condition the structure of surface soils: (1) Miocene materials form the two mountainous regions in the southeast and northeast parts of the island; (2) Pleistocene volcanism conform a northeast-southwest central rift zone, partially occupied by quaternary sedimentary deposits; (3) approximately 21,000 years (ka) old (upper Pleistocene) volcanic materials from eruption of the Corona volcano at the northeast area; and (4) the historical eruptions of AD 1730–1736 and AD 1824 (Supplemental Figure S5) (Barrera and García 2011). The different age of the volcanic materials and the climatic variations throughout the Quaternary are the main reasons for the existence of a wide range of soil typologies in Lanzarote. The soils with the greatest representation on the island are the Aridisols (Calcids, Argids, Salids) and Entisols (Psamments, Orthents, Fluvents), and to a lesser extent Vertisols (Torrerts) and Andisols (Torrands) (Supplemental Figure S6; Soil Survey Staff 2014).

Beneficial minerals originate from dusts of the Saharan and Sahel regions of Africa (Criado and Dorta 2003; Menéndez et al. 2014; Mizota and Matsuhisa 1995; Muhs et al. 2010). Carried by the trade winds, the minerals in these deposits consist of quartz, calcite, dolomite, magnetite, aragonite, and halite (Menéndez et al. 2007). On the northeast coastal region near the La Corona volcano, the eolian deposits have been identified based upon their trace element geochemistry and constitute 44–59% of the non-sandy soil deposits (Muhs et al. 2010). The Sahara/Sahel dust is a very important source of iron and phosphorus, though the extent of deposition is likely uneven and will be influenced by aspect, topography, and elevation (Bristo, Hudson-Edwards, and Chappell 2010).

Materials and methods

Prior to soil sampling the island landscape was divided into different areas. This was based on a previous review of the landscape features (Díaz et al. 2005; Díaz et al. 2011; Tejedor et al. 2004) and remote sensing using high resolution orthophotos and the Canary Islands' crops map (Gobierno de Canarias 2015), with later field verification. The five main groups of soils, mapped using ESRI ArcGIS Desktop, consisted of run-off capture soils (RCS); terraced soils (TS); tephra mulched soils (TMS); eolian sand mulched soils (SMS); and non-farmed soils (NFS).

Soil sampling and analysis

To assess the current chemical fertility of Lanzarote soils a total of 420 soil samples, 177 from non-farmed soils and 243 from agricultural soils, were taken within different field campaigns between September 2010 and September 2016 (Supplemental Figure S7). Soil samples for each category were distributed in order to cover most of the defined areas. Portions of the island surface occupied by lava flows were not tested. Distributions of soils currently under irrigation were not sampled since contributions from desalinized water or recycled municipal water may introduce contamination. Each sample was the combination of three soil subsamples collected from the arable layer (top 25 cm). For mulched soils (covered with pyroclasts or eolian sand), these materials were removed from the surface prior to sampling. Sampled soils were most commonly classified as Torrifluvents, Paleargids, Calciargids, Natrargids, Haplocalcids, Petrocalcids and Salids (Soil Survey Staff 2014) and had surface soil textures ranging from sandy to clay. Regions along the coast that did not show any evidence of farming were also tested. The Ajaches Mountain region in the southwestern part of Lanzarote with its extensive terrace complexes and fields was not part of this study since access to the area was very difficult. Soil sampling within this area has recently occurred and is the subject of a different investigation.

Soil samples were air-dried and passed through a 2 mm screen prior to analysis. Analyses were performed using standard methods (Soil Survey Staff 1996): pH (pH_e), electrical conductivity (EC_e), and soluble boron (B_e) in saturated paste extracts; soluble cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) in saturated paste extract by ion chromatography; sodium adsorption ratio (SAR) from Ca^{2+}, Mg^{2+} and Na^{+} concentrations in the saturated paste extract; exchangeable cations by equilibrium extraction using 1 M ammonium acetate (pH 7.0) for Na^{+} and K^{+}, and 1 M sodium acetate (pH 8.2) for Ca^{2+} and Mg^{2+}, and subsequent determination by atomic absorption/emission spectrometry; cation exchange capacity (CEC) by barium acetate saturation and calcium replacement; exchangeable sodium percentage (ESP) was indirectly calculated from SAR values (US Salinity Laboratory 1969); calcium carbonate equivalent ($CaCO_3$) using gravimetric determination by reaction with hydrochloric acid; organic carbon (OC) by potassium dichromate oxidation and subsequent spectrophotometric measurement; total nitrogen (TN) by micro-Kjeldahl; available phosphorus (P) by the Olsen method; micronutrients

(Fe, Mn, Cu, and Zn) by extraction with DTPA and subsequent determination by atomic absorption spectrometry.

Statistical and geostatistical analysis

Statistical methods were implemented using Statistical Package for the Social Sciences (SPSS; Version 25.0). The level of significance for all tests was set to $p < 0.05$. To detect differences in soil chemical parameters among all sites, ANOVA and a post hoc Tukey's test were used. A Kuskal–Wallis test and a non-parametric Tukey-type multiple comparisons test were used when parameters did not conform to a normal distribution (Kolmogorov Smirnov test) and homogeneity of variance (Levene test). Principal components analysis (PCA) was carried out using CANOCO (Version 4.5) to examine ordination and distribution of soil samples with regard to soil chemical and environmental variables.

Different methods and sources have been used to develop the cartography of this work, but we rely principally on ArcGIS Desktop (ESRI's ArcGIS Desktop 10.8 software) and its different geoprocessing and geostatistical analysis and cartographic production tools.

The maps for Mean Annual Precipitation and Mean Annual Air Temperature have been developed from data compiled by the State Meteorological Agency (AEMET 2012), with the averaged data referring to climatic series for the years 1970–2000. The pixel resolution was 250×250 m. For Lanzarote we had to resize the archipelago data and use the island's own ranges of values, relying on the maximum and minimum digital levels of each of the variables and using a color ramp for the meteorological phenomenon represented. Similarly, using previously published maps and applying FAO methodologies on potential evapotranspiration, the Aridity Index map has been produced. A map for Surface Slope was created from the altimetric values of the Digital Terrain Model (DTM) available from the Spanish National Geographic Institute (IGN). These data are derived from a LiDAR point cloud, and have a resolution of 5×5 m per pixel.

The maps for Soil pH, Electrical Conductivity, Cation Exchange Capacity and the Exchangeable Sodium Percentage were developed through interpolation using our analyzed samples. Different geostatistical procedures were followed to develop a model for the entire island surface. The following geostatistical algorithms were used: (1) inverse weighting by distance, in cases where the changes are gradually determined by the distances between the samples used (Cation Exchange Capacity map); (2) Kriging, when the referred attribute presented spatial variations that did not show a preferred direction and required an analysis of these spatial variations and that the attributes be measured at different points (Exchangeable Sodium Percentage); (3) variants of this last method of geostatistical analysis have also been used, such as Empirical Bayesian Kriging, which allows a greater manual adjustment of the interpolation parameters. This was used for the Electrical Conductivity map.

A last group of maps, mainly descriptive and modified to reduce complexity, have been prepared from existing data sources (Geological Map, Crop Types, Soils Map) that include the Government of the Canary Islands and Canarian universities. In all maps, the default values of the algorithms have been modified, excluding extreme values (e.g., those very close to the shoreline break), or reducing or enlarging the search radii in the

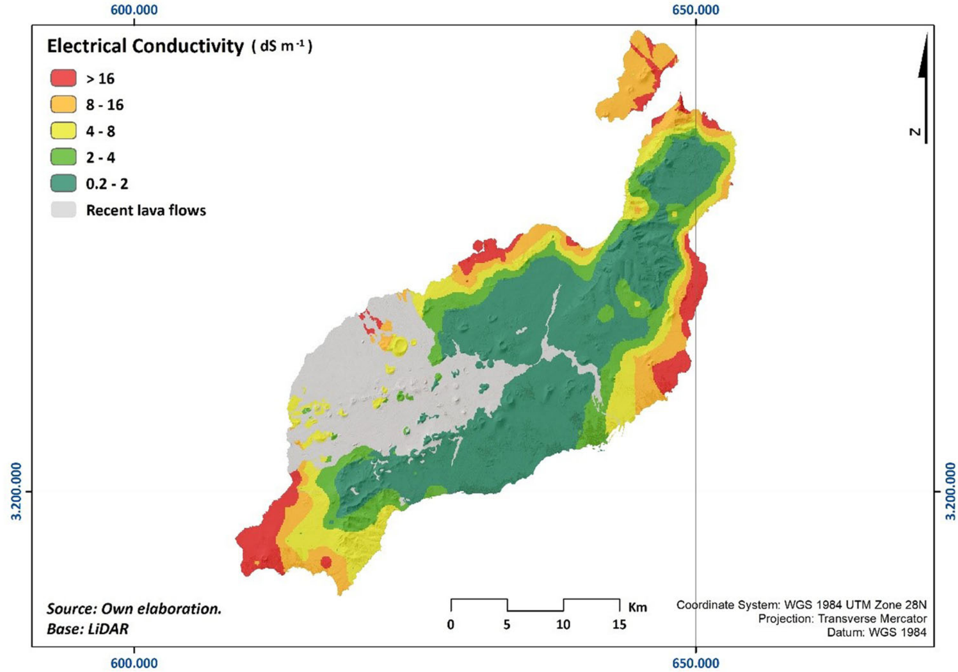

Figure 5. Electrical conductivity values for Lanzarote soil samples.

neighboring values, weighing their influence and modifying the weight of the search sectors, orienting them according to the island morphology and environmental patterns (i.e., prevailing winds, geological substrate). A detailed explanation of the geostatistical models used can be found in Williams (1998) and Mitas and Mitasova (1999).

Results

Geographical distribution of agricultural systems

Geographical analysis and mapping of the field systems and agricultural stone infrastructure shows restricted spatial distributions for various types of agroecosystems (Figure 2). Five main groups were identified: (1) runoff-capture soils (RCS; known locally as "gavias"); (2) terraced soils (TS; known locally as "bancales" and "cadenas"); (3) tephra mulched soils (TMS; known locally as "arenados"); (4) open-field systems covered by naturally occurring eolian sand deposits referred to as sand mulched soils (SMS; known locally as "jables"); and (5) non-farmed soils (NFS). Runoff-capture soils (RCS) cover the least amount of land area, approximately 600 hectares (Figure 2). This technique is based on increasing water availability for crops by means of capturing run-off generated during intensive rainstorms in leveled and dammed plots used as cropping areas (Figure 3a). Earthen catchment basins may be positioned on the lower parts of drainages, on nearly level land, and are defined by stone retaining walls or/and earthen embankments surrounding an agricultural plot. These enclosures harvest enough water from the few annual rainfall events to produce a mature crop. They are located at the base of slopes in the southwest, north central and northeast areas of Lanzarote, often at

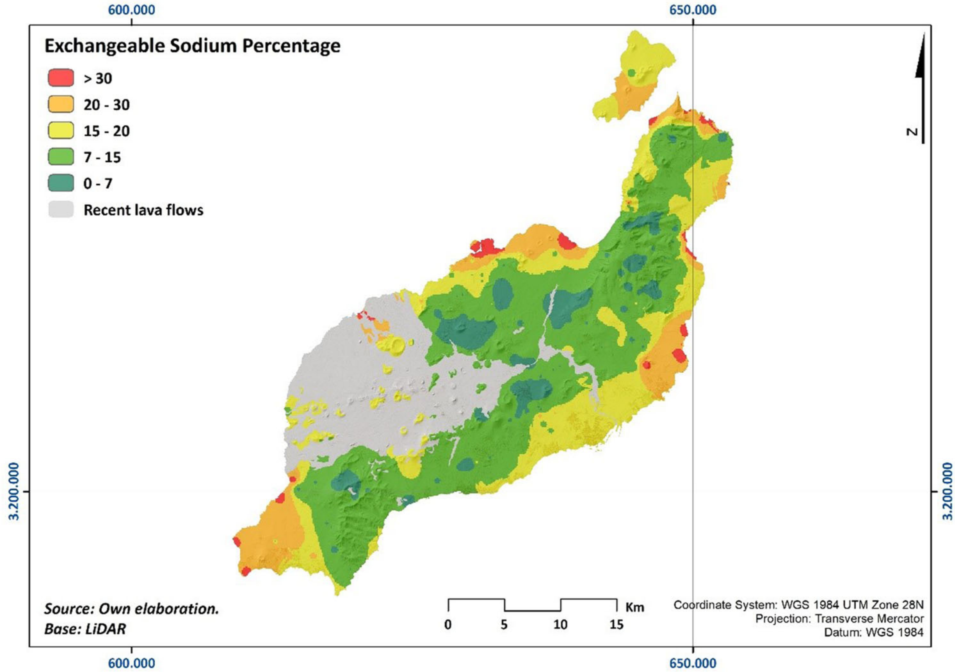

Figure 6. Soil exchangeable sodium percentage on the island of Lanzarote.

the margin of more mountainous terrains (Figure 2). They are mainly developed over Pliocene geological materials and Argids and Calcids soils, and primarily in very arid areas (AI ∼ 0.09). The "gavia" system can be included in the type of runoff-capture agricultural system known as macro-catchment (Lövenstein 1994), since the catchment area to cultivated plot size ratio varies from 8:1 to 50:1. Current crops in this system are cereals (e.g., wheat), legumes (e.g., lentils), and corn (Table 1) (Díaz et al. 2011).

Terraced soils (TS), are located on both slightly and steeply sloping terrains at the margins of volcanic cones and in the steep sided valleys of the mountainous regions, occupying an area of 2650 ha. (Figure 2). Terrace front retaining walls of stacked stone run across the slope to retain soil, creating horizontal areas, or areas with little slope, where there were none, and modifying the soil profile to make it more effective for water infiltration, and water storage, avoiding soil erosion and also facilitating agricultural labor (Figure 3b). Most terrace complexes (∼70%) are placed over Miocene geological materials, and Torriorthents and Petrocalcids soils, in areas with relatively high aridity index (average ∼ 0.12) (Table 1). Traditionally these systems have been dedicated to cereals cultivation (Gobierno de Canarias 2015).

Tephra mulched fields (TMS) with surrounding rock walls are present on lower sloping terrains throughout the island (Figure 2; Figure 3c). This technique originated after the Timanfaya volcanic eruptions of AD 1730–1736 deposited up to 1–3 meters of 0.5–8 mm diameter tephra over a large part of the southwest portion of the island. Agricultural plantings have both been established within this deposit, forming a landscape known as "geria or natural arenados," and by transporting the cinders to remote fields where they are laid down in a layer 8–15 cm thick over the soil surface ("artificial arenados"). Usually, volcanic tephra is transported from quarries and placed over the

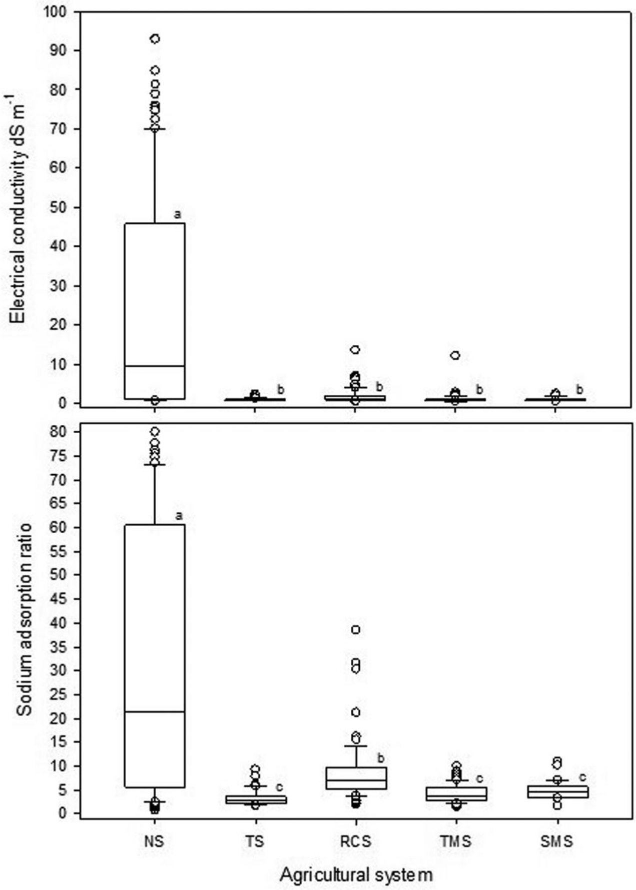

Figure 7. Salinity and sodicity in soil arable layer (0–30 cm) of different agricultural systems in Lanzarote Island compare to non-farmed soils; $n = 30–178$; NS: nonfarmed soils; TS: terrace soils; RCS: runoff capture soils; TMS: tephra mulched soils; SMS: sand mulched soils; identical lower-case letters indicate no significant differences ($p < 0.05$) among the systems.

original soil, very often soils of former runoff-capture fields. The most common crops planted historically are grape vines, onions, potatoes, sweet potatoes, pumpkins, maize, beans, and lentils (Díaz 2004; Gobierno de Canarias 2015). Tephra mulched fields occupied a wide range of soils types (e.g., Argids, Haplocalcids) and commonly developed over Pleistocene geological substrates. This is the most widely established agricultural technique in the island (~13,700 ha; Table 1).

Sand mulched soils (SMS) are observed in the central part of the island (Figure 2; Figure 3d), and occur on a low elevation plain suitable for larger plowed fields, where there has been a continuous natural addition of fine eolian calcareous sand from north shore marine and non-marine deposits since ca. AD 1750 (Cabrera, Alonso, and Alcántara-Carrio 2006). Prior to this date cultivation would have occurred on open terrain without infrastructure other than stone field boundaries or rudimentary earth walls to retain runoff. The sands cover a region 21 km long (N-S) and 10 to 4 km wide (E-W). Depth of the deposit is highly variable but can reach several meters in some areas, being only 30 cm in others. Soils covered by a relatively thin sand layer (usually less

Table 1. Characteristics and environmental variables for the main agroecosystems identified in Lanzarote Island. RCS, runoff-capture soils; TS, terraced soils; SMS, sand mulched soils; TMS, tephra mulched soils.

Attribute	TS	RCS	TMS	SMS
Main geologic substrate	Miocene volcanism	Pliocene volcanism	Pleistoce volcanism	Plio-quaternary sedimentary deposits
Main soil type	Torriorthents, Petrocalcids	Paleargids, Calciargids, Haplocalcids	Argids, Haplocalcids	Haplocalcids
Mean surface slope (%)	17.4	3.9	5.4	3.2
Mean annual rainfall (mm)	165.7	130.2	145.2	144.2
Mean aridity index	0.12	0.09	0.12	0.10
Main crops	Cereals	Cereals, legumes, corn	Potatoes, grapes, onions, corn	Sweet potatoes
Area occupied (ha)	2653	606	13669	5424

than 1 m) have been used for crop production (approximately 5400 ha). Soils covered by eolian sand are classified as Haplocalcids and have been developed from Plio-Quaternary geological materials. In this central plain, the aridity index varies from 0.08 to 0.12, Table 1). The main crop in this system was sweet potato (Figure 3d) (Gobierno de Canarias 2015). Non-farmed soils (NFS) are terrains that show no evidence of agricultural stone infrastructure or surface layers consisting of tephra or natural sands. These soils tend to be coastally located, but no estimate of the area was calculated.

Soil chemical fertility

The island of Lanzarote exhibits a wide variety of landforms that are anticipated to be of varying suitability for the agricultural production of domesticates such as grains, potatoes, onions, grapes, and cactus. The underlying geology ranges from dissected Pleistocene mountain ranges with old soils to historic lava flows with little, or no, soil development (Supplemental Figures S5 and S6). Annual rainfall amounts vary from near 100 mm at low coastal elevations to slightly more than 200 mm in the more elevated northeastern mountain region (Supplemental Figure S1). However, the assessment of preferential landscapes for cultivation by European agriculturalists should first look beyond the simple covariance of slope and rainfall and examine how soil chemistry and nutrient levels enhance or limit the productivity of regions; factors that would have been recognized within a few years by the colonial islanders' assessment of the terrain. Therefore, we look at the spatial variation in soil pH, sodicity, electrical conductivity, and soil nutrients across the landscape to determine which areas are unsuitable, or potentially preferable, for agriculture. We then use multivariate analysis to identify favorable geographical niches based upon soil properties, topography, and rainfall and the type of agricultural systems utilized on the respective landforms.

The surface soils of Lanzarote are overwhelmingly moderate to high in alkalinity (Figure 4). Soils of elevated pH (pH 8.5 to 9.1) cover a large area along the central part of the southern coast and an interior region immediately to the north. Smaller distributions are scattered elsewhere. Moderately alkaline soils (pH 7.5 to 8.5) cover the majority of Lanzarote and near neutral soils, or slightly acidic soils (pH 6.6 to 7.0) exist as

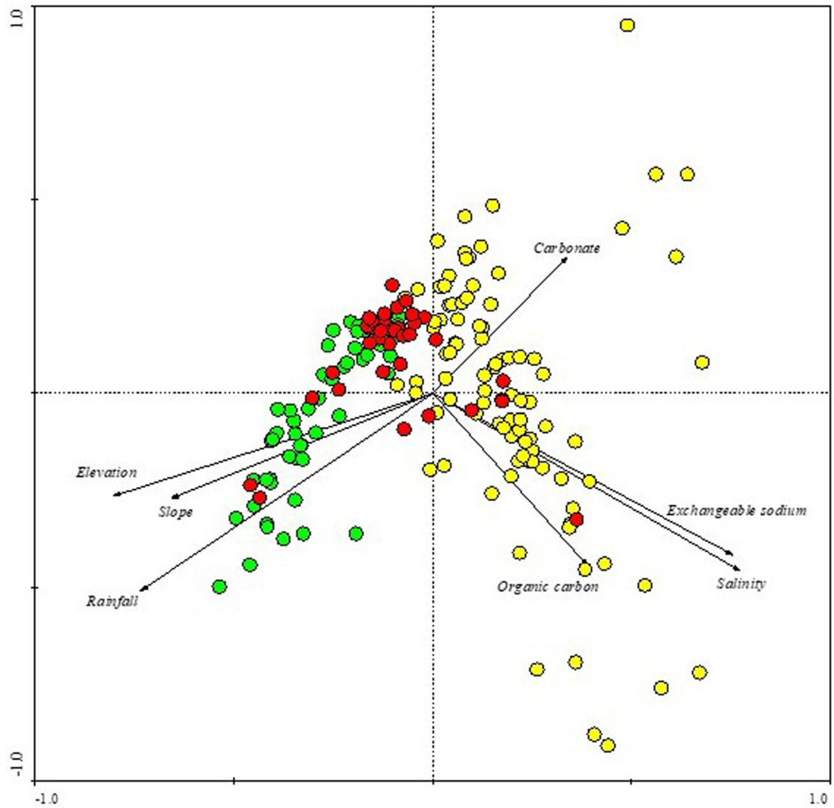

Figure 8. Principal component analysis of non-farmed soils ($n = 36–92$).

small pockets at four distinct localities. Because of the arid conditions, we anticipated the lack of neutral to acidic soils since rainwater leaching is greatly reduced (Bloom and Skyllberg 2012) and weathered silicate, aluminosilicates containing Na^+, K^+, Ca^{2+}, and Mg^{2+} are added by natural weathering, erosion, and wind deposition.

Excessively alkaline soils are often an indicator of the high accumulation of soluble salts that may include Cl^-, $SO_4{}^{2-}$, HCO^{3-}, Na^+, Ca^{2+} and Mg^{2+} in different concentrations and relative proportions (Mau and Porporato 2016). Saline soils of this nature are characteristic of arid and semi-arid regions such as Lanzarote (Bernstein 1975). These natural salts in an insular environment form as a result of marine spray accumulation and natural mineral weathering, but unlike more humid regions, they are not removed by rainfall leaching into the deeper soil horizons. The distribution of electrical conductivity values (EC in dSm^{-1}) follows a distributional pattern from the coastal areas to the interior (Figure 5). Soils with EC values more than $4\,dSm^{-1}$ are considered to have excessive amounts of salt for most crop development and many near coastal locations have EC values ranging between 8 and $64\,dSm^{-1}$ (Arora and Dagar 2019).

Soils with elevated levels of exchangeable Na^+ are unfavorable for agriculture since it could modify soil structure through clay dispersion which in turn reduces water infiltration and facilitates water runoff (Arora and Dagar 2019). Soil compaction and reduced aeration hinder plant growth, especially in the early phases where root development is

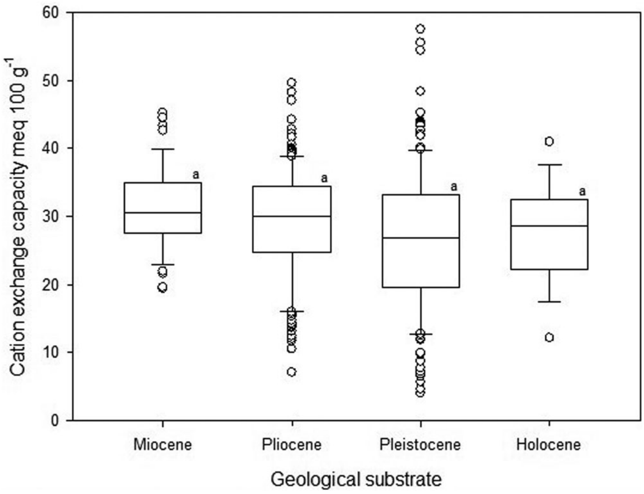

Figure 9. Soil cation exchange capacity by geological substrate: Miocene 14.5–5.7 mya, Pliocene 5.7–2.6 mya; Pleistocene 2.6–0.7 mya, Holocene (10,000 ya); $n = 15–174$; ; identical lower-case letters indicate no significant differences ($p < 0.05$) among the substrates.

important. Sodic soils are soils where more than 15% of cation exchange sites are occupied by sodium ions (Bernstein 1975). On Lanzarote, high Na^+ and Cl^- levels originate from the ocean spray that is carried inland by the strong winds. Figure 6 illustrates the distribution of exchangeable sodium percentage values (ESP%) across the Lanzarote landscape. High ESP ratios are always located at near coastal locations and most of the intermediate ESP rankings (15–30%) are also proximate to the coastline. The interior of the island is generally of low sodicity and more suited for agriculture as is a segment of the southeast coast.

The unsuitability of saline-sodic soils for agriculture should have been easily recognizable to colonial farmers. To assess this hypothesis, we constructed box plots of soil EC and SAR for each of the recognizable agricultural field systems. As seen in Figure 7, both EC and SAR taken from the upper 30 cm of the non-farmed soils (most at the coastal areas) have mean values and much larger overall ranges compared to similar samples from terraces, run-off capture plots, tephra mulched fields, and sand mulched fields. As an additional evaluation of land usage, a principal component analysis of non-farmed soils in coastal, interior, and mountainous regions was conducted to determine their locational properties. In Figure 8, coastal non-farmed soils (yellow circles) are characterized by high salinity and exchangeable sodium plus elevated carbonate levels and relatively higher organic matter. In contrast, non-farmed soils in mountainous regions (green circles) are located in a region of higher rainfall, and the soils are low in carbonates, of moderate organic matter, and are steeply sloping; the latter which may account for their lack of use. Interior non-farmed soils (red circles) tend to be very low in organic matter. It seems evident that non-farmed soils on each of the terrains possessed an undesirable property. The lack of farming at these locations over many centuries suggests that colonial farmers were aware of the unsuitability of these soils for agriculture and avoided them.

With the majority of near-coastal saline locations eliminated from the agricultural system, the question now becomes whether there are regions of the island that are more naturally fertile and would have been potentially more productive because of nutrient

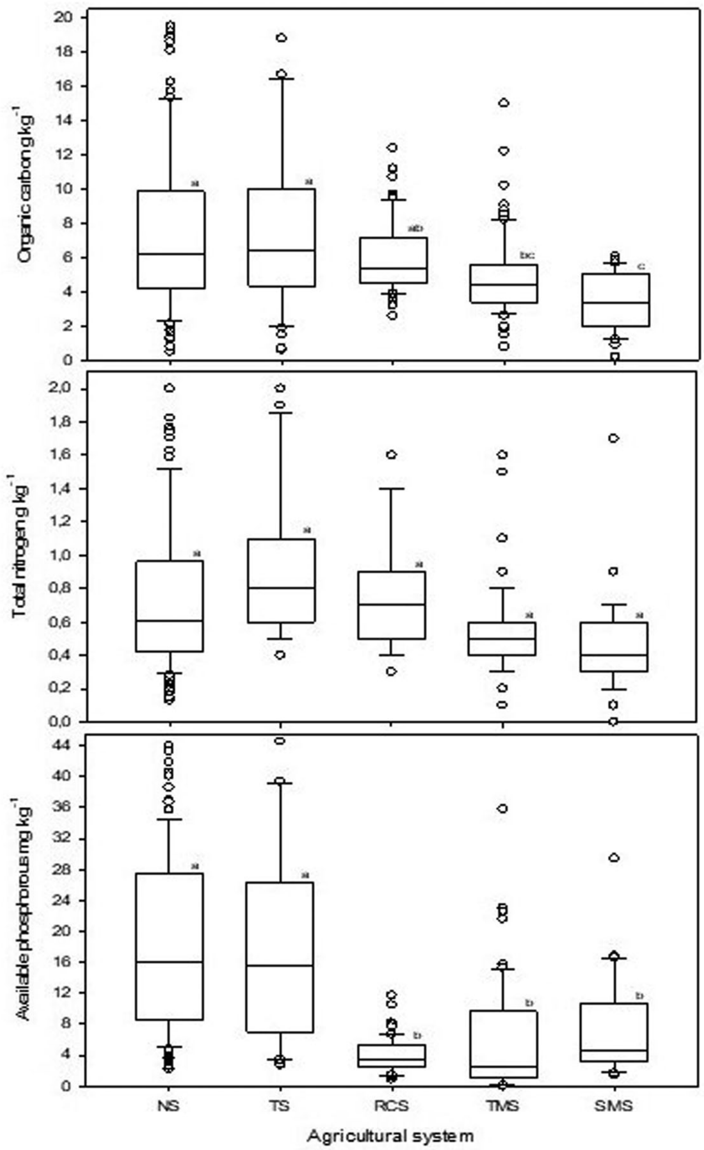

Figure 10. Organic carbon and nutrient content in soil arable layer (0∇30 cm) of different agricultural systems in Lanzarote Island compare to non-farmed soils; $n = 30\nabla178$; NS: non-farmed soils; TS: terrace soils; RCS: runoff capture soils; TMS: tephra mulched soils; SMS: sand mulched soils; identical lower-case letters indicate no significant differences ($p < 0.05$) among the systems.

enhancement. To evaluate this question, we first examined the nutrient status of soils on the four different soil substrates of Lanzarote since soil fertility may be impacted by substrate age and the degree of leaching over the many millennia. The impact of high rainfall on soil nutrient levels over time has been clearly documented in Hawaîi (Chadwick et al. 2003; Vitousek et al. 2004) and Rapa Nui (Easter Island) (Ladefoged et al. 2010; Puleston et al. 2017). At these locations, higher elevation terrains have significantly greater annual rainfall and a reduced nutrient supply that is a result of long-term mineral weathering and leaching (for a summary see Vitousek et al. 2004).

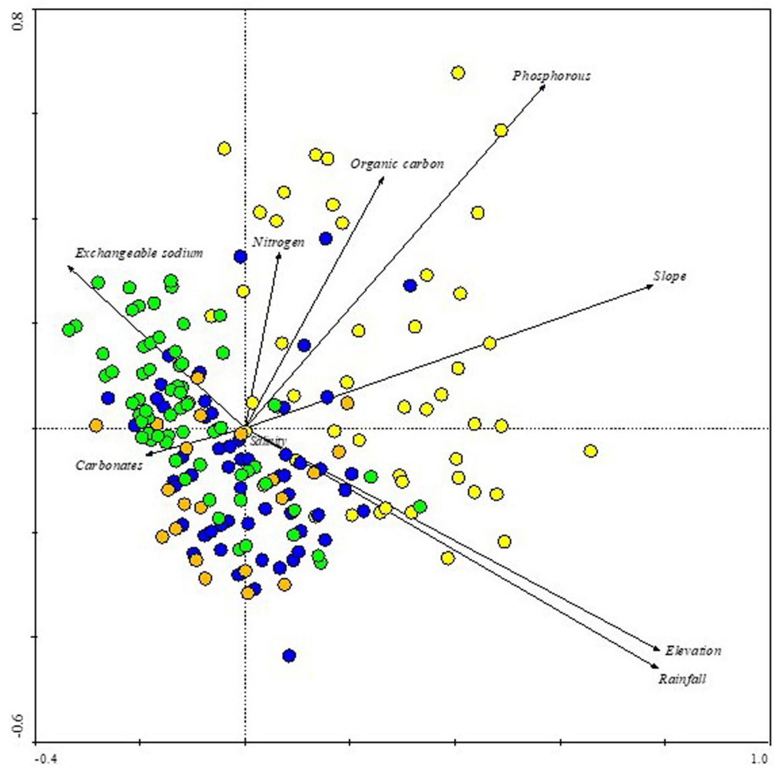

Figure 11. Principal component analysis of farmed soils; n = 30–80.

As noted above, the geological substrates of Lanzarote range from the Middle Miocene (14.5–13.5 Ma) to the nineteenth century. In Figure 9, the CEC values (meq/ $100g^{-1}$) have been plotted by substrate age from left (oldest) to right (youngest). The distributions of values for substrates are approximately the same with a CEC range between 20 meq/$100g^{-1}$ and 40 meq/$100g^{-1}$. The mapping of these CEC values (Supplemental Figure S8) shows the distribution of the CEC measurements across the island. The few low (0–10 meq/$100g^{-1}$) values are located near the coast and linked to sandy textures. Medium and high CEC values are near uniformly dispersed along the island.

Similar to CEC values, organic matter and nutrient contents did not show a discontinuous distribution pattern over the island. All soils (with the exception of some coastal locations) tended to be low in organic carbon (average $\sim$ 7.0 g kg^{-1}) and nitrogen (average $\sim$ 0.8 g kg^{-1}). Non-farmed soils and terraced soils were slightly enriched in soil available phosphorus (average $\sim$12.9 mg kg^{-1}) possibly as a result of a greater air-borne dust deposition in mountain areas originating each year from northern Africa (Muhs et al. 2010; von Suchodoletz et al. 2010). P could accumulate as a result of a lower plant uptake by natural vegetation (e.g., terraces were the first system to be abandoned and recolonized by natural vegetation). No significant differences in organic carbon (OC) and total nitrogen (TN) were found between agricultural systems and non-farmed soils, although a decreasing trend can be observed from non-farmed and terraced soils to the most intensively cropped systems with mulched soils (Figure 10). In the case of P that trend was statistically significant (Figure 10). Soil micronutrient contents were not different between agricultural systems and levels of Fe, Mn, Cu and Zn averaged 31.2, 18.9, 1.7 and 1.3 mg kg^{-1}, respectively, for the entire insular territory. This analysis suggests that soil fertility played a minor role in the distribution of the four distinct types of field systems (terraces, gavias, tephra mulched fields, *el jable* fields). It is probable that terrain features such as slope, elevation, and a modest variation in elevation dependent rainfall were the more influential determinants.

To assess this hypothesis a discriminant grouping analysis was conducted using elevation (masl), rainfall amounts (mm), terrain percent slope, and soil chemical parameters at each of the 243 soil sampling locations were classified by the type of agricultural field system (Figure 11). Three discernable groupings are present in the discriminant analysis output. In the two right hand quadrants, a dispersed group consisting mostly of terraced soils (TS) is present, mainly characterized by being located on sloped terrain and to a lesser extent by higher nutrients content. In the upper left quadrant, run-off capture soils (RCS) form a spatial cluster, distinguished for being located at low elevation and rainfall areas, and show a high percentage of exchangeable sodium and slightly increased carbonate content. Finally, in the lower left quadrant, tephra-mulched soils (TMS) and sand mulched soils (SMS) are closely associated, characterized by intermediate levels in altitude and rainfall, slightly increased carbonate content, and the lowest level in terms of nutrient content. Salinity (EC) does not appear as a relevant parameter for the system distribution.

Discussion

In the beginning of this paper we discussed the strength of our approach in treating islands as model systems (Kirch 2007; Vitousek 2004). In circumscribed landscapes where ecological, geochemical, and climatic variation are frequently less complex and spatially restricted compared to expansive continental settings (DiNapoli and Leppard 2018), we often have the opportunity to identify those aspects of the environment considered to be most central to understanding the interaction between human and natural systems. In our case, we have a well-defined starting point with the Spanish conquest in the late fifteenth century and a clearly documented human agenda of commodity production for export to profitable markets. What followed in the next four centuries was a series of agricultural (niche construction) experiments that sought to determine if Lanzarote farmers could be economically competitive in a global market given the numerous environmental constraints of the island landscape.

The first Spanish and Portuguese agrarians to settle on Lanzarote came from the southern arid region of the Iberian Peninsula. Even with a familiarity in farming the drier regions, there was a limited *a priori* knowledge of land suitability for agriculture. An arid landscape without many ecological markers of fertility may have been initially difficult to interpret. But the colonial Europeans were occupying an inherited landscape, and observations on Indigenous farming practices that focused on cereal production provided important clues. Knowledge transmission from the Indigenous people almost certainly occurred. Yet there were many potential problems for colonial farmers. There were geologically old and leached soils deprived of nutrients, and the surface soil in places was redeposited by wind from adjacent poor quality eroded soils. Nutrient uptake by plants would have been inhibited in places by the extremely arid conditions. Thus, a myriad of intervening variables may not have been fully understood by the immigrant agriculturalist, at least initially. The aridity of Lanzarote prevented the colonial wild harvesting of orchil lichen and the planting of the water needy sugarcane and agriculture emphasized cereal production. It is possible that cereals were cultivated in expanded forms of *gavias* catchment basin constructions or in open fields during the years when sufficient rainfall occurred. During this early sixteenth century period of colonial inceptive niche construction, grain varieties from Spain and other crops such as potatoes, sweet potatoes, and corn were introduced (Gil González 2005).

The early colonial farmers on Lanzarote faced a number of soil suitability issues that constrained agricultural production. The first among these challenges was the high salinity of soils (Figure 6) that prevented agriculture altogether in some areas. Located in the southwest, northcentral, and southeastern areas these soils were characterized by very high exchangeable sodium with an ESP of 30% or higher, and they are therefore classified as sodic. Saline-sodic soils are characterized by bare ground sometimes with a salt surface crust and have limited natural plant growth. Sodium and chloride are added to these soils largely through marine sea sprays carried by high seasonal winds. These marginal areas constituted a large amount of land not suited for farming.

A comparison of the location of field systems (Figure 2) with the occurrence of high ($>$4dS m^{-1}) electrical conductivity (Figure 5) and 20–30% percent exchangeable sodium (Figure 6) reveals that architecturally recognizable field systems are substantially less prevalent within these areas. Soils located further inland were usually very low in organic matter and nutrients, with the exception of phosphorus added by airborne dust from northern Africa (Muhs et al. 2010; von Suchodoletz et al. 2010). The distribution of soils with elevated cation exchange capacity values of 20–30 meq/$100g^{-1}$ or higher were present, but these soils are more-or-less uniformly distributed and do not constitute nutrient rich zones, or "sweet spots," that could have been targeted by agriculturalists. Regional variations important for farming appear to center around the spatial variation in rainfall and terrain features that could be integrated into the production system.

The most striking feature of the Lanzarote agricultural system is the extensive use of portable rocks and small boulders for field system infrastructure in the forms of plot boundaries, water diversion alignments, and terrace complexes. We do not currently know where the first colonial field systems were established and how they expanded, but the entire interior of the island was eventually transformed through the introduction of new varieties of cereals, the inceptive niche construction retooling of indigenous practices, and the establishment of open fields and hill-slope terraces. The early colonial farmers had specific production objectives in mind and built infrastructural improvements in areas that fundamentally changed the ecological relationships between plants and soil microorganisms resulting in higher soil fertility and crop productivity.

This immense human effort occurred at both the arid low elevations, where rainfall was 150 mm per year or less, and the more elevated highlands, where rainfall averages are about 250 mm per year. Irrespective of location, rainfall on Lanzarote is highly unpredictable and often occurs as short and relatively intensive rainfall events that generate high amounts of surface runoff. Water capture features such as *gavias* directed slope runoff into lower fields where the water and fresh sediment ponded and enough water was retained within the fine sediments to enhance soil generation processes and bring crops to maturity. The invention of this water capture method is currently thought to have originated with the Indigenous peoples and expanded upon after colonial intervention (Perez et al. 1999). Although currently runoff-capture systems constitute only a very small fraction of the total areas covered by agricultural architecture, probably it was the most important and extended form of crop production during the pre-colonial and early colonial periods, later surpassed by other systems based on inorganic mulching which were much more efficient in water conservation (Díaz 2004; Díaz et al. 2005).

In 1730–1736, and to a lesser extent in 1824, a series of volcanic eruptions covered the western third of Lanzarote. The Timanfaya lava flow and associated volcanic tephra covered existing agricultural fields, and took them out of production. The amount of area removed from farming was approximately 226 km^2 (Becerril et al. 2017) and it can be assumed that despite the counteractive niche construction activities of colonial farmers, the volcanic activity cut the agricultural outputs of the island significantly. Residents considered the lost land as some of the most fertile on Lanzarote and petitioned immediately for new property (Tous 1997). The volcanic activity resulted in loss of property, economic collapse, and an out-migration of people (Becerril et al. 2017).

Despite the destructive nature of the Timanfaya volcanic eruptions of the early eighteenth century, they created an unanticipated opportunity that changed the course of agricultural development for the next two centuries. The water conservation benefits of the new and vast deposits of volcanic tephra were realized within 30 years of the first eruptions in AD 1730–1736, and a new cycle of inceptive niche construction began. Introduced grape vines and fruit trees were planted beneath the surface covering (De León and Quintana 1999). Tephra, or stone mulching, is a method practiced in other arid and semi-arid regions of the world as a water retention technique (Lightfoot 1996; Stevenson et al. 2006; Wozniak 2018), and the occurrence on Lanzarote is an example of independent invention. While wine production in the Canary Islands collapsed in the early eighteenth century, production of wine and fruit on Lanzarote persisted throughout the eighteenth century in these anthropogenic stone mulched environments.

Beginning around AD 1750, observations in the Teguise town hall records noted a series of violent storms that moved deep deposits of "sand" into the center of the island at La Vega de Tao. The marine carbonate sand deposits (*Jables*) continued to expand noticeably in the next 40 years, and local authorities lamented the loss of arable land (Hernández-Pacheco 1909). The spread of the carbonate-sands was stimulated by human removal of coastal vegetation used as fuel for the production of "barrel stone" or soda ash from barrilla (*Mesembryanthemum crystallinum*) plants (Hernández and Rodríguez 1995). This anthropogenic de-vegetation destabilized the coastal sediments and increased interior eolian deposition. Accumulation continued and while colonial farmers employed counteractive niche construction techniques to ameliorate their impact, these wind-blown carbonate deposits of marine organisms eventually covered an area of 90 km^2 that extended from the town of Famara on the north coast to the southern shoreline 21 km distant (Cabrera, Alonso, and Alcántara-Carrio 2006).

During the late eighteenth century, colonial farmers began to make use of this transformed landscape through processes of inceptive and proactive niche construction. In these areas they created productive zones similar to that of the tephra mulched fields. In portions of *el jable* where the sand accumulations were less than a meter deep, sweet potatoes were successfully grown with a planting pit technology. The carbonate sands were first removed to reach the underlying substrate and then mainly fertilized with manure and refilled with sands capping the pit to serve as a moisture barrier (Jiménez et al. 2005). This niche construction created feedbacks between moisture levels, soil microorganisms, and soil nutrients, and provided a medium for crops to flourish and reach maturity. This innovation may have helped alleviate local subsistence stress during this difficult economic period.

During the nineteenth century, Lanzarote farmers participated in the harvesting and export of cochineal insects to European markets. The introduced cochineal insects lived on cactus pear (*Opuntia maxima*) host plants, and farmers engaged in inceptive and proactive niche construction with the creation of walled field systems and mulched plots which enhanced the survivorship of the cochineal insect and its host plant by reducing the selective pressures on both. The *Opuntia sp.* host plant is very drought tolerant (Nobel 1988) and its shallow rooting (Inglese et al. 2017) meant that it would benefit even from small rainfall events. The species does well with more than 300 mm of rain per year (Inglese et al. 2017), but the majority of the Lanzarote landscape experiences rainfall amounts of 150–250 mm/year, which is at the margin of tolerance even with a surface mulch. The presence of tephra mulch served to maintain a higher subsurface humidity and dampen stressful temperature and moisture oscillations during the day. In addition, while *Opuntia sp.* prefers a slightly alkaline soil (Zegbe, Serna Pérez, and Mena Covarrubias 2015), the plant biology is easily impacted by dissolved salts (Nerd, Karadi, and Mizrahi 1991). It has been shown that tephra mulch reduces the level of salinity in the upper soil horizon thus favoring a healthy functioning of the plant (Tejedor et al. 2003a, 2003b, 2007) and the growth of the cochineal insects.

Further innovations included the high field stone walls surrounding cactus plantings which lessened the constant winds characteristic of Lanzarote. This buffering was advantageous for the cochineal insect that builds its web on the surface of the cactus. Breeding studies show that excessive winds can prevent the secure attachment of the insect's nest to the cactus cladode (Aquino 1992, see Portillo and Vigueras 2017), and while young insects use wind to disperse to adjacent plants, high winds result in a larger dispersal distance and a greater risk of not landing on an adjacent cactus cladode (Flores 1995, see Portillo and Vigueras 2017). Any one of these two factors reduces the insect's survival. Although much of cochineal breeding was eventually done by human transfer, the construction of wind barriers removed a significant selective pressure and assisted with successful breeding.

The export of cochineal insects to European markets was highly profitable and exports from the Canary Islands reached 24.6 million libras (11.3 metric tons) at its peak (Silva and Bosa 2006), but Lanzarote was a more limited producer compared to Gran Canaria and Tenerife which generated 95% of the total production (Hernández 1990). If decision making on Lanzarote was similar to the other Canary Islands such as Tenerife, then the areas within higher moisture zones on Lanzarote were probably brought into production first and this area would have been the mountainous regions located in the northwest (Supplemental Figure S1). We can speculate that more marginal (drier) areas were then added in the face of market demand. One of the strengths of tephra mulching technology would be that it allowed for plantings to be established in drier areas but without a great decline in yield. The soils studies reported here indicated that on Lanzarote these were moderately fertile, but they were not depleted. As such, cochineal production could have expanded past the end of the nineteenth century. Although carbon and nitrogen levels are low in this arid region (Díaz 2004), soil depletion was not a factor in the economic collapse of Lanzarote and the explanation is best supported by external market factors.

Conclusion

Agricultural niche construction on Lanzarote was a historically contingent process where geological and climatic events resulted in unique opportunities for European agricultural development which were radically different from the traditional agriculture practices of the Indigenous population. Human agency as a driver behind colonial agricultural development and profit maximization is clearly documented in the written historical record of the Canary Islands. The implementation of colonial inceptive and proactive niche construction on Lanzarote was constrained by severe aridity and saline-sodic, poor nutrient soils and initially confined farmers to raising predominantly cereals. Infrastructure development may have initially mimicked Indigenous dryland farming with fields on valley floors fed by surface runoff from lateral slopes. Innovations soon followed by the addition of larger surface water capture methods, such as catchment basin construction (*gavias*) and terrace constructions on steeper landforms. During the eighteenth century, the anthropogenic clearing of vegetation from the coast and a series of storms stimulated eolian deposition of carbonate sand and the creation of a new niche that sweet potato farmers refined and exploited. After the Timanfaya eruptions of AD 1730–1736 and the creation of a vast deposit of particulate lapilli, or tephra, in the south-central third of the island, water conservation through the application of tephra mulch (*arenados*) was implemented, and this allowed the expansion of agriculture into larger areas. This new technology created a niche that was well suited for raising pear cactus as a host for the cochineal insect, as the nutrient and moisture requirements for this plant were low. This technology facilitated the rapid growth of a monocrop agricultural economy that helped create a vast island-wide infrastructure. The nineteenth century collapse of cochineal production was triggered by external market forces with attempts to increase yields and lower prices, impossible within a moisture limited environment of overall low fertility. The various episodes of colonial agriculture on Lanzarote were successful but ultimately not sustainable in the face of external economic forces.

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Disclosure statement

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Figure S1. Mean annual precipitation in Lanzarote Island (30-year series; 1970-2000). Raw data from AEMET.

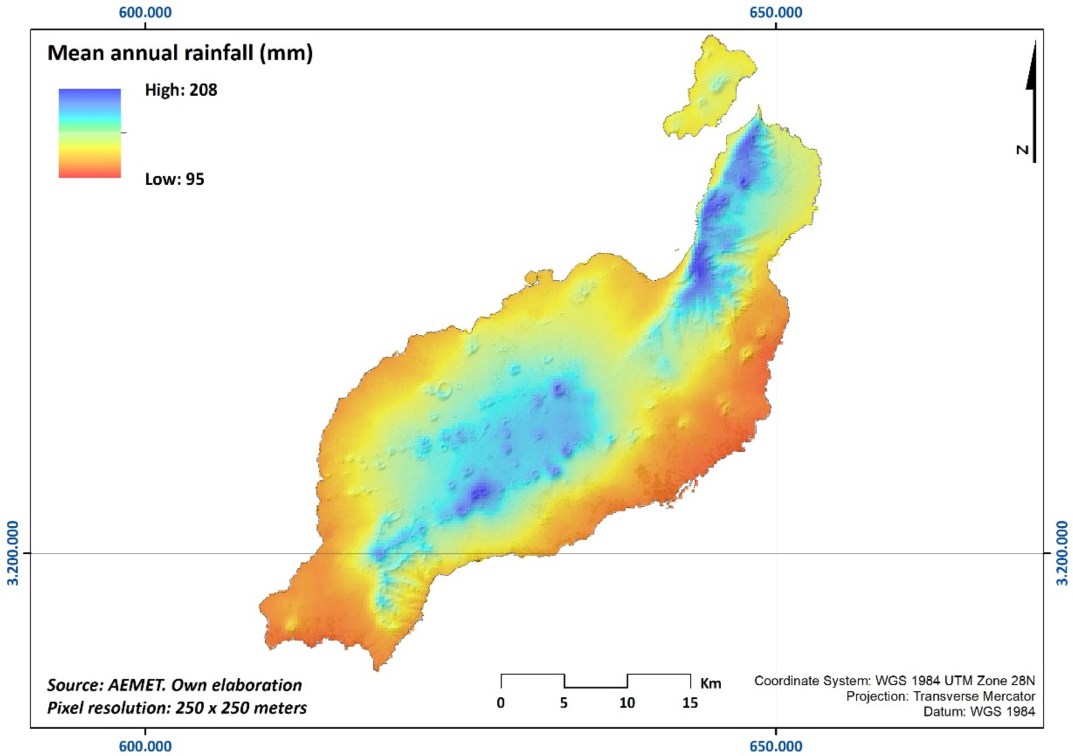

Figure S2. Mean annual air temperature in Lanzarote Island (30-year series; 1970-2000). Raw data from AEMET.

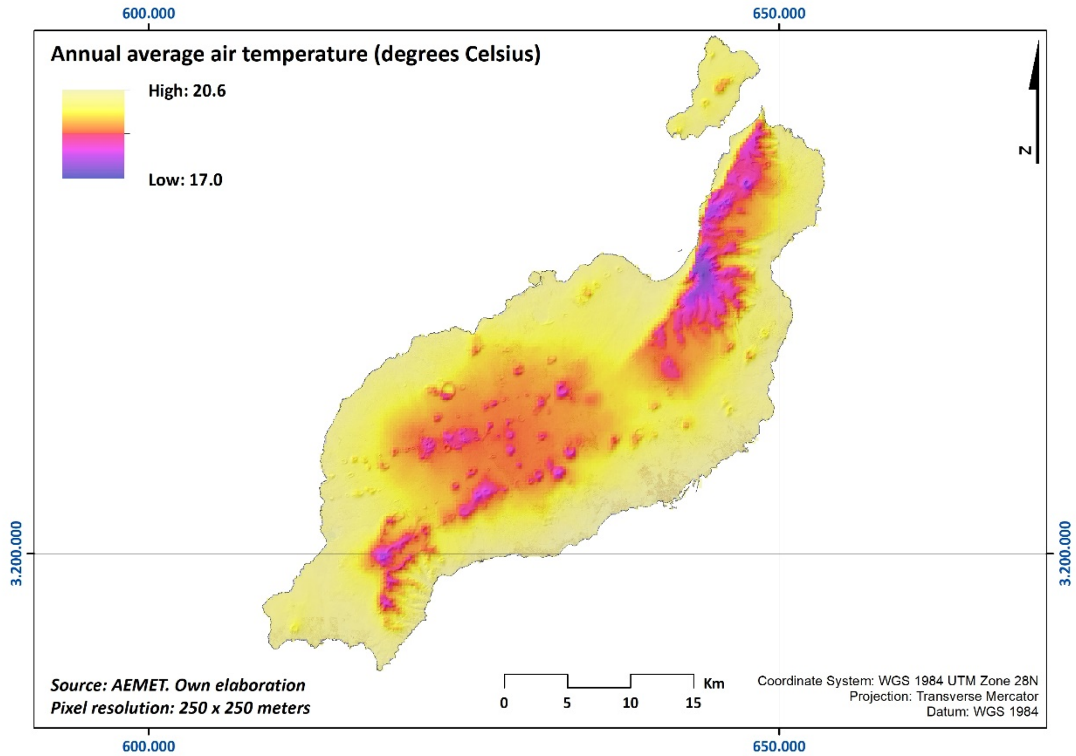

Figure S3. Aridity Index for Lanzarote Island (30-year series; 1970-2000). Potential evapotranspiration calculated using FAO Penman-Monteith equation.

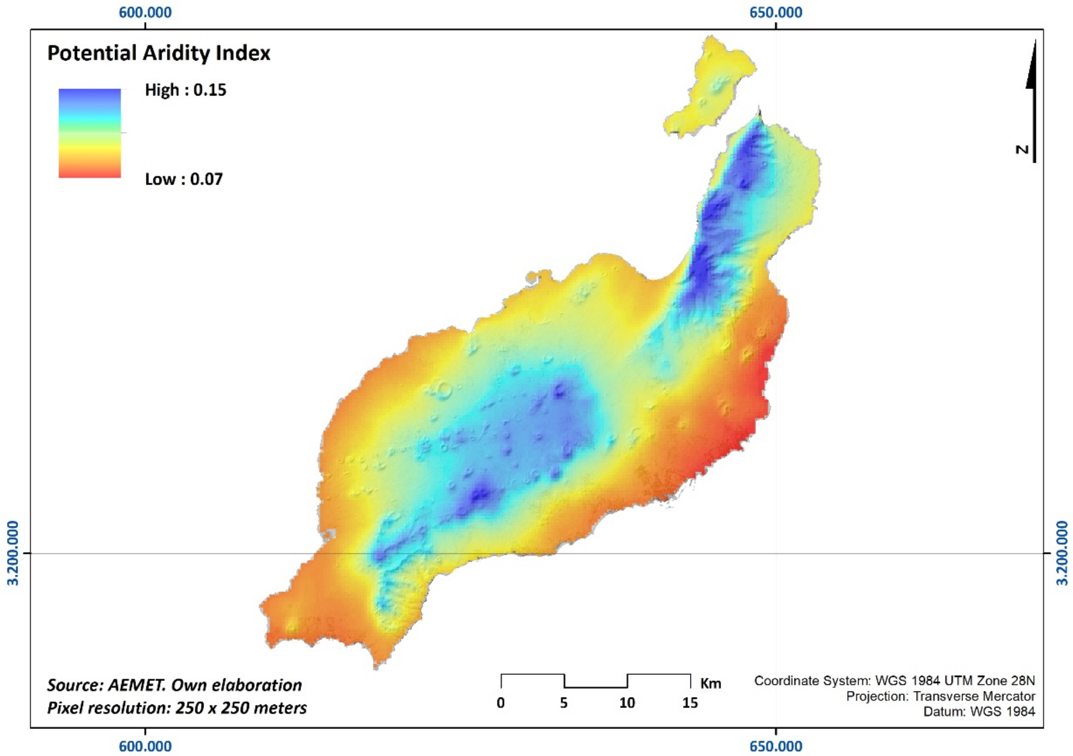

Figure S4. Surface slope distribution on Lanzarote Island. LiDAR data from IGN.

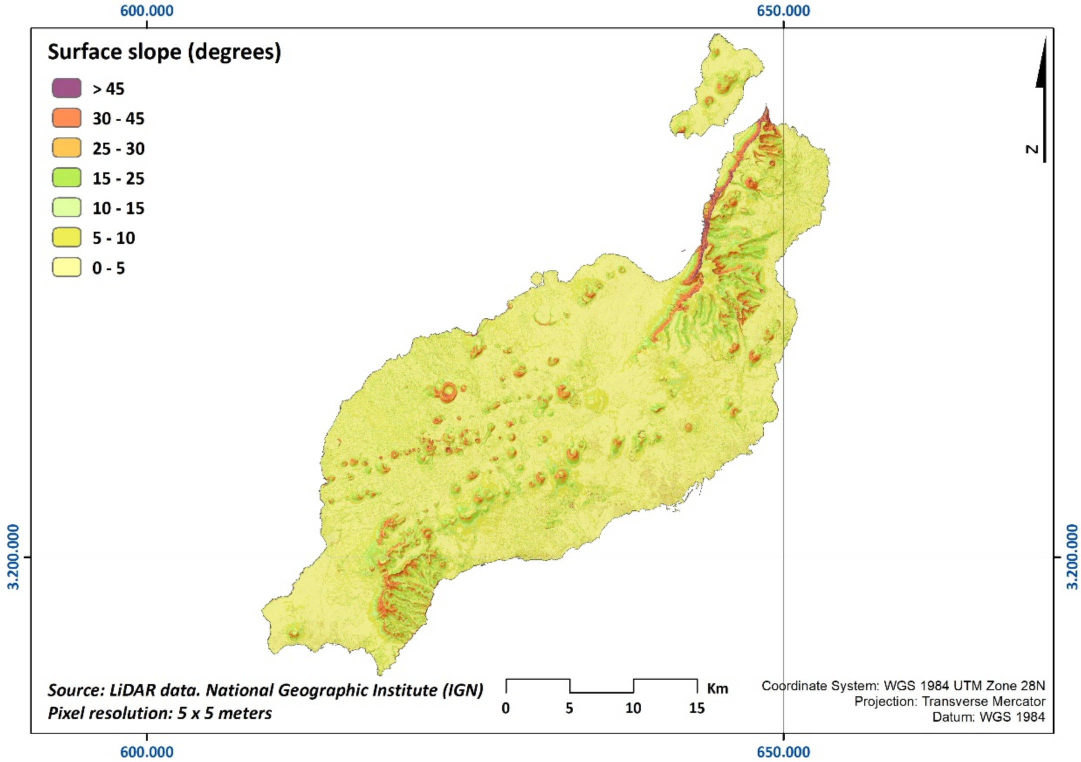

Figure S5. Geological map of Lanzarote Island. Adapted from Barrera and García (2011).

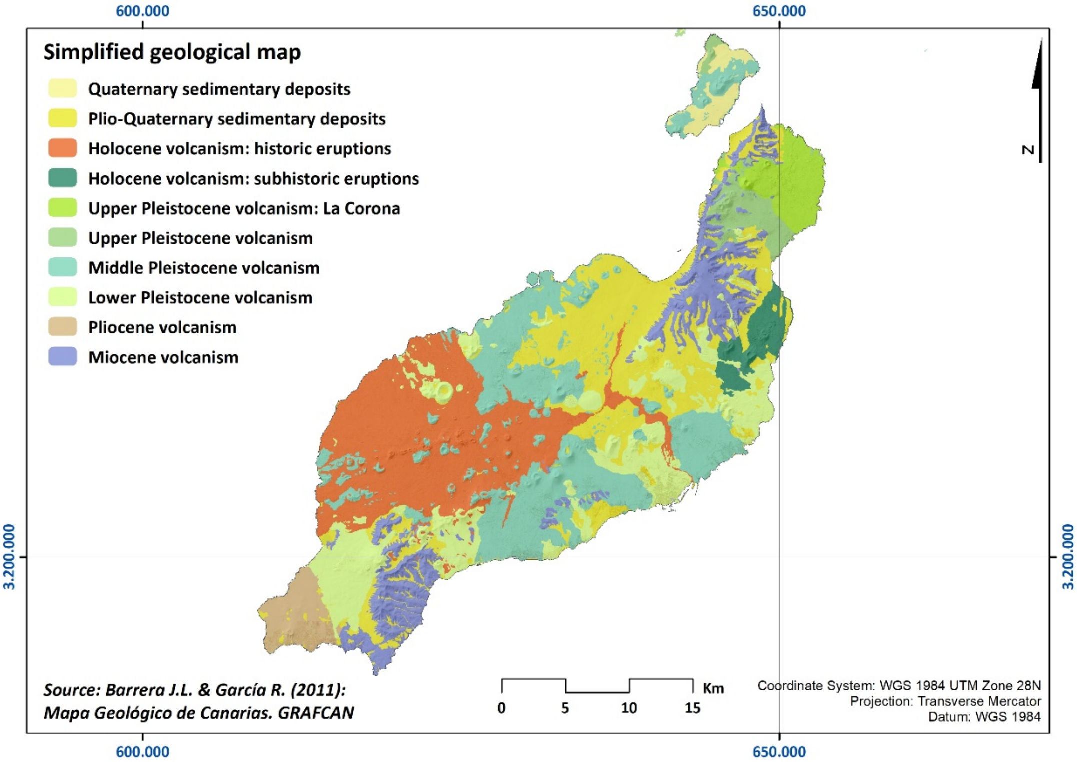

Figure S6. Soil map of Lanzarote Island. Soil Taxonomy 2014. Adapted from Rodríguez (2011).

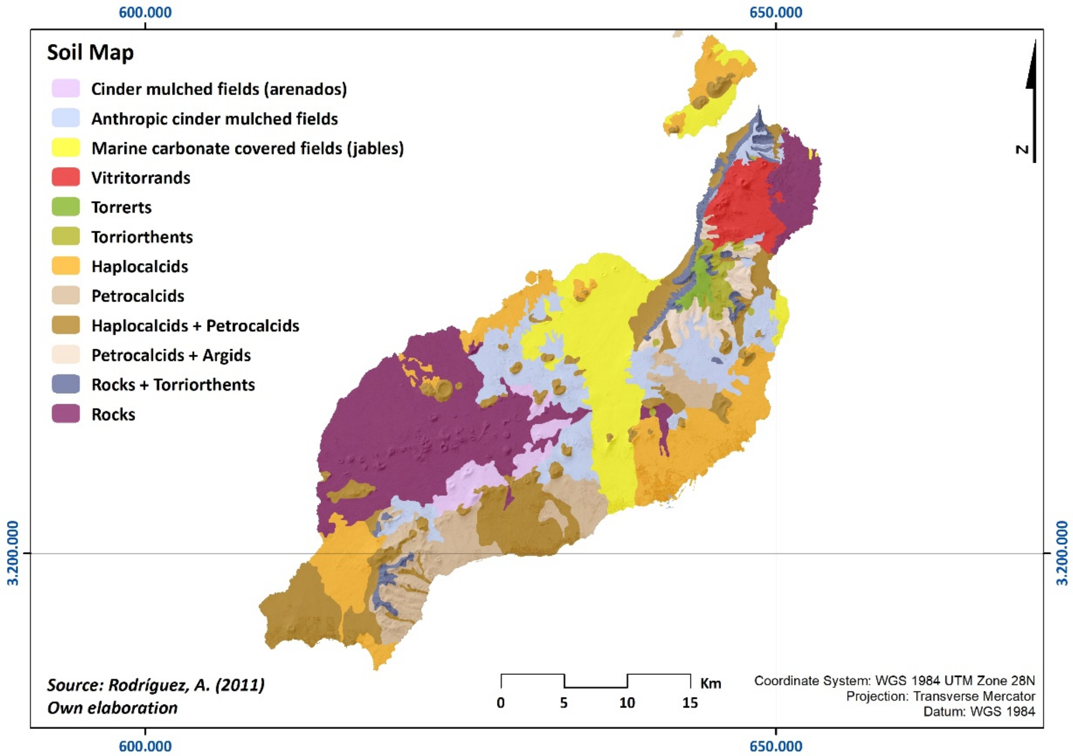

Figure S7: Soil sampling locations on Lanzarote, Canary Islands, Spain.

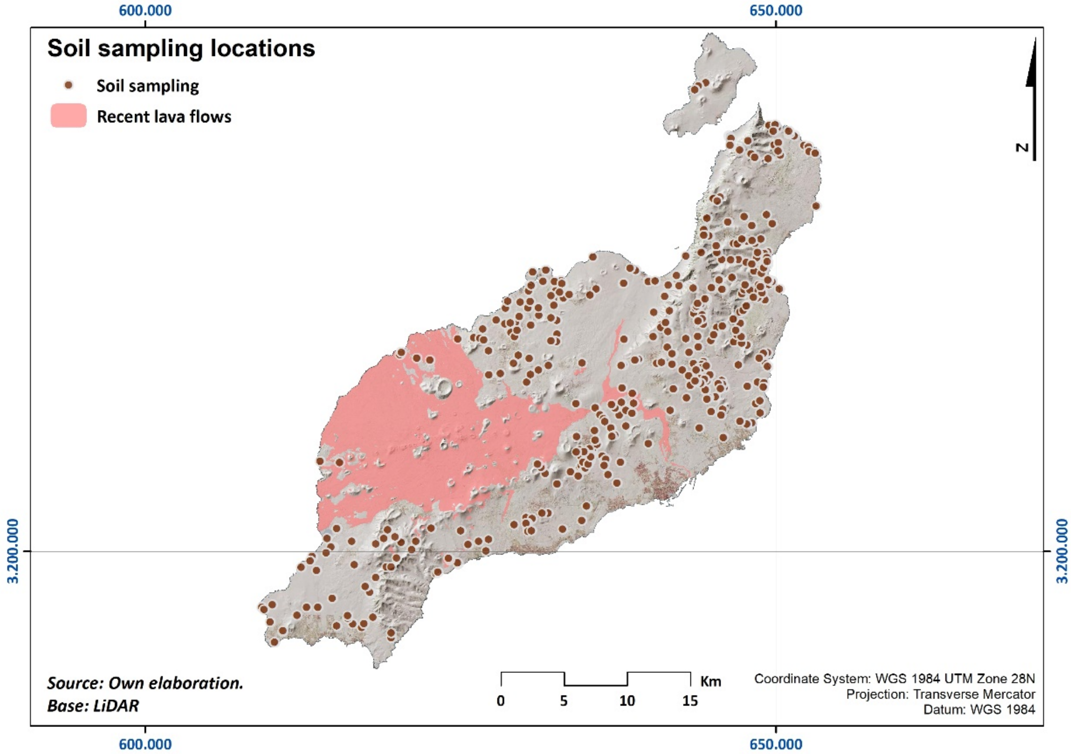

Figure S8: Cation exchange capacity on the island of Lanzarote.