Science of the Total Environment xxx (xxxx) xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Deforestation by historical lime industry in an arid aeolian sedimentary system: An applied and methodological research

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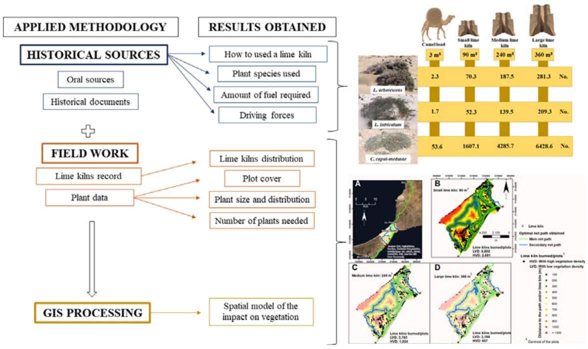
HIGHLIGHTS

- The historical deforestation by the lime industry in a dune system is analysed.
- A methodology is developed to assess deforestation.
- The lime industry produced biogeomorphological alterations.
- Historical deforestation driving forces were socioeconomical and spatial.
- The driving forces of the current vegetation recovery are being technological.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 September 2021
Received in revised form 11 November 2021
Accepted 23 November 2021
Available online xxxx

Editor: Fernando A.L. Pacheco

Keywords:
Deforestation
Driving forces
Lime kiln
Historical ecology
Limestone production
Logging

ABSTRACT

Traditional land uses have been altering aeolian sedimentary systems for centuries through the removal of plant material for grazing, fuel or farming purposes. However, few studies have been able to quantify the deforestation process associated with these land uses due to the complexity that this entails and the limitations of the historical sources. In this context, the aim of this work is to develop a methodology that allows to reconstruct, evaluate, measure and locate the effects of deforestation processes. The methodology, based on the interpretation of historical documents, oral interviews and publications in the literature; was applied to a case study in Jandía (Fuerteventura, Canary Islands, Spain). On the basis of morphological measurements of the types of plant used to fire lime kilns, the current available biovolume was determined and an estimation made of the surface area affected by plant removal. The data obtained were integrated and analysed through a geographic information system (GIS) in order to quantify the impact of the lime kiln industry on the vegetation in the study area. The main results show that to fire a large-sized lime kiln oven it would be necessary to clear a low-density vegetation area of 21,826.08 m^2 (or a a high-density vegetation area of 3075.72 m^2) using three main species (*Launaea arborescens*, *Lycium intricatum* and *Convolvulus caput-madusae*). It was also found that distances of up to 38 km had to be travelled to obtain the vegetation required to fire the kilns. It is concluded that a number of impacts resulted from the demands of the limestone industry, particularly on plant communities, the abundance of certain species and flora richness, as well as modifications to geomorphological processes and the eventual collapse of the activity in the 1960s through overexploitation of the plant material. The present research allows us to learn from past experiences in which industries lacked proper planning and thus their activity led to their own collapse and rapid environmental degradation.

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http://dx.doi.org/10.1016/j.scitotenv.2021.152009

Please cite this article as: N. Marrero-Rodríguez, L. García-Romero, A.I. Hernández-Cordero, et al., Deforestation by historical lime industry in an arid aeolian sedimentary system:..., Science of the Total Environment, http://dx.doi.org/10.1016/j.scitotenv.2021.152009

1. Introduction

Aeolian sedimentary systems are among the ecosystems that have suffered most as the result of human uses and their evolution over the course of time (Thomas and Wiggs, 2008), whether this use has been to obtain fuel or materials for construction or for grazing purposes (Kutiel et al., 2004; Levin and Ben-Dor, 2004; Provoost et al., 2011; Sciandrello et al., 2015; Hoffman and Rohde, 2007). More recently, recreational uses (Sanromualdo-Collado et al., 2021) and urbanization processes have been the leading causes of degradation (Feng et al., 2021). The reconstruction of these uses in the present work is approached through the methodological framework of historical ecology (Szabó, 2015), using a wide variety of sources (Miller, 1999; Bürgi et al., 2000; Nüsser, 2001; Skovlin et al., 2001; Petit and Lambin, 2002; Axelsson et al., 2002; Pinto and Partidário, 2012; Raska et al., 2015), and with the aim of preserving cultural heritage in ecosystems and landscapes, understanding historical trajectories, and improving ecosystem and landscape management (Bürgi and Gimmi, 2007).

Apart from farming and grazing, one of the oldest human activities that has contributed to the alteration of aeolian sedimentary systems is the production of lime. At global level, the lime industry and the techniques employed in it have evolved substantially over the course of history. Archaeological references indicate an industry with a 16,000-year-long history, while the first written references date back to Marcus Pourcious Cato (234–149 BCE) and his description of how to build and use a lime kiln (Swallow and Carrington, 1995; Wernecke, 2008). One of the many historical uses of lime was to soak corn kernels in water to dissolve the outer shell, thereby releasing proteins and vitamins (Food Agricultural Organization of the United Nations, 1992). Mesoamerican communities chewed lime and tobacco together to release nicotine (Miner, 1939; Marcus and Flannery, 2004), purify water, accelerate the decomposition of buried corpses, regulate the pH of agricultural soils, and as decorative paint, among other uses (Manzano-Cabrera, 2016). However, it has been for construction purposes that vast quantities of this product have been required and demanded, especially for local consumption or exportation (Marrero-Rodríguez et al., 2020a, 2020b). This demand has resulted in substantial deforestation (Diamond, 2005), as huge amounts of fuel are required for its production (Abrams and Freter, 1996; Barba and Cordova Frunz, 1999; Schreiner, 2002). In this regard, some works have analysed and discussed the environmental degradation process associated with the lime kiln industry in the Mayan civilization in Central America (Wernecke, 2008). However, there is a gap in the scientific literature when it comes to addressing reconstructions of the impact of specific historical activities that have led to the degradation of an ecosystem. Normally, the approach used when considering historical deforestation is to treat it is a general phenomenon, but this does not take into account the different species involved or the specific needs of each industry. In contrast, the approach used in the present study links and connects information gathered from historical and oral sources with specific characteristics of the lime kiln industry, as well as with the types of vegetation in the study area and their particular characteristics.

The lime kiln industry in the arid aeolian sedimentary systems of the Canary Islands (Spain) seems to have been common and to have had three main consequences: the exploitation of large areas as quarries for limestone extraction, sediment remobilization, and massive deforestation associated with fuel demand on the islands of La Graciosa and Fuerteventura (Santana-Cordero et al., 2016; Marrero-Rodríguez et al., 2020a). The amount of fuel that is demanded is conditioned by the type of vegetation (Schreiner, 2002; Marrero-Rodríguez et al., 2020b), the type of kiln used (Wernecke, 2008), the composition of the limestone (Schreiner, 2002), and the experience of the worker in charge of firing the kiln.

It has been shown in the literature that the use of vegetation results in alterations in plant community population structures (Sala et al., 1986), changes in species richness (Kutiel et al., 1999; Faggi and Dadon, 2011; Báldi et al., 2013), remobilization of sand sheets (Hoffman and Rohde, 2007; Marrero-Rodríguez et al., 2021), and erosion processes (Angassa, 2014).

In previous works, given the complexity involved, historical deforestation processes have not been not quantified or spatialized. In this context, there is a gap in the scientific literature that methodologically addresses historical deforestation processes. To fill this gap, the methodology proposed and applied in the present work allows a reconstruction of the deforestation process by combining oral sources, historical documents and field work. The information obtained is then quantified and spatialized using a geographical information system (GIS). In this regard, the main aim of this work is to develop a methodology that allows to reconstruct, evaluate, measure and locate the effects of deforestation processes and apply that methodology to a case study on the island of Fuerteventura (Canary Islands, Spain) involving the historical lime kiln industry. In turn, the specific aims sequenced of the case study are: i) to create a list of the species that could be burned in lime kilns and to determine the amount of vegetation required by the industry; ii) to measure the surface area of the aeolian system that was affected and the number of plants used; iii) to find and analyse the driving forces behind the intensity of the deforestation process and vegetation recovery after the decline and disappearance of the lime kiln industry.

2. Study area

The aeolian sedimentary system of Jandía, with an area of 54 km^2, is located on the southern coast of the island of Fuerteventura in the municipality of Pájara (Fig. 1). The area has been described as having a warm desert climate with marked aridity (Alonso et al., 2011). The scarce and highly irregular precipitations are concentrated in just a few days of the year, and do not usually exceed 100 mm. The high temperatures, with annual averages of around 20 °C, the intense insolation and the strong and frequent winds favour evaporation (Alcantará-Carrió, 2003). The isthmus is covered by sand, predominantly biogenic. The sediments come from the erosion of aeolianite deposits and quaternary calcareous crusts located in the inner part of the isthmus and from occasional sandy contributions from the current beaches or the erosion of the materials that constitute the cliffs of Barlovento (Alcántara-Carrió, 2003; Alcántara-Carrió et al., 2010). The sediments are subject to almost continuous aeolian transport by the dominant NW winds which form the nebkha field, a rampant dune on the southern limit of the windward side and two falling dunes in Sotavento (Alcántara-Carrió, 2003; Alcántara-Carrió et al., 2010). Aeolian transport takes place in a SSE direction (Alcántara-Carrió and Alonso, 2002; Alcántara-Carrió et al., 2010; red arrows in Fig. 1) and marine dynamics are responsible for redistributing the sediments southwards (blue arrows in Fig. 1).

Vegetation at the present time consists of shrub and herbaceous plant communities, principally xerophilic, halophilic and psammophilous species. According to the Canary Islands vegetation map (Del Arco, 2006), most of the area is occupied by the phytosociological association *Polycarpaeo niveae-Lotetum lancerottensis*, fundamentally constituted of chamaephytes like *Polycarpaea nivea* and *Lotus lancerottensis*, which establish themselves on compact sandy substrates or sandy-rocky substrates. Also of some importance is the *Euphorbio paraliae-Cyperetum capitati* association, a community comprising herbaceous psammophilic and chamaephyte species like *Euphorbia paralias* and *Cyperus capitatus*, associated to mobile sand areas. However, physiognomically, the dominant species are the shrubs *L. arborescens* and *Salsola vermiculata*. Jandía is also home to one of the most important populations of *C. caput-medusae*, a small halophilic shrub endemic to the Canary Islands which has been included in the vulnerable category of the Canary Islands Catalogue of Protected Species and in Appendices II and IV of the Habitat Directive.

The Isthmus of Jandía was used only as grazing land until approximately 1850, when references about obtaining fuel there appear for the first time in the historical documents. These traditional activities ceased with the emergence of tourism in the island, from 1960 onwards. The rise of tourism resulted in the extraction of aggregates for construction and the creation of urbanizations, infrastructures and tourist facilities along different coastal areas of the isthmus (Marrero-Rodríguez et al., 2020a). At present, the area considered in the study has two main urban centres

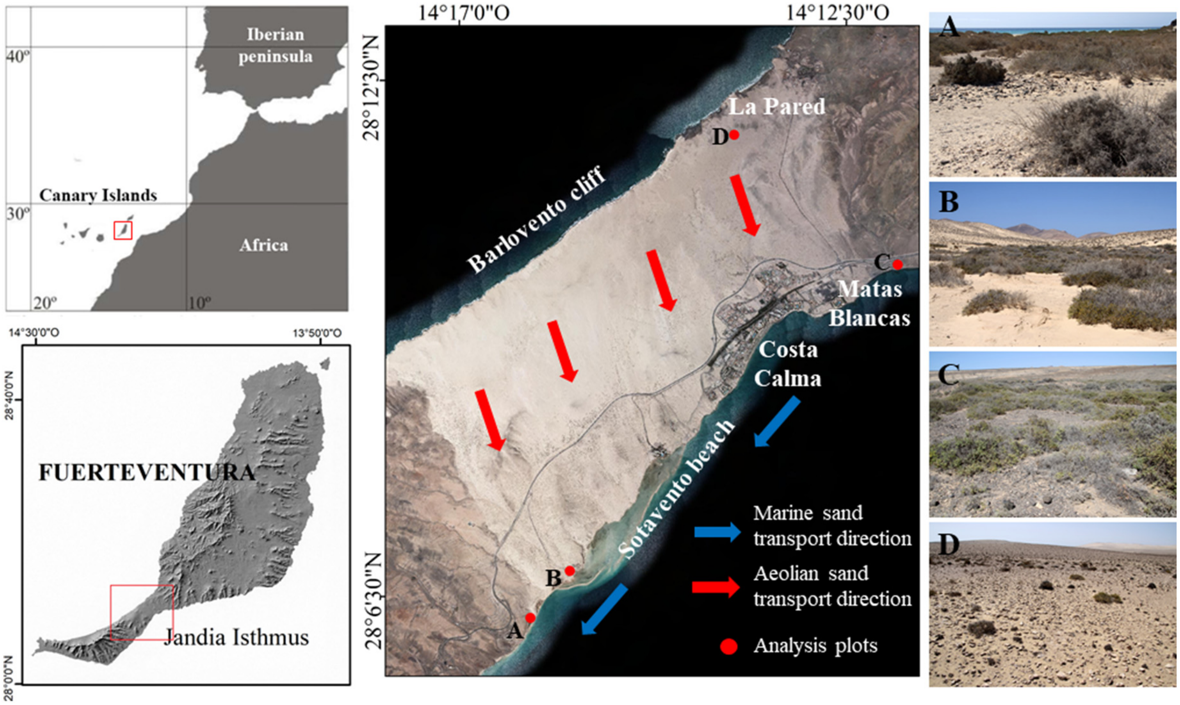

Fig. 1. Location of the study area and plots. General view of the plots in photographs on the right. 2019 digital orthophoto source: SDI Canarias (Gobierno de Canarias, GRAFCAN, S.A.).

(Costa Calma and La Pared). The development of tourism has led to alterations to the aeolian sedimentary system, especially in terms of the erosion of the beaches of the southern coast due to the reduction in the supply of sediments to the coast from inland sedimentary deposits. This reduction has been due to the generation of physical barriers through the construction of tourist complexes and roadways, as well as sand extraction and landscaping along the roadways (Alonso et al., 2002).

3. Methodology

The methodology that has been developed can be divided into three main parts: the analysis of the historical sources and the oral interviews that are conducted as part of the methodology, field data collection, and the processing of the information obtained in the two previous steps in a GIS (Fig. 2).

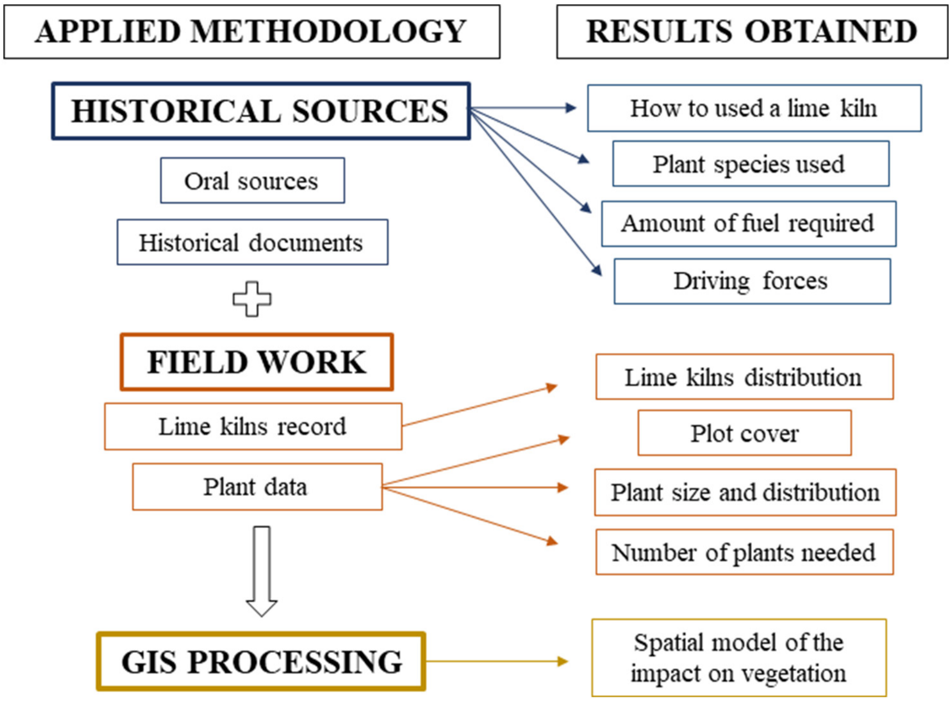

Fig. 2. Methodological scheme and results obtained from the historical sources, the field work and GIS processing.

3.1. Historical sources

Among the most relevant historical documents used for this work is the report prepared by the secretary of the Pájara City Council (Fuerteventura, Canary Islands), Mr. Justo P. Villalba, in 1868, titled "Description of the *Dehesa de Jandía*". In this document, consideration is given to the uses of the land at the time and to its potential uses (Villalba, 1868). The minutes of the corresponding Fuerteventura Island Council meeting (Roldán, 1966, 1967, 1970) are also reviewed. In addition, an analysis is undertaken of the information recorded in a video of the burning of limestone made in Tefía (Fuerteventura), as well as that contained in an inventory of lime kilns stored in the archives of the Island Council of Fuerteventura. A total of 8 oral interviews were also held with the last lime kiln workers still alive with the aim of gathering information on the activity. The interviews were conducted following the oral history methodology (Fogerty, 2005), which is based on a semi-structured conversation, with an open script, between an interviewer and an interviewee. The interviewees were aged between 73 and 101, and were people who had personally been involved in firing lime kilns in the study area. In this way, it was possible to find out which species were used as fuel, the areas from which the fuel was obtained, the characteristics of the lime kilns (such as their shape and size), the number of firewood loads required to burn a single kiln (camels were used to transport the material), and the quantity of fuel (m^3) needed (the capacity of the small-sized kilns was 90 m^3, of the medium-sized ones 240 m^3, and of the large-sized ones 360 m^3). In the historical documents and oral interviews, the species are called by their common name. By way of example, the genera *Salsola*, *Suaeda*, and *Schizogyne* are all commonly called *salty plants*. Therefore, the common names were taken, and all the species that receive this name and that have current populations or for which there are historical records of their presence on the island of Fuerteventura were selected. In addition, it was considered that when a common name appeared in a specific document, all the species of that genus would have potentially been introduced into the kilns.

3.2. Analysis of the impact on vegetation of the lime industry in the aeolian sedimentary system

In order to determine the impact of the lime industry on vegetation in the aeolian sedimentary system of Jandía, an estimation was first made of the surface area affected by the removal of the amount of plant material required to generate this product according to the particular characteristics of that material. For this, the first step was to calculate the biovolume that could be obtained through the removal of vegetation in a specific area and compare it with the amount required for lime kiln operation. That is, based on the amount of vegetation currently present in the area, it was possible to determine through extrapolation the amount that would have been required for each lime kiln size. Consideration was also given to the fact that not all plant species were suitable for lime kiln firing. Based on the information recorded in the historical sources, three species were selected: *Launaea arborescens*, *Lycium intricatum* and *Convolvulus caput-madusae* (see excerpt of the review and report to Francisco Cabrera and Justo P. Villaba in the Results section). These plant species were the preferred choices to fire the lime kilns. To determine the currently existing biovolume and compare it with what was required for a lime kiln operation according to the oral sources, a field campaign was carried out over the course of September 2020. This time of the year was chosen as the oral sources indicated that the best moment to harvest the vegetation was at the end of the dry season when it burnt best. Disused lime kilns were located during the field campaign, and specimens of the three previously mentioned species were identified in the areas around the kilns. Plots were marked in areas close to the ovens where these species were present in order to measure the morphological characteristics of each plant. The variables that were measured in each specimen were height, largest diameter and smallest diameter. The data were recorded for a total of four plots (Fig. 1), with each plot having a surface area of 1250 m^2 (50 m long × 25 m wide). Three plots were situated in the immediate surrounding area of the kilns (plots A, B and C), and one in a kiln-free area as the toponym of that particular area (The Wall) was cited by various of the oral sources as a plant collection site (plot D). The measured variables allowed calculation of the biovolume based on a cylindrical morphotype through the following equation (Blanco Oyonarte and Navarro Cerrillo, 2003):

$$B_v = \pi * \left[\frac{Dm}{2}\right]^2 * h \tag{1}$$

where Bv is biovolume in cubic meters, Dm is mean diameter (metres) and h is height.

The result of this formula was then multiplied by a correction factor according to the porosity (Baldauf, 2017) of each of the three sampled plant species. This allows a more precise biovolume estimation. A correction factor of 1 was applied to the two low porosity species, *Launaea arborescens* and *Convolvulus caput-medusae*, and a correction factor of 0.5 to the species of higher porosity, *Lycium intricatum,* the result of its lower compactness.

Given the variable characteristics of the plants in the different plots (plant cover and plant size), the different vegetation conditions were also identified during the field campaign in order to estimate with precision the affected surface area. For this, the following were calculated: the number of individual plants of the optimal species for lime kiln firing, plant cover (m^2), total biovolume and vegetation density. This latter datum was obtained based on the method developed by Mostacedo and Fredericksen (2000) to calculate tree density per hectare, as follows:

$$Dh = \frac{10000}{(\overline{D})\ 2} \tag{2}$$

where Dh is density per hectare and $\overline{D}$ is average distance between the central points.

On the basis of these variables, a cluster analysis was then performed using the Ward method (Euclidean distance) to group plots with similar vegetation conditions and to determine the surface area affected by removal of this vegetation according to its characteristics. Through the mean biovolume of each cluster group, and using plot size as reference (1250 m^2), it was determined how much surface area was affected by each lime kiln firing according to lime kiln size (small-sized = 90 m^3 capacity, medium-sized = 240 m^3 capacity, and large-sized = 360 m^3 capacity) and the different characteristics of the vegetation, using a direct proportion calculation.

3.2.1. Spatial model of the impact on vegetation of the lime kiln industry

In order to determine the spatial impact of the lime industry on the aeolian sedimentary system of Jandía, we considered the following questions:

i) Where did the vegetation removal take place? The optimal routes to the lime kilns were calculated using the toponyms that appear in the historical and oral sources (sites of vegetation removal and sites where the lime kiln workers lived), and as basepoint the digital elevation model (DEM) obtained from a LiDAR flight (spatial resolution of 1 m - corresponding to 2017). The routes, although adapted to the optimal conditions of the terrain (slope, secondary net path), were corrected to avoid large volumes of sand that would hinder transport by foot or with pack animals such as camels (slope + aeolian landforms, main net path).

ii) Where were the plots/zones of highest/lowest vegetation? The 2017 orthophoto was used (spatial resolution: 0.25 m and resampled to 1 m) to develop the procedure proposed by García-Romero et al. (2018) to calculate and classify vegetation density in arid aeolian sedimentary systems through airborne data sources. This procedure resulted in 4 vegetation density categories. Two were characterised as low vegetation densities and zones (fishnet tools in GIS) with dimensions that were calculated on the basis of the data of plots B and D (low vegetation) were assigned to them. The other two categories obtained were higher vegetation densities and zones were assigned to them with dimensions that were calculated on the basis of the data of plots A and C (abundant vegetation).

iii) How many lime kiln firings could the aeolian sedimentary system of Jandía provide? A maximum count of all the zones with the dimensions and characteristics determined on the basis of the calculations made was performed, and these were situated in the zones obtained according to vegetation density in the answer to the previous question. Finally, the distance was calculated (near tools in GIS) to the optimal routes and kilns in order to interpret their spatial distribution.

3.2.2. Analysis of the driving forces

The analysis of driving forces was undertaken following a shortened version of the procedure proposed by Bürgi et al. (2005), as in that case the methodology was applied to an industry developed in a specific space and period of time rather than to the general evolution of a landscape. In this regard, although there are other driving forces that altered the aeolian sedimentary system of Jandía, in the present study only those related to the lime kiln industry are analysed. This analysis involved two main steps: i) definition of activity and landscape, in which basic information about the industry and study area is described; ii) system analysis, which focuses on driving forces, their scales, and changes to physical landscape elements. The driving forces are presented in relation to the two main processes associated to the lime kiln industry in this context. Deforestation and vegetation recovery after the decline and cessation of the activity.

4. Results

The lime industry activity began in the Canary Islands shortly after they had been conquered by the Spanish (15th century) and continued until approximately the end of the 1960s. However, the industry underwent important changes after the beginning of the 20th century that conditioned the demand for vegetation. These included shipments of unburnt limestone due to the demand for its use in other islands where there was a shortage of plant material for lime kiln firing, the appearance of coal as an alternative fuel source, and the displacement of the lime kiln industry to industrial zones and ports as the demand for lime rose. From the 1960s onwards, the importation of vast quantities of cements and synthetic paints resulted in a rapid decline of the lime business throughout the archipelago. Although the demand for plant material coincided with the commencement of the lime industry shortly after the conquest of the islands, it was a relatively minor activity until the middle of the 19th century when demand began to increase significantly. It can therefore be concluded that the highest demand for vegetation in the Jandía peninsula took place in a period extending from approximately 1850 to 1960.

4.1. Species likely to be used as fuel in the kilns

A list of plants that could be used as fuel in the lime kilns was generated on the basis of various historical documents, the revised bibliography and different oral sources (Table 1).

To understand why a particular plant would have been chosen as fuel it is important to understand the lime kiln firing process and the structure of the kiln. The kilns have a grate under which a hole is dug that is filled with plant material which will burn when the kiln is initially fired. Here, the ashes left over from the burning of the plants will accumulate (Fig. 3A and B). At the base of the kiln is a small opening through which fuel can be introduced (Fig. 3C) and the kiln fired. The size of the opening must be small enough to minimize the escape of heat but large enough to allow the introduction of fuel. The kiln is fired at night (Fig. 3D and E), as the lower temperatures allow the lime kiln operator to carry out his work next to the kiln, which can reach temperatures of up to 1000 °C. Each time a lime kiln operation is performed, fuel needs to be introduced via the lower opening of the kiln over a period of approximately 48 h until the process is concluded (Fig. 3F).

With these characteristics in mind and as ascertained in the oral interviews that were held, the species to be introduced into the kiln had to meet certain requirements. The plants that were introduced could not leave excessive amounts of ash after their burning as this could end up silting up the space dug beneath the grate bars of the kiln and result in the stone remaining raw and unsellable. In addition, according to the interviewees, some woody plants burn too slowly and do not give off enough heat to reach the upper part of the kiln, which could be up to 3 m high, where the stone is situated. In addition, if the plant material did not burn quickly enough, the opening through which the fuel was introduced could be blocked and impede the further introduction of fuel. As mentioned, fuel had to be introduced over the course of approximately 48 h (this task was normally performed with two operators working in turns), and the use of heavy plant material would make the firing process more difficult. This was commented on in the oral interviews:

Aulaga [*L. arborescens]* was the most used because if there were too many *salty bushes* [*Salsola*, *Suaeda* and *Schizogyne* species] the kiln would fill up with ashes, and the ash would reach to where the stone was and you wouldn't be able to carry on firing it. *Espino* [*L. intricatum*] was also put in there and *chaparro* [*C. caput-medusae*]. The *chaparros*, when they're big like they are now, have roots like asphalt and burn in a moment. I used to spend the whole year firing the kilns, although there were times when it took up to three months to find all the vegetation needed […]. *Tarajales* [*T. canariensis*] we wouldn't use. They're too heavy and don't burn quickly enough and clog up the mouth of the kiln. They make charcoal and not ash. […]. That's why later the city council began to give out licenses because there was less and less vegetation to cut and they'd give you permission to cut only what was needed for the kiln […]. At the end, as I say, I was spending up to three months or more to gather the vegetation because there were no plants left to fire the kiln, and you could only fire the kiln three or four times a year unless you had money to buy coal [Oral report by Francisco Cabrera].

The species that met the requirements previously described were therefore as follows: *L. arborescens, L. intricatum* and *C. caput-medusae.* The use of

Table 1
Species likely to be used for lime kiln firing.

Name	Currently present in the study area	Reason for non use	References
Asparagus nesiotes *Asparagus pastorianus* *Asparagus umbellatus* *Asparagus scoparius* *Asparagus plocamoides*	No		Historical documents
Convolvulus caput-medusae	Yes		Oral and Manzano-Cabrera, 2016
Euphorbia canariensis	System limits		Oral and Sabaté-Bel, 1993
Launaea arborescens	Yes		Oral, historical documents, Manzano-Cabrera (2016)
Lycium intricatum	Yes		Oral and historical documents
Nicotia glauca	Yes	Used for cooking	Oral and Santana-Cordero et al. (2016)
Plocama pendula	No	Other uses	Oral and Sabaté-Bel (1993)
Salsola vermiculata	Yes	Silts up kiln with ash	Historical documents
Salsola divaricata	Yes	Silts up kiln with ash	Historical documents
Schizogyne sericea	No	Insufficient heat generation	Historical documents
Tamarix canariensis	Yes	Other uses	Manzano-Cabrera (2016)

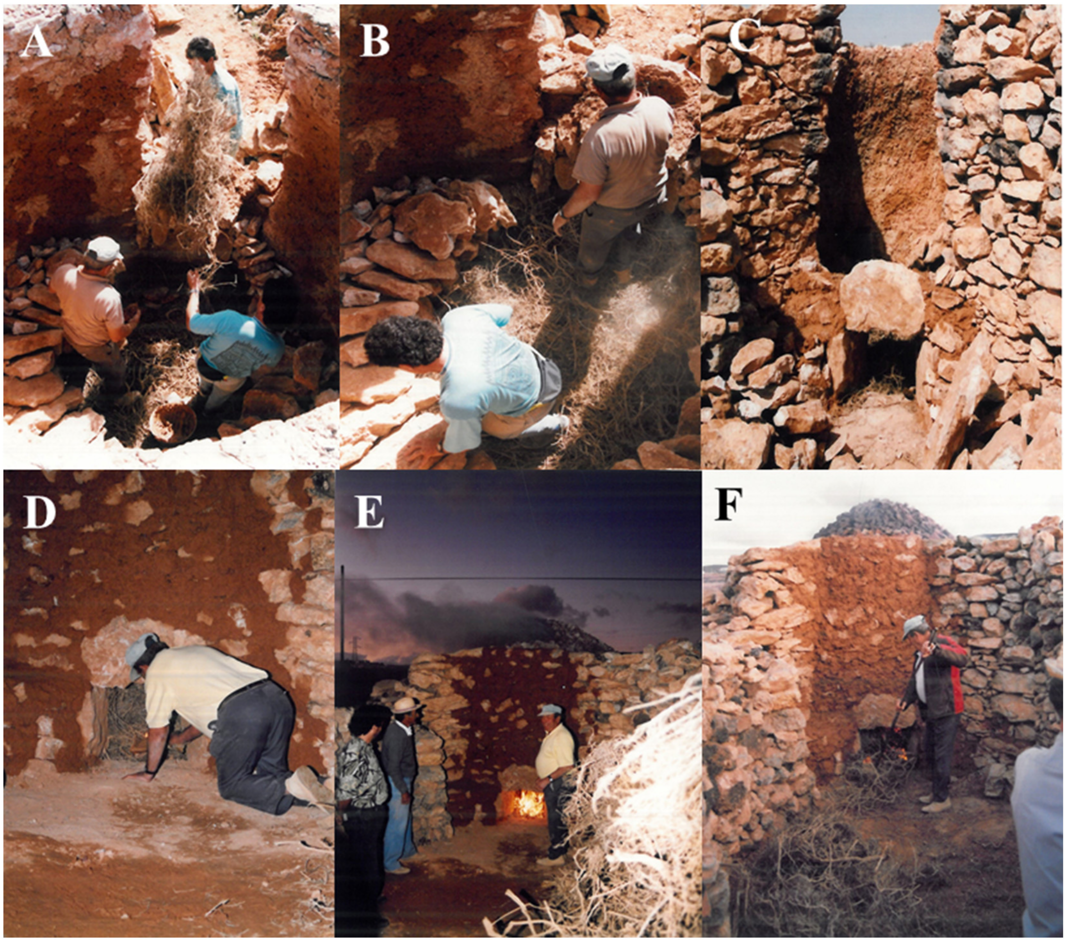

Fig. 3. Lime kiln firing process (Source: Archivo Histórico of the Cabildo de Fuerteventura).

L. arborecens was mentioned in several of the interviews and often appears in the sources consulted. It seems that it was the most commonly used plant species in the kilns due to its rapid growth, recolonization capacity and the diverse habitats where it grew. According to the oral sources, the sand surrounding the plant would have been removed and the roots of the plant, which could extend for several metres, extracted for burning. The use of *L. intricatum* must also have been very common as it is mentioned in many of the documents consulted. With respect to the genus *Aspargus,* there are very few references in the written sources to its use and none of the interviewees spoke of it being used in the kilns, although it is included in a 17th century contract for the collection of firewood required for the firing of a lime kiln in Fuerteventura. *Euphorbia canariensis* and *Plocama pendula* were referred to in the oral sources, but only as material used very occasionally when better and more commonly used alternatives were unavailable or in short supply. With respect to *E. canariensis*, this species does not tolerate sandy substrates, although it was found in the immediate surroundings of the study area and the oral sources described how they would throw stones at specimens of this species in inaccessible areas so that they would fall and could be used. *P. pendula* is also mentioned in the historical documents as being used on the island of Fuerteventura, but there are very few populations left. Finally, *Nicotia glauca* is an exotic invasive species in the Canary archipelago. It appears that it was used abundantly as firewood in the kilns according to the oral sources.

Among the species that can be considered doubtful in terms of their use in the kilns are the so-called *salty bushes* (*Salsola*, *Suaeda* and *Schizogyne* species). In this case, the oral sources contradict the information that appears in the historical documents, according to which these species silt up the kiln or, in the case of *Schizogyne sericea*, do not generate sufficient heat for combustion of the limestone. *Tamarix canariensis* is a small tree which is uncommon in Fuerteventura and its use was officially regulated as it was (and still is) one of the few sources of wood on the island. It was the preferred choice to manufacture farm tools.

4.2. Methodology to measure the effects of historical deforestation by the lime industry

Through the oral interviews, it was found obtained that a camel load corresponded to 12 sheaves (about 1 m long × 0.5 m wide × 0.5 m high). There were three kiln sizes: small ones which would require about 30 camel loads or 90 m^3 of fuel, medium-sized ones which would require 60–80 loads (180–240 m^3 of fuel) and, finally, large-sized ones which would require 100–120 loads (300–360 m^3 of fuel).

A total of 269 plants (333.85 m^3) were measured in the four plots (Table 2): 151 specimens of *L. arborescens* (193.57 m^3), 80 of *L. intricatum* (137.61 m^3) and 48 of *C. caput-medusae* (2.67 m^3). The dendrogram of

Table 2
Data used in the cluster analysis. Vegetation density and cover of the plots, number of individuals and biovolume of analysis plots. La: *Launaea arborescens*; Li: *Lycium intricatum*; Cc: *Convolvulus caput-medusae*.

Plot	Species cover (m^2)			Number of individuals			Total plot	Biovolume (m^3)			Total plot
	La	Li	Cc	La	Li	Cc		La	Li	Cc	
A	52.5	191.6	0	18	26	0	44	35.4	102.4	0	137.8
B	0.9	66.2	0	2	13	0	15	0.4	33.4	0	33.8
C	186.4	0.8	0	85	3	0	88	154.5	0.3	0	154.8
D	9.7	8.7	8.9	38	28	58	124	3.2	1.5	2.7	7.4

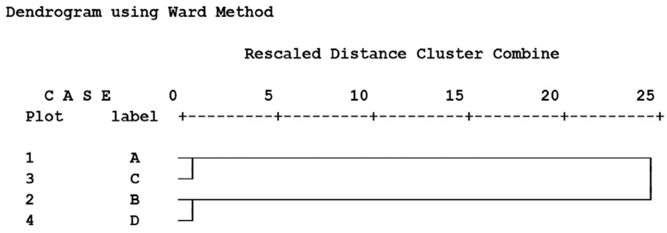

Fig. 4. Dendrogram using the Ward method with plot density association.

Fig. 4 shows 2 groups, plots A and C, which are characterised by abundant vegetation, and plots B and D, which are characterised by low amounts of vegetation. Table 2 shows the data used for the cluster analysis classified by plot and plant species.

On the basis of this data, it was noted that the number of plants required to fire a lime kiln varied depending on the plant species used (Fig. 5), as well as their age and size. In general, the use of adult specimens was prioritized, but in all likelihood use would also have been made of young specimens when vegetation was scarce. In summary, for the smallest kilns, a total of 70.3 specimens of *L. arborescens,* 52.5 of *L. intricatum* or 1607.1 of *C. caput-medusae* would have been required, and for the largest size kilns a total of 281.3 specimens of *L. arborescens,* 209.3 of *L. intricatum* or 6428.6 of *C. caput-medusae.*

In terms of surface area, and according to the data obtained in the field sampling campaign, a total of 5456.52 m^2 in areas of low vegetation density conditions or 768.93 m^2 in high density areas would have had to be cleared for the small-sized kilns. On the same basis, for the medium-sized (240 m^3) and large-sized (360 m^3) kilns, the totals for low density areas would have been 14,550.72 m^2 and 21,826.08 m^2, respectively, and for high density areas, 2050.48 m^2 and 3075.72 m^2, respectively. This would have allowed 1034 small-sized kilns to be fired in high vegetation density conditions and 3193 in low vegetation density conditions (Fig. 6C); and for large-sized kilns 657 in high density conditions and 2186 in low density conditions (Fig. 6D). The sources report that the lime kiln operators would travel distances of up to 37.80 km from Ajuy and 16.16 km to Morro Jable in Punta de Jandía to obtain vegetation. In addition, it can be seen that vegetation density is lower in the areas surrounding the optimal routes that the lime kiln workers would have used to obtain their fuel (Fig. 6).

In a report published by the Island Council of Fuerteventura in 1966, it is recorded that the lime kiln industry was the most important activity on the island and that in 1964 over 74,000 t of lime product were exported. If the preparation of this product had been undertaken solely in the study area and using vegetation from the area to fire the kilns, a total of 246,667 camel loads would have been required, which in turn would be the equivalent of clearing an approximate surface area of between 6,322,075.21 and 67,297,170.94 m^2.

4.3. Driving forces of deforestation and vegetation recovery

In Jandía, the lime kiln industry was an economic activity that served as an alternative to a system based on an extremely precarious primary sector that was highly dependent on arid climate conditions where water was (and continues to be) a very scarce resource due to the irregular and very occasional precipitations. It is frequently recorded in the minutes of the Island Government that, due to the continued absence of rains and the depletion of grain on the island, vessels leaving the island should only load limestone. That is, this market offered certain economic guarantees against other activities. This explains the mass proliferation of kilns along the coast of the Jandía peninsula given the export opportunities avialble. In effect, the, mostly local, driving forces (Table 3) that were behind this industry and, hence, the deforestation process, are socioeconomic (6) and natural/spatial (2) (Fig. 7).

A report from 1868 comments that vegetation is becoming scarce along the Jandía coast due to its being used to fire the kilns that have been constructed nearby:

The best limestone is found in large quantities along the east coast from Matas Blancas to Pezenescal and is one of the biggest export items from Jandía […]. There are significant amounts from Matas Blancas onwards all along the coast to Butihondo: it is also found from here to La Punta, though in lower quantities. The best quality limestone in Jandía, and perhaps even in the whole island, is found in Matas Blancas […]. What you find in Dehesa, as well as in all of Fuerteventura, are small bushes, such as *aulaga* [*L. arborescens*], *salty bushes* [*Salsola*, *Suaeda* and *Schizogyne*

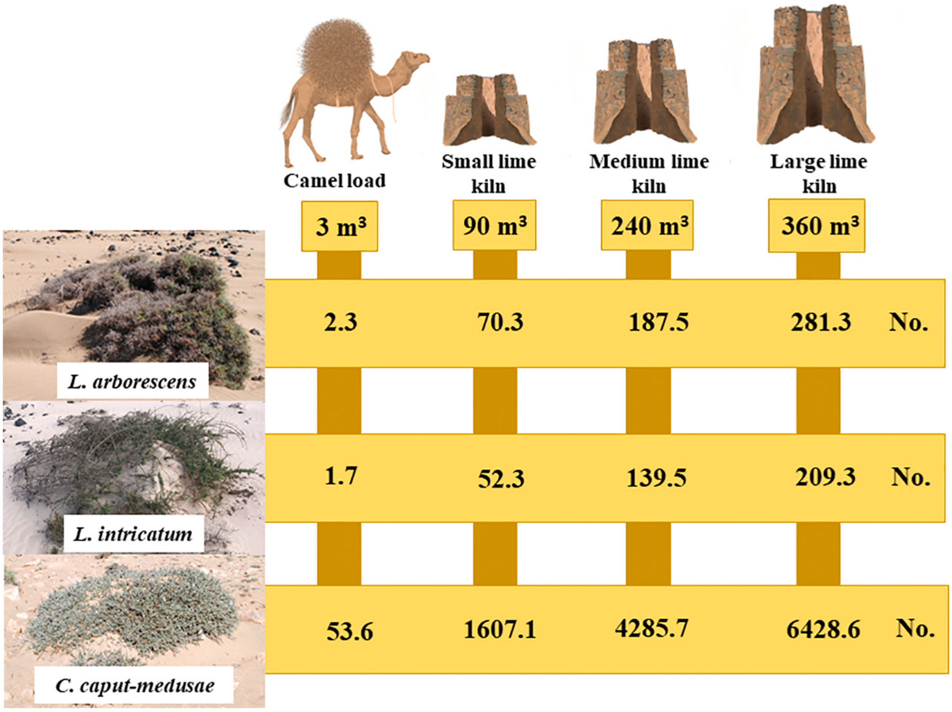

Fig. 5. Number of individual plants required for the three lime kiln sizes. It can be seen in the photos on the left how the three species form nebkhas.

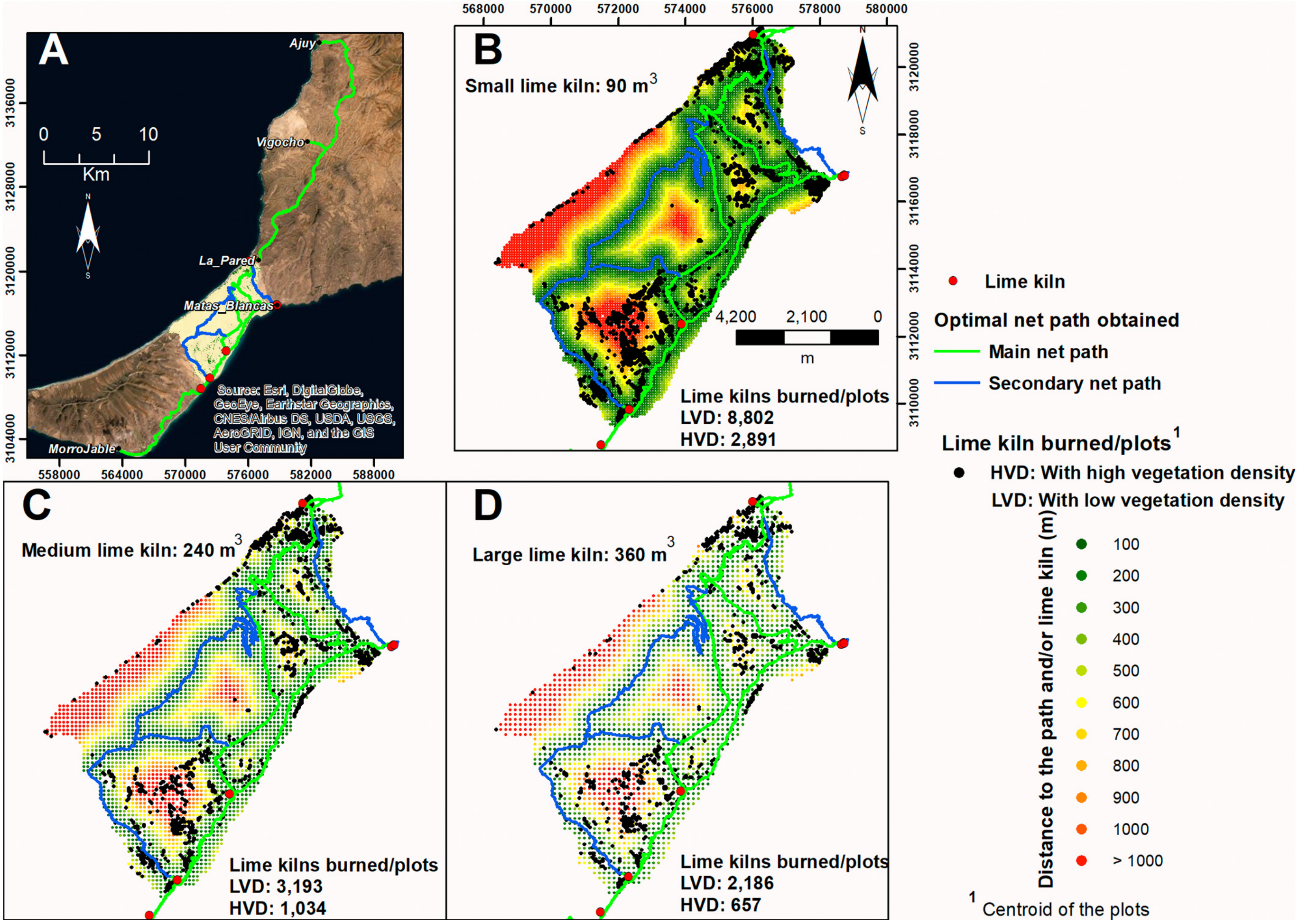

Fig. 6. Distribution of lime kilns, optimal routes obtained and maximum number of lime kilns fired/plot according to vegetation density. A. Optimal routes and toponyms mentioned in the historical sources. B. Small-sized lime kilns fired/plot. *C. Medium*-sized lime kilns fired/plot. D. Large-sized lime kilns fired/plot.

species], *espino* [*L. intricatum*], etc. They are used both for grazing and lime kiln firing. In Jandía you can find them in El Jable and in all the valleys, as well as fairly abundant amounts further inland and higher up. They are not found so frequently by the coasts, because as these are closer to the kilns, which are all along the coastline, they have been used to fire them. Although they are not strictly speaking scarce, today there are not too many specimens to be found [Report from the Secretary of the City Council of Pájara: Justo P. Villaba, 1868].

Table 3
Driving forces behind the deforestation and vegetation recovery process. Type of driving force: S: Socioeconomical; N/S: Natural/Spatial; C: Cultural; T: Technological; P: political. Scale: L: Local; R: Regional; N: National; I: International.

Deforestation	Vegetation recovery
S: High external demand (R, N, I)	S: External demand reduction (R, N, I)
S: High local demand (L)	S: Local demand reduction (L)
S: Opportunity for job creation (L)	C: Learning logging techniques from experienced workers (L)
S: Increase in the number of workers (L)	T: Importation of coal (I)
S: Low monetary cost of *L. arborecens* in public property (L)	T: Importation of synthetic paint and aggregates (N)
S: Low cost of traditional kilns (L)	T: Creation of kilns to burn the stone in exportation sites (R)
N/S: Geological characteristics (L)	T: Displacement of activity to industrial ovens in the capital (L)
N/S: Irregular climate conditions unfavourable to agriculture or livestock (L)	P: Government regulation for the removal of vegetation (L)
	N/S: Slow vegetation recovery (L)

Two types of kiln were used in Jandía, one type where the stone was used for local dwellings, and the other type for exportation of burned limestone to other islands in the archipelago. Only a few of the first type were built and they were generally situated close to the small population centres.

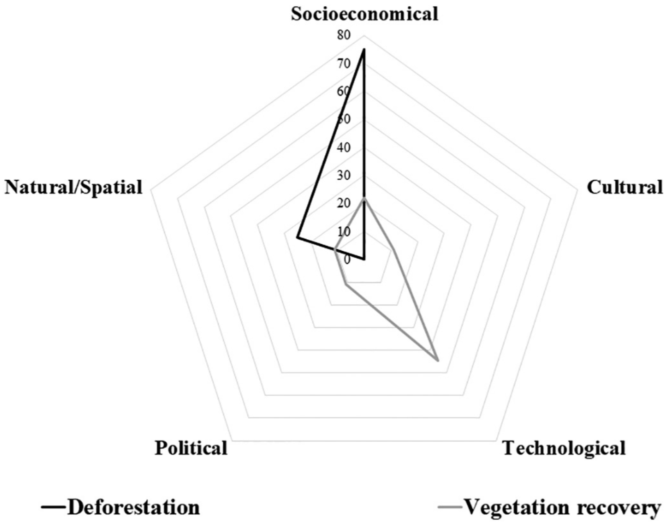

Fig. 7. Types of driving force behind the deforestation and vegetation recovery process.

By way of example, in the case of Punta de Jandía (some 20 km from the study area), the oral sources claim that the stage was reached when there was no more plant material to burn and that the lime kiln operations had to be carried out with coal imported from other islands. However, in other areas, and as the use of these kilns was only for occasional repair jobs in small villages, the oral sources claim that there were no shortages of plant material for the few kiln firings that took place. The kilns used for exportation purposes were found practically all along the Sotavento coast (Fig. 6) of the aeolian system, and the lime kiln firing was done with plant material. However, at the start of the 1950s, coal ovens began to be built or the existing kilns were modified in order to speed up the burning process.

The lime kiln operators who could not afford to buy coal would go to this area to collect plant material to fire the kilns. The oral sources, however, reflect the problem of the growing scarcity of vegetation. Some kiln operators remarked how they needed to walk further and further, up to 43 km, in search of fuel, requiring several days and thus increasing the time between one lime kiln firing and the next (up to three months) due to the difficulty in finding fuel. The depletion of the vegetation contributed to the transition to the use of coal, which also resulted in reduced profits as the coal had to be purchased and the final product was of a lower quality (and hence lower price) as the coal generated a considerable amount of impurities. In addition, the fact that kiln operators could not afford to buy coal saw an increase in the sale of raw limestone in the capital and in its exportation to other islands in the archipelago to be burned there.

The lime kiln industry began to decline from approximately 1960 onwards. The importation of synthetic paints and cement, as well as the use of coal, had the side effect of a spontaneous recovery of the vegetation. This recovery was then the result of technological advances in the industry and the gradual reduction in local and external demand (Fig. 7 and Table 3).

5. Discussion

The discussion of this research focuses on two main topics: i) the development of the methodology that allows the reconstruction, evaluation and analysis of the impact of the lime industry on the vegetation; ii) the application of the methodology, the information obtained and the effects detected on the vegetation.

5.1. Methodology to measure historical deforestation by the lime industry

With respect to the methodology, previous studies have estimated that a 2 m high lime kiln that generated between 8000 and 8400 kg of lime product would have required approximately 43 m^3 of firewood for its operation (Morris et al., 1931). Based on these initial data, other authors have estimated that 11 m^3 of wood are required to generate 10 m^3 of lime product, which in turn would mean felling 0.13 ha of forest (Abrams and Rue, 1988; Wernecke, 2008). According to Santana-Cordero et al. (2016), a lime kiln on the island of La Graciosa (Canary Islands) would consume the equivalent of 20 camel loads. On this basis, the same authors estimated that in the final stage of the lime kiln industry at least 5100 camel loads were required solely for new constructions and the restoration of existing dwellings. The same study also records that the kiln workers were obliged to travel longer and longer distances to obtain fuel, as the firewood became scarcer in the immediate surroundings of the population settlements, causing them to have to make their way to the northernmost point of the island, some 6 km away.

The comparison of the data obtained in the aforementioned studies and those reported in the present work requires a careful analysis as there are several aspects that need to be taken into account: for example, the capacity of the different plants to generate heat and the different types of kiln that were used (and not just their size), as more sophisticated kilns have a better heat-retaining capacity.

Nonetheless, the present study incorporates various advancements with respect to the works of other authors such as Morris et al. (1931), Abrams and Rue (1988) or Santana-Cordero et al. (2016), as it takes into account different variables in the analysis that is undertaken, including historical sources, field plant measurements, the number and exact dimensions of the sheaths or bundles of plant material transported by the camels, the different plant species that were used, and the size of the different kilns.

However, it should also be acknowledged that little is known as yet about the recovery capacity of the different plant species and the vegetation in general. In this respect, it is hoped to undertake a new research study. Some limitations of the methodology should be noted. Firstly, the exact contribution of the vegetation in recovering the aeolian system is not included. Secondly, the measurements are carried out on the current ecosystem, the conditions of which (distribution of species and vegetation cover) differ from those of the study period. And thirdly, as this is a historical process the oral sources in particular are limited and indeed gradually disappearing (Fogerty, 2005; Marrero-Rodríguez et al., 2020a). Nonetheless, the present study also opens up the possibility of other research lines to better understand the deforestation process and other consequences of the lime industry. In this regard, the kilns and their immediate surroundings should be excavated with a view to extracting new information about their date of construction, the approximate number of times the kilns were fired, and the species that were used to fire them (although various species were found in the present reconstruction using oral sources and limited historical documents, others may have been used which are no longer found in the isthmus).

The methodology developed in the present paper can be applied to other historical and current land uses and for the planning of new land uses that depend on the removal of vegetation. Furthermore, this type of study allows us to learn from past experiences in which industries lacked proper planning and thus their activity led to their own collapse and rapid environmental degradation. In this respect, this paper contributes to achieving Goal 12 (responsible consumption and production) of the United Nations 2030 Agenda for Sustainable Development.

5.2. Deforestation process due to the lime industry

This work comprises a qualitative and quantitative approach in an analysis of the impact of the lime kiln industry on an arid aeolian sedimentary system. In the case study of Jandía, the removal of vegetation, as well as the resulting transformation of landforms, was due to the need to acquire fuel to burn in the lime kilns (Marrero-Rodríguez et al., 2020a). Determining the number of times that each kiln was fired was an impossible task on the basis of the sources used. However, it was found in the sources that the lime kiln operators had to travel some distance from the aeolian sedimentary system in search of vegetation. That is, the data obtained suggest that the number of possible times that a lime kiln could have been fired using plant material found in the system itself was exceeded, as too would have been the vegetation recovery rate.

Traditional uses that have a high fuel demand can a priori result in generalised deforestation but, in reality, their impact on ecosystems is far more complex. In the case of Jandía, there was a huge demand for plant material to fire the lime kilns, but this demand was at the same time selective (Marrero-Rodríguez et al., 2020a, 2020b) as in other aeolian sedimentary systems (Santana-Cordero et al., 2016). This was due to the preference for certain species which were more efficient for lime kiln firing. These characteristics, revealed in the oral interviews, have also been reported by other authors in Portugal, although they propose that the use of bushes is related to the impurities that contaminate the lime product when other materials are used (Margalha et al., 2008) and not with the silting up of the kiln, as was the case in Jandía.

The most immediate consequence of land clearing to obtain plant material to fire the kilns must have been a reduction in species richness, as has been identified for other land uses also developed in dune systems (Kutiel et al., 1999). In addition, the fact that 2- and 3-year-old adult specimens were preferred would have had consequences on the population structure of the plant communities. The importance of the age of the plant is related to its reproductive stage and can be key to an entire population's growth or decline, and even the extinction of some species.

In a second stage, the reduced availability of the species that were preferred to fire the kilns would have meant the lime kiln operators being necessarily less selective, using less optimal species and at the same time younger specimens of the more preferred species. This would explain how some species would become scarce. By way of example, a scarcity was reported in Fuerteventura in the 1970s of a plant species, *C. caput-medusae* (Kunkel, 1977), whose aerial and subaerial parts were both used to fire the lime kilns. The cessation of the lime kiln activity may have enabled the recovery of this plant species, though today its distribution is limited to specific locations in Fuerteventura and Gran Canaria (Brandes, 2001; Olangua Corral, 2009).

Deforestation of the Jandía peninsula contributed considerably to the decline of the lime kiln industry because of the increased difficulty to obtain plant material to fire the kilns. External demand for this product was a determining factor in the deforestation processes, whereas in other similar ecosystems in the archipelago like the island of La Graciosa the kilns were only fired for work in new constructions or occasional repairs (Santana-Cordero et al., 2016). The demand for vegetation was also high for cattle, sheep and goat grazing (Hoffman and Rohde, 2007), the manufacture of different farm tools, and as fuel for households and for the construction and other industries (Santana-Cordero et al., 2016). It would have been the combination of these uses, together with the lime kiln industry, that resulted in the generalised deforestation of the aeolian system.

The exploitation of the vegetation also had an impact on the dynamics of natural processes in terms of the remobilization of sand sheets (Marrero-Rodríguez et al., 2020a). The traditional land uses resulted in overexploitation of the vegetation and, consequently, its capacity to stabilize the sand. This resulted in highly mobile aeolian sedimentary landforms, including sand sheets (Santana-Cordero et al., 2016). These used to be considerably more widespread than in the present day when the predominant landforms are nebkhas, indicating a recolonization of the vegetation (Marrero-Rodríguez et al., 2020c). In addition, the deforestation process also favoured generalised erosion processes due to the rhexistatic conditions producing the beach and landforms progradation (Marrero-Rodríguez et al., 2020a) as it happened in Ebro Delta (Guillén and Palanques, 1997). However, currently coastal erosion is affecting both ecosystem due to a lack in the sediment provided by aeolian transport in Jandía and by the river in Ebro Delta (Jiménez et al., 1997; Valdemoro et al., 2007).

6. Conclusions

For a long period (1850–1960), the lime kiln industry was one of the most important economic activities on Fuerteventura Island. This was due, on the one hand, to the highly irregular income from agriculture and livestock-rearing as the result of difficult climate conditions and, on the other, to the abundance of limestone compared to the other older islands in the archipelago.

The deforestation process was very selective as not all the vegetation could be used in the lime kilns. The three plant species that were most preferred to fire the lime kilns were *L. arborescens*, *L. intricatum* and *C. caput-medusae*. However, their long-term exploitation led to an important depletion of the population of some species and, consequently, to the collapse of the industry when insufficient plant material was available and other, expensive, fuel sources had to be imported to the island to fire the kilns. As these species serve to establish nebkhas, their removal for use as fuel in the lime kilns also resulted in sediment remobilization of the nebkhas.

To fire the smallest of the three kiln sizes used on the island, it would have been necessary to clear an area of 5456.52 m^2 if the vegetation density was low, or 768.93 m^2 in the case of a high vegetation density area. In most of the studies published to date, deforestation has been analysed as a general process involving complete vegetation cover removal, but this research shows that some historical deforestation processes are selective, and not general, in that they may be subject to the specific needs of one (or more) particular industry/ies.

It is apparent from the results of the study that the lime kiln industry played a very significant role in terms of modification of the vegetation in the aeolian sedimentary system of Jandía and other areas of the island, impacting on the types of plant community currently present in the area, as well as their spatial distribution and flora composition and structure. This is key to understanding the historical evolution of the flora, vegetation and the geomorphological processes of the dune systems of the Canary Islands. Finally, the methodology developed in the present paper can be applied to other historical and current land uses and for the planning of new land uses that depend on the removal of vegetation.

CRediT authorship contribution statement

Néstor Marrero-Rodríguez: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Leví García-Romero:** Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Antonio I. Hernández-Cordero:** Supervision, Data curation, Formal analysis, Validation. **Carolina Peña-Alonso:** Data curation, Validation. **Emma Pérez-Chacón Espino:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that there is not conflict of interest.

Acknowledgements

This article is a contribution of the CSO2016-79673-R Project funded by the Spanish Government's National Plan for R + D + i (innovation), co-financed by the ERDF. The second author was a beneficiary of a PhD contract of the Canary Islands Agency for Research, Innovation and Information and the European Social Fund (ESF). This article is a publication of the Océano y Clima Unit of the University of Las Palmas de Gran Canaria, an R + D + i CSIC-associate unit.

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