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Identifying the *chaîne opératoire* of club-rush (*Bolboschoenus glaucus* (Lam.) S.G.Sm) tuber exploitation during the Early Natufian in the Black Desert (northeastern Jordan)

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A R T I C L E I N F O

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A B S T R A C T

Club-rush (*Bolboschoenus* spp. (Asch.) Palla) is one of the most common edible wild plant taxa found at Epipaleolithic and Neolithic sites in southwest Asia. At the Early Natufian site of Shubayqa 1 (Black Desert, Jordan) thousands of club-rush rhizome-tuber remains and hundreds of fragments of prepared meals were found. The evidence indicated that the underground storage organs of this plant were recurrently used as a source of food 14,600 years ago. To determine how Early Natufian communities gathered, processed and transformed club-rush tubers into food, we designed an interdisciplinary study that combined experimental archaeology, archaeobotany, and ground and chipped stone tool analyses. We conducted more than 50 specific experiments over three years, and based on the experimental materials produced we inferred that 1) the best season for club-rush rhizome-tuber collection in the region was spring-summer time; 2) that the primary method to harvest the plant would have been uprooting; and 3) that the most efficient approaches to obtain perfectly peeled and clean rhizome-tubers could have entailed drying, roasting and gentle grinding of the tubers. Overall, our work provides important information to reconstruct the *chaîne opératoire* for club-rush tuber exploitation in the past. The experimental data and modern reference datasets allow us to interpret the archaeological material found at Shubayqa 1, and start identifying some of the activities that Natufian communities in the Black Desert undertook in relation to the exploitation of this particular source of food.

1. Introduction

Club-rush (*Bolboschoenus* spp. (Asch.) Palla) is a semi-aquatic plant of the Cyperaceae family and represents one of the most common edible wild plant taxa attested at late Epipalaeolithic and early Neolithic sites in southwest Asia (see most recent data reviews Arranz-Otaegui et al. 2018a, Wallace et al. 2019, Arranz Otaegui and Roe, under review). Its nutlets have been recovered from hundreds of archaeological sites, sometimes in proportions larger than those recorded for key cereal and legume crops (Savard et al. 2006). It has been suggested that extensive club-rush stands could have provided people with a stable source of food in prehistoric times, and the tubers in particular could have constituted a staple food resource (Hillman 1989, Hillman et al. 1989, Wollstonecroft 2009). Indeed, club-rush and other genera of the Cyperaceae family are well known for their highly calorific tubers and green shoots. Nutrient analysis of one of the species named sea club-rush (*Bolboschoenus maritimus* (L.) Palla) show protein, lipid, and carbohydrate contents similar to those recorded for important root foods like potato (Kantrud 1996, Wollstonecroft 2007).

Despite the economic potential of club-rush tubers, their presence in archaeological sites has been quite limited until now (see description of factors affecting the preservation and identification of underground storage organs in archaeological sites in Hillman et al. 1993, Hather 2000, Arranz-Otaegui et al. 2018a). Only a handful of Mesolithic and Neolithic sites in Europe (Perry 1999), Egypt (Hillman 1989, Hillman et al. 1989, Hather 1995) and Turkey (Hastorf et al. 2000) report the presence of club-rush tubers in their plant assemblages, and at most of these sites it has not been possible to establish a clear relationship between the presence of club-rush tubers and their use as a source of food.

Nevertheless, in the last years, methodological advances such as the

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study of accidentally carbonised remains of processed plant foods (also referred to as "amorphous remains") have started to provide direct evidence for the use of club-rush tubers in food preparations. For example, at the Neolithic agricultural site of Çatalhöyük in Turkey, club-rush type parenchyma and vascular tissue were recorded in carbonised remains of flat-bread like remains (Gonzalez-Carretero et al. 2017). Similarly, new evidence shows that club-rush tubers served as a source of food for the preceding late Pleistocene hunter-gatherer communities. At the Early Natufian site of Shubayqa 1, dated to 14,600–14,200 cal. BP and located in the Black Desert of northeastern Jordan (Betts 1998, Richter et al. 2017), two large stone-lined fireplaces were discovered in 2012 containing an exceptionally well-preserved assemblages of plant macro-remains (Arranz-Otaegui et al. 2018a, Arranz-Otaegui et al. 2018b). The archaeobotanical analysis of these fireplaces yielded more than 67,000 plant remains including at least 95 taxa belonging to key families like the Cyperaceae (sedges), Poaceae (grasses), Brassicaceae (mustard family), and Fabaceae (legumes), among others. However, the uniqueness of the assemblage relied on two main finds:

1) From the total remains recovered, 53,827 (79,8% of the assemblage) represented club-rush rhizome-tubers remains (Arranz-Otaegui et al. 2018a). This find represents one of the largest assemblages of prehistoric underground storage organs ever recovered. Apart from the tubers, other elements of the plant such as the stems, the rhizomes and rootlets, as well as some irregular fragments of burnt clay remains with Cyperaceae stem impressions were also recovered.

2) Apart from these, the two fireplaces from Shubayqa 1 comprised hundreds of fragments of prepared plant-based meals (Arranz-Otaegui et al. 2018b, see Arranz-Otaegui et al. in prep. for the description of the tuber-based food products). A scanning electron microscopy-based analysis of the matrix indicated that 24 of these remains bear characteristics typical of flat-bread like products. In terms of ingredients, 15 contained cereal tissues and at least five showed the presence of root-type starch as well as parenchyma cells and vascular tissue consistent with that identified in club-rush tubers.

The large number of club-rush tubers and their presence in the food remains showed that Early Natufian groups in the region recurrently exploited this particular plant as a source of food. However, these finds also prompted new questions like: Why was such a large number of tubers carbonised in the fireplaces? Were they accidentally carbonised during the processing stage (e.g. roasting to facilitate the peeling), or during cooking? And perhaps more important, what was the step-by-step process in the preparation of the club-rush tuber-based foods?.

To answer these questions and determine how Early Natufian communities gathered, processed and transformed this particular plant into food we designed an interdisciplinary experimental program that combined archaeobotany, ethnobotany, and stone-tool analyses. The study complements the pioneering work conducted by M. Wollstonecroft (Wollstonecroft and Erkal 1999, Wollstonecroft 2007, 2009, Wollstonecroft et al. 2008, 2011) and G. Hillman (Hillman 1989, Hillman et al. 1989), which focused on determining general tuber yields, harvesting efficiency, quantitative nutrient composition, digestibility and palatability among other key aspects. To reconstruct the *chaîne opératoire* for club-rush tuber exploitation at Shubayqa 1 the experiments were divided into three main blocks: 1) club-rush plant gathering, 2) processing and 3) cooking. In this paper the first two stages of the *chaîne opératoire* are tackled and several hypotheses in relation to club-rush tuber gathering and processing are tested. Upcoming publications will expand this initial work by covering the final cooking stages (Arranz-Otaegui et al. in prep.), as well as providing extended comparative analyses of the experimental and archaeological flint and ground stone tool assemblages and the associated plant residues (Pedersen et al. in prep., Jörgensen-Lindahl et al. in prep.).

Overall, this work provides important information to understand how club-rush tubers could have been exploited as a source food in the past. It determines the step-by-step actions and specific gestures involved in their exploitation, tests a number of possible gathering and processing strategies, and provides key data on the amount of time and effort needed to carry out each of the activities. The experimental data and modern reference datasets produced in this work allow us to interpret the archaeological evidence found at Shubayqa 1, and in so doing, start identifying some of the activities that Natufian communities in the Black Desert undertook in relation to the exploitation of this particular root food.

2. Materials and methods

2.1. The plant

The taxonomic study of the club-rush nutlets found at Shubayqa 1 indicated the presence of *B. glaucus* (Lam.) S.G.M., and whilst the presence of other species cannot be fully discarded and, it is considered likely that most of the recovered club-rush tuber remains belonged to this particular species (Arranz-Otaegui et al. 2018a). *B. glaucus* is indeed the most heat-tolerant species of club-rush and it can be found around the Mediterranean, northern Spain and southern France, as well as in sub-Saharan Africa and several parts of Asia (Browning et al. 1998, Hroudová et al. 2007, Wollstonecroft et al. 2011). It primarily grows in freshwater environments, along rivers and river floodplains, but it has also been recorded in secondary habitats (i.e. near villages) and in relatively saline water stands (ibid). The tubers of this plant can be collected in three main growing stages: immature tubers, which represent young tubers freshly grown in the year; adult or ripe tubers; and mature or old tubers from previous years.

Whilst ethnobotanical research indicates that the stems, nutlets, and tubers of club-rushes can be used for a number of purposes including food, fuel, building material, and raw materials for weaving (see Rivera-Nuñez and Obón de Castro 1991, Simpson and Inglis, 2001, Wollstonecroft 2007), in this study we centre on the tubers and their use as a source of food. This is important to highlight since if the plant was gathered for other purposes (e.g. raw material for basketry) its *chaîne opératoire*, including when and how the plant was gathered and processed, could have differed considerably.

2.2. Description of the experimental activities

Experimental work took place in the Black Desert of northeastern Jordan in 2017, 2018 and 2019, during the field excavation seasons in the Shubayqa area. More than 50 experimental activities were carried out, and a total of 22 people participated. For each experiment, we recorded the type of activity and its objective, a description of the materials used (number, volume, weight, size), the tools used, the people involved in their use, the duration of the activity, the start and end products and discarded materials. Photographs were taken for documentation purposes throughout (see individual image credits in the Supplementary Materials). In this work we present the results of 20 of the experiments carried out in relation to club-rush harvesting and processing.

2.2.1. Club-rush harvesting activities

Experimental harvesting of club-rush plants was carried out at Lake Burqu', a rainfed water body on the edge of the Black Desert (Jordan), some 70 km east of Shubayqa 1 (Fig. 1). Augmented by a modern dam (Helms 1991), the lake covers up to 32 ha at its high stand, although its level fluctuates greatly both seasonally and annually, with a maximum depth of c. 4–5 m recorded in the centre of the main water pond. The edge of the lake is dominated by vast monospecific stands of club-rush plants. The plants grow primarily in the shores of the fresh-water ponds, in thick patches (1–3 m width and maximum of 1.2 m depth), separated by spaces of open water and basalt boulders. The substrate in the area is silt, and includes small amounts of basalt pebbles.

In the different harvesting experiments the total height of the plants and the resulting volume of the plant materials gathered were measured

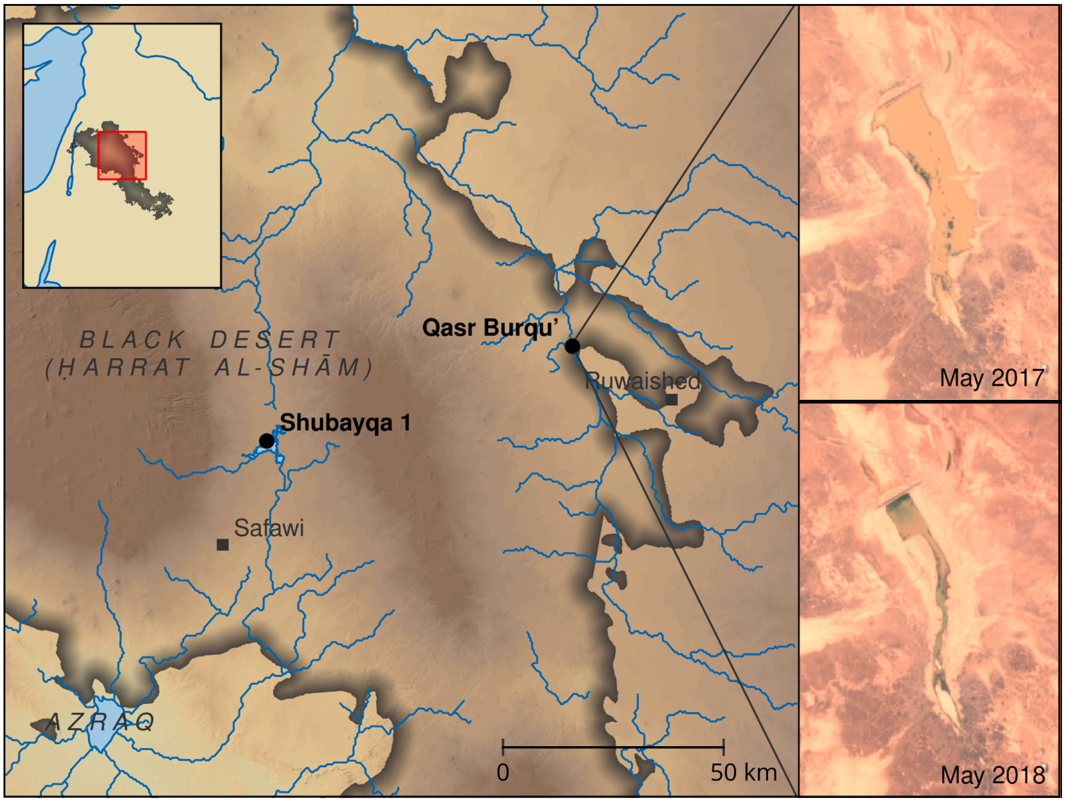

Fig. 1. Location of Shubayqa 1 and Qasr Burqu' within the Harrat al-Sham. Inset, right: Sentinel-2 satellite imagery of Lake Burqu'.

and recorded. The work was commonly carried out by groups of 2–3 people. Club-rush tuber harvesting was carried out in four main harvesting seasons: February and May of 2017, May of 2018 and June of 2019, in order to cover the whole life cycle of the plant. It should be stated that the club-rush tuber harvesting activities did not cause damage to the stands. Around 5–8 m^2 of club-rush plant materials were gathered per year, less than 0.1 % of the total available stands in the area. Besides, in order to avoid damage, harvesting areas were rotated every year, following protocols established by biologists to safeguard the correct growth of club-rush species (Kantrud 1996). Besides, it has been recorded that controlled human and/or animal predation can stimulate plant growth and increase the overall club-rush biomass (Charpentier et al. 1998, Clevering and van Gulik 1997).

2.2.2. Club-rush processing activities

The second block of activities involved the processing of the plants. These activities were carried by small groups of volunteers (between 2 and 5 people), both in Lake Burqu' and in the field station in Safawi. The tuber processing experiments involved cutting, drying, roasting, and grinding/pounding. For these specific fire installations and experimental replicas of stone tools were produced.

2.3. Description of the experimental materials and fire installations used

To conduct the gathering and processing experiments, stone and wooden tools, including ground stone replicas, a sickle, and a digging stick (Fig. 2), as well as four main fire installations were produced based on ethnographic sources and the archaeological evidence recovered at Shubayqa 1 (see Supplementary Materials for detailed information on how these tools and installations were made).

2.3.1. Ground stone tools

Ethnobotanical accounts indicate the regular use of ground stone tools to process underground storage organs (e.g. Gott 1982). Our initial work sought to evaluate which of the two main gestures, that is grinding and pounding, would be most likely in the processing and peeling of the tubers. For this purpose two tool pairs were manufactured: a mortar and pestle (pounding pair Fig. 2A), including a wooden pestle (Fig. 2B); and a handstone and quern (grinding pair Fig. 2C). The tools were made using local basalt stones, replicating the characteristics of those recovered at Shubayqa 1(see supplementary Fig. 1, also Pedersen et al. 2016, Pedersen 2021).

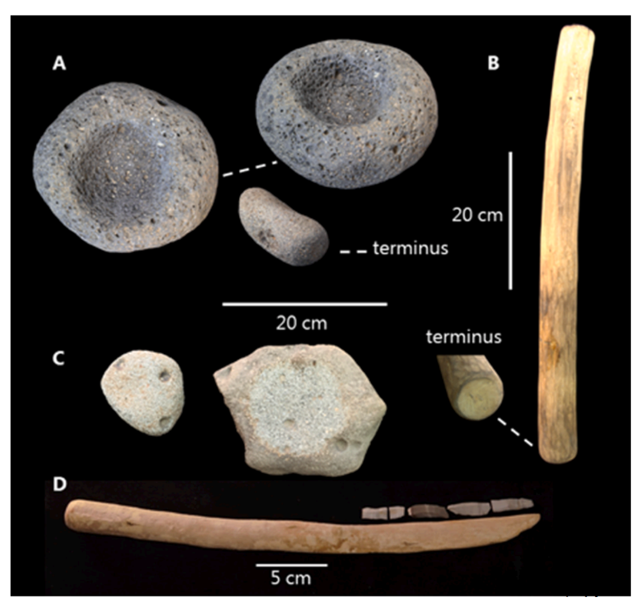

Fig. 2. Images of the experimental tool replicas: A) basalt mortar (GSX.9) and pestle (GSX.10); B) wooden pestle; C) basalt quern (GSX.5) and handstone (GSX.6); D) sickle inserts (EXLI66-69, left to right) and wooden handle.

2.3.1.1. Grinding pair. The quern (GSX.5) was 21 cm in length, 16 cm in width and c. 5 cm in thickness, with a weight of 3134 g. A naturally stable and flat side of the basalt boulder was designated the base and a circular depression was fashioned using basalt hammerstones on the opposite side of the flat boulder. The finished circular depression, the quern face, had a diameter of 9.6 cm and a depth of 0.6 cm. The exterior and sides of the quern were not modified. The handstone (GSX.6) was made on a sub-circular basalt cobble, with a final length of 11 cm, width of 9 cm and thickness of 3.5 cm, weight of 732 g, with only a single modified surface. A second ad-hoc grinding pair consisting of an elongated slab GSX.7 (24 cm long, width 15–16 cm and thickness 6.5 cm) and a sub-rectangular handstone GSX.8 (12 cm long, width 9 cm and thickness 6.5 cm) was also produced.

2.3.1.2. Pounding pair. Previous work by Prof. Gordon Hillman found that the inedible outer layers of raw club-rush tubers could be expediently de-husked in a deep mortar provided the mortar had a curved internal bowl, was deeply filled with tubers, and that the pounding end of the pestle was likewise curved, all of which prevent crushing while efficiently dehusking (Hillman in personal communication noted by Wollstonecroft 2007, 339). We attempted to perform a similar kind of processing using a replica of the shallower concave (<10 cm deep) bowl-type mortars found in Early Natufian contexts at Shubayqa 1 (see detailed description in the supplementary material). The basalt mortar (GSX.9) weighed 5800 g, and was 19 cm wide and 12 cm tall. It featured a circular mortar hole (active surface), c. 12.5 cm in diameter, 5.5 cm deep and a volume of 265 ml, with a concave profile. The basalt pestle (GSX.10) had a length of 14 cm, width/thickness of 5.5–6.5 cm and a weight of 900 gr. In addition, a wooden pestle was made out of a large *Ficus carica* (fig) branch. It was 61 cm long and 5.2 cm diameter/width with a weight of 900 g.

2.3.2. The sickle

Sickles are traditionally associated with cereal gathering in Southwest Asia (Maeda et al. 2016), but in this case a sickle was made to test if

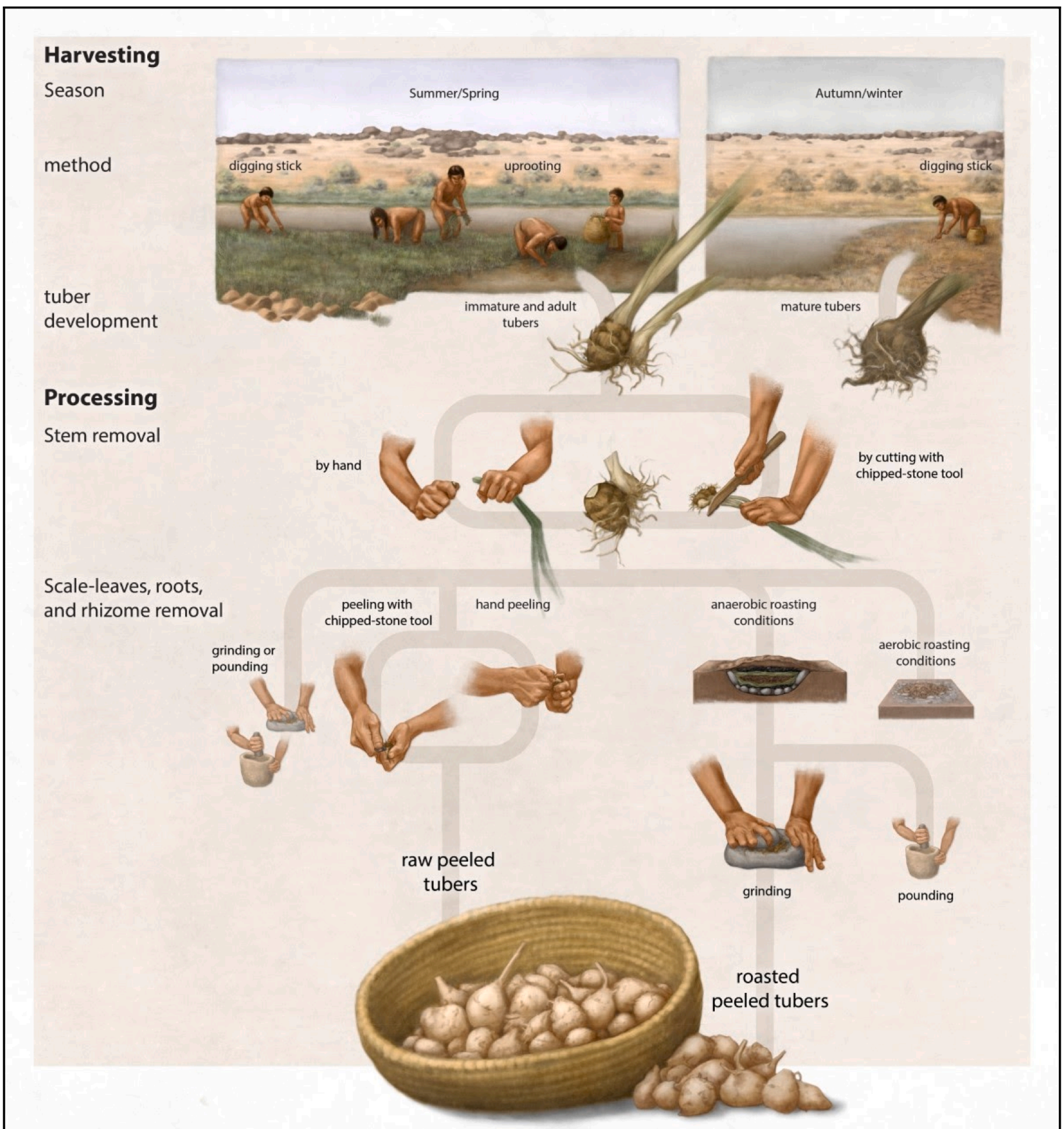

Fig. 3. Club-rush tuber exploitation scheme. Gathering and processing methods tested and the most likely choices based on the archaeological evidence gathered at Shubayqa 1.

this type of tool could be used in the processing of club-rush, particularly for the separation of the stems from the underground storage organs. The experimentally produced use-wear traces were then used as references for the interpretation of the archaeological material. The sickle (sickle B) was hafted with four backed bladelets, based on the chipped stone tools recovered from the fireplaces of Shubayqa 1 where the club-rush tubers were found (Arranz-Otaegui et al. 2018a). This assemblage contained a large amount of microliths where different types of backed bladelets dominated, followed by lunates. Use-wear analysis identified at least one artefact with silica gloss and several pieces that had been used on soft and soft-medium materials, such as most plant materials (Jörgensen-Lindahl in prep.). Further information about the archaeological tools will be published in a separate paper in due course. The replicated bladelets each measured around 3 × 0.7 cm and were hafted in a parallel line, creating a continuous cutting edge of c. 12 cm (Fig. 2D). They were shaped by abrupt retouch using direct percussion-on-anvil technique with a finishing pass of pressure technique. Water-soluble rabbit skin glue was used as hafting adhesive. The chert used for the production of the microliths was sourced locally within the limestone formations of the Al' Azraq Depression in Jordan. The wooden handle was carved from fresh fig wood and measured 35 cm in length with a circumference of 9 cm.

Use-wear analysis was carried out using the combined approach of low- and high-power microscopy. A stereoscopic Heerbrugg Wild M38, x6.4, x16 and x40 with View Solutions GXM L12 and fiber optic adjustable light sources was used for the initial low-power investigation, and a Leica DM2700M (x5, x10, x20 and x40 objectives and x10 ocular eyepieces) was used for the high-power examination. Prior to the analysis, the bladelets were cleaned for 30 minutes in an ultrasonic tank in a solution of de-mineralized water and detergent. The temperature of the water was set to 50 °C.

2.3.3. Digging stick

Digging sticks have been ethnographically attested for as tools to harvest tubers and other underground storage organs (e.g. Vincent 1985), and they have been exceptionally preserved in several archaeological sites across the world starting from the Middle Palaeolithic (Golson 2017, Nugent 2006, Hoffmann et al. 2016, Revedin et al. 2020, Rios-Garaizar et al. 2018, López-Bultó et al. 2020a, 2020b). In this study, a digging stick was manufactured to test if this type of tool increased the efficiency during club-rush harvesting. A c. 50 cm long wooden stick with a pointed and slightly rounded active end and a circumference of 8 cm was produced from fresh fig wood. Although the morphology of ethnographically documented digging sticks range from spatulated to sharpened ends and vary in overall length and thickness, we decided to use the digging sticks used by Hadza women for uprooting tubers as reference for our experiment (Vincent 1985, Revedin et al. 2020).

Fig. 4. A) Club-rush stands in Qasr Burqu' (May 2017). B) Club-rush tuber gathering by uprooting. C) Club-rush tuber gathering with a digging stick.

2.3.4. Fire installations

Roasting is reported as an important activity linked to root-food exploitation in various ethnographic, historic and ethnobotanical accounts around the world, although it has been primarily linked to cooking activities (Wollstonecroft 2007 and references therein). In this study, two fire pits (A and B) and two pit-ovens (A and B) were built in order to roast the club-rush tubers under aerobic and anaerobic conditions and test if this method could optimise the peeling of the club-rush tubers. The fire installations used in the experiments were all made with basalt stones, with the same characteristics as the fireplaces found at the Early Natufian Shubayqa 1 (see full description in Richter et al. 2017, Arranz-Otaegui et al. 2018a). They were concave and circular with the edges lined with basalt rocks. They measured between 46 and 54 cm (externally) and 30–34 cm (internally, inside the basalt stone lining) in diameter and with a depth of c. 16–17 cm.

3. Results and discussion

In the following sections we describe and discuss the experimental work carried out, list the main activities involved in the gathering and processing of club-rush tubers, and qualitatively evaluate the efficiency of the different approaches tested by followed (Fig. 3). We also describe and highlight some of the key traits (taphonomic features on tuber remains, use-wear, etc.) that these activities left in the experimental materials, which are used to interpret the archaeological evidence gathered at Shubayqa 1.

3.1. Club-rush tuber gathering: Timing and methods

The first fundamental step was to gather the tubers, and in so doing provide answers to two main questions: (i) which were the most efficient methods/tools to gather club-rush tubers?; and (ii) what was the best time of the year for tuber gathering?.

3.1.1. Evaluating different tuber gathering methods

The initial evaluation of the club-rush harvesting methods involved two main approaches: uprooting and the use of digging sticks (Fig. 4). Despite the extensive ethnographic and archaeological evidence that relate root food gathering with the use of digging sticks (see Materials and Methods section), our experiments in the Black Desert showed that digging sticks would not have been necessary in order to gather club-rush tubers. These tools showed some efficiency during autumn and winter time, when lake levels fall and a digging tool was necessary to remove the dry and compacted soil around the tubers. However, during spring and summer time, which coincides with the optimal harvesting season of the tubers (see section 3.1.2.1), the plants grew under water, in soft mud, which allowed direct uprooting. We gathered the plants by holding the basal part of the stem with bare hands, and pulling up groups of 5–8 plants in a slow motion to avoid breaking the stems and losing the underground storage organs. Thus, during this particular time of the year, uprooting was qualitatively speaking faster and more efficient than the use of digging sticks.

3.1.2. Differences on the types and quantities of tubers recovered

Previous studies have shown that *B. maritimus* (*sensu lato*, including *B. glaucus*) produces effective yields that make tuber harvesting a worthwhile activity in comparison to other plant foods (Wollstonecroft 2007, 2009, Wollstonecroft and Erkal 1999). In the harvesting experiments conducted previously, production rates (i.e. grams of peeled

Table 1
Club-rush tuber collections and timings. * Note that the club-rush tubers in experiment #1 were completely dried at the time of gathering, and the weight makes reference to air-dried plant materials.

	Experiment	Season	Life cycle of the plant	Average size of the plants (*n* of specimens measured)	Type of rhizome tubers available	People involved in harvesting	Total time spent gathering	Weight of unprocessed fresh rhizome tubers	Grams (fresh peeled)/ hour/ person
Harvesting 1	Gathering experiment #1 (February 2017)	Winter	Hibernacles	–	Old/mature	1	10 min.	80 gr*	256.6*
Harvesting 2	Gathering experiment #2 (May 2017)	Spring	Juvenile plant growth	c. 35–60 cm (*22*)	Adult and young	1	75 min.	771 gr	329.8
Harvesting 3	Gathering experiment #3 (May 2018)	Spring	Juvenile plant growth	c. 20 cm (*20*)	Adult and young	4	90 min.	7564 gr	673.70
Harvesting 4	Gathering experiment #4 (June 2019)	Late spring-summer	Adult plant growth, fruiting time	c. 60–70 cm (*35*)	Adult and young	2	110 min.	4043 gr	589.50

tubers gathered per hour) vary from 1271.8 g/h/person in the Pevensey marsh (England, Wollstonecroft 2007) to 521.8 g/h/person in the Konya Basin (ibid). In the experimental gathering carried out in this study, the production rates were similar to those in the Konya Basin, c. 531 g/h/person on average. Nevertheless, the production rates attested in Qasr Burqu' should be considered with caution since significant differences were observed in the types, sizes and availability of tubers that could be gathered depending on three factors: the gathering season, the rainfall conditions prevalent each year, and whether tuber harvesting was selective or arbitrary.

3.1.2.1. Factor 1: Gathering season. Our harvesting experiments involved gathering activities in autumn/winter as well as spring/summer time (see Table 1, for details on the harvesting times and types of recovered plant materials).

Autumn/Winter time. Autumn is the rainy season in Jordan and it is the seedling season for club-rush. During this time the shores of lake Burqu' are inundated, and only dry plants from previous years are visible. It is possible to gather club-rush tubers from September to March, but the materials recovered in autumn/winter only comprise old and very fibrous tubers. These old tubers are overall larger than the adult and young immature tubers available during springtime (c. 2.5–3 cm breadth and 3–4 cm length). They are commonly rounded in shape, with similar breadth and length sizes, and they have a hard and thick dark outer cortex, composed of fibrous materials. Old club-rush tubers require intensive processing to make them edible, and in some species like *Cyperus rotundus* (nutgrass) they are directly considered as inedible (Hillman 1989).

Spring/Summer time. In springtime club-rush seedlings begin to grow, and apart from mature fibrous tubers from previous years, new adult and young immature tubers can be harvested. Adult tubers are overall smaller in size than old fibrous tubers (c. 1–2.5 cm breadth and 1–2.7 cm length) and they are commonly elongated, although some round-shaped specimens were also recorded. The outer cortex is normally light brown to yellowish. Young immature tubers derive from plants that are still growing, the stems of which are still short (c. 20 cm) and thin. They are characterised by their relatively small size (c. 0.3–0.7 cm breadth and 0.3–1.5 cm length), round shape and soft and white outer cortex, which unlike that on adult tubers, can be easily removed by hand rubbing. Wollstonecroft (2009) reports that in the case of the sister-species *B. maritimus*, immature tubers can be eaten raw without peeling or processing. She further indicates that although they could have constituted an occasional food, it is unlikely young tubers contributed significantly to human diets due to their overall low nutrient value. We also noted that in summer time, the plants that were already fruiting had on average smaller tubers (c. 1 cm in breadth) than the plants that were still in the process of maturation, which had tubers with an average breadth size of 2–2.5 cm. This is due to the fact that the plants use the energy stored in the underground storage organs for flowering and fruiting, leading to a general reduction in tuber size. Indeed, previous studies show that tubers collected during winter and spring/early summer time would have been overall richer in carbohydrates and other nutrients than those gathered during summer (Wollstonecroft 2007, 2009).

To provide additional insights into the possible season of harvesting of the club-rush tubers at Shubayqa 1, a preliminary comparison of the size of the charred archaeological and modern specimens was carried out. The modern specimens were carbonised under low heating regimes (see details in Table 3, processing experiment #14). Width and length of a total of 103 archaeological and 179 modern specimens were measured digitally, using the Helicon Remote software (ver. 3.9.0 W). Average, maximum and minimum measurements are shown in Table 2. The results indicate differences in the width and lengths of the measured tubers (see also scatter plot in Supplementary Materials). The club-rush tubers from Shubayqa 1 were larger in average breadth size (0.9–1 cm) than modern carbonised tubers gathered in lake Burqu' (0.8 cm), but the main difference relied on the length–width ratios (Table 2). The club-rush tubers from Shubayqa 1 showed average length–width ratios of 1.35 and 1.39, meaning that most of the tubers were round shaped (i.e. similar width and length sizes). The length–width ratios in modern carbonised tubers were instead of 1.67 and 1.68 respectively, meaning that they exhibited an elongated shape (i.e. they were considerably longer than wider).

It is beyond the scope of the present study to identify the reasons for

Table 2
Comparison of modern and archaeological size of carbonised club-rush tubers.

Charred club-rush assemblages	Number of tubers measured	Maximum (mm)		Average (mm)		Minimum (mm)		Lenght/Width ratios
		Width	Lenght	Width	Lenght	Width	Lenght	
Modern 2018 (spring)	*67*	17.84	27.31	8.54	13.41	2.90	5.68	1.67
Modern 2019 (late spring/summer)	*112*	13.92	33.43	8.29	13.90	4.93	5.35	1.68
Shubayqa 1 (early phase)	*52*	17.28	23.72	9.37	12.35	4.60	8.20	1.39
Shubayqa 1 (late phase)	*51*	14.85	20.09	9.97	13.04	5.49	7.97	1.35

these growth patterns since changes in biological production can be attributed to many factors (Clevering et al. 1995; Kantrud 1996 Lieffers and Shay 1982). However, during the fieldwork at least two potential reasons were noted that could have conditioned the size of the gathered tubers, and should be considered in order to interpret the material obtained at Shubayqa 1, namely: rainfall and selective gathering practices.

3.1.2.2. Factor 2: Rainfall conditions. The growth of club-rush plants in the Qasr Burqu' area seemed to have been conditioned by changes in the rainfall. According to the nearest weather station located in Ruwaished (c. 24 km southeast of Burqu') in 2018, the annual average rainfall decreased from c. 46 mm as recorded over the period 2000–2019 to only 26 mm (Menne et al. 2012a, 2012b). Such a dramatic reduction in water availability was also noted during our gathering experiments. In 2017, which was an average year in terms of precipitation, club-rush plants had reached c. 60–70 cm in height by the first week of May, whereas in 2018, they were only 20 cm tall in the same period. Besides, the minimum and maximum sizes of the tubers gathered in 2017 was of 0.5–2.5 cm width and 1.5–3.7 cm length (n = 35), compared to 0.3–1.8 cm width and 0.7–2.7 cm length (n = 67) in 2018. Thus, changes in the amount of precipitation probably conditioned both the availability of club-rush stands and the size of the tubers that could have been gathered.

3.1.2.3. Factor 3: Selective gathering and management practices. Differences in the size of the tubers could also be dependent upon selective v. arbitrary harvesting of the plant materials. It has been previously

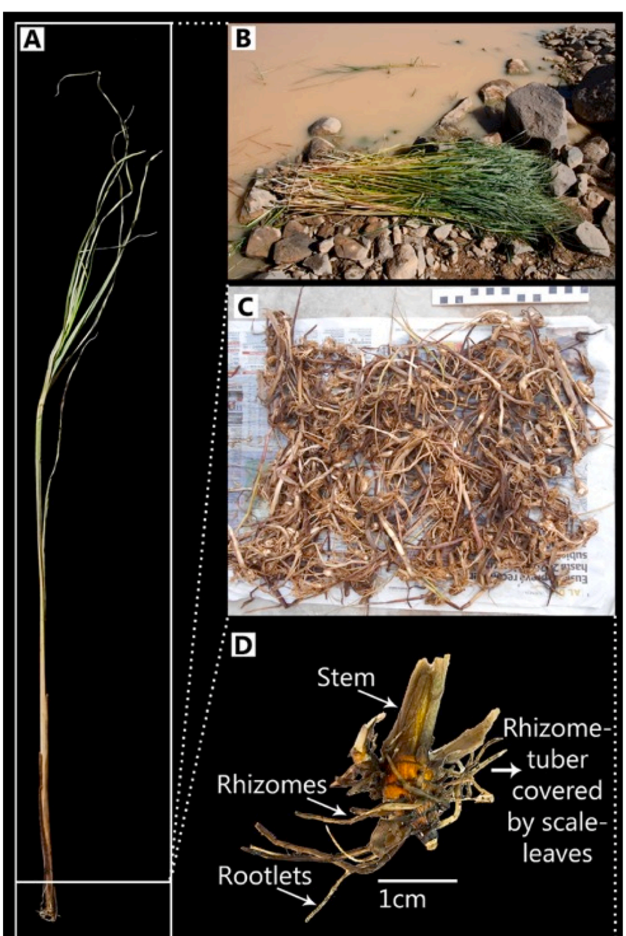

Fig. 5. A) Unprocessed club-rush plant, showing aerial and underground parts; B) separated stems and C) underground storage organs; D) detail of a rhizome-tuber covered by scale-leaves, basal part of the stem, rhizomes and rootlets.

suggested that hunting and gathering groups could have recognised whether tubers were worth harvesting based on the characteristic of the stems visible above ground (Wollstonecroft 2009). During our field observations we noticed that the larger the overall height and thickness of the plant stems visible above water, the larger the tubers underneath. This pattern has also been pointed out by other authors, which indicate that the annual aboveground growth of sea club-rush occurs in conjunction with specific patterns of below-ground production (Kantrud 1996, Lieffers and Shay 1982). In addition, we also documented differences in the size of the tubers depending on the growing location of the plants within the lake (based on the measurement of 48 plants). The plants that grew far away from the shoreline, that is, plants that were permanently under-water, were overall larger in size. These plants had an average of c. 60 cm in height, whereas those that were closest to the shoreline were half the size, c. 35 cm long in average.

Apart from this, plant management activities could also have conditioned the size of the club-rush tubers available at Shubayqa 1. Denham et al. (2020) note that increased number of edible organs and the increased size of edible vegetative organs (the organ used for clonal propagation) are some of the key domestication traits in asexually propagated plants. Indeed, changes in the morphology of plants and tubers have been noted in root crops like *Dioscorea* yams (Hather 2000). Besides, it is well-documented in several root foods like nutgrass, club-rush, yams, and *Typha* (cattail) that tuber production is stimulated due to soil disturbance, like that produced during tuber digging (Hillman 1989, Hallam 1983, Holm et al. 1981, Gott 1982). An intensive exploitation and selection of club-rush tubers during the Natufian could therefore constitute a possible factor to explain the overall larger average size and rounded shape of the tubers found at Shubayqa 1.

3.2. Club-rush processing activities

Once club-rush plants were harvested, the materials had to be further processed. These processing activities involved two main tasks: 1) the separation of the aerial (stems) from the underground parts (rhizome, tubers, roots); and 2) the peeling of underground parts to remove scale-leaves, roots and rhizomes to obtain clean tubers (Fig. 5). In Table 3, the results of the main tuber processing methods and activities carried out are detailed.

3.2.1. Separating the aerial and underground plant parts

Two main processing methods were tested: separate the plant parts by hand pulling and cutting the stems using tools (see Table 3, processing experiments #1–4, Fig. 6).

Initially, the stems were separated from the underground storage organs by hand, when the plants were still wet (processing experiments #2 and 4, Fig. 6A). This activity was carried out immediately after harvesting the tubers on the shore of the lake, by small groups of 2–3 people. This method was particularly suitable to process spring-summer club-rush plants that had green stems. The main advantage of separating the stems by hand was that the basal part of the stem was completely removed from the top end of the tuber, leaving a clean scar (see Fig. 3 "stem removal"). The main disadvantage was that hand pulling required some strength and was not practicable for every participant.

An alternative method for separating the aerial and underground parts was to cut the stems (processing experiments #1, 3 and 4, Fig. 6B). Both chert tools and modern metal knives were used, showing no clear differences in terms of efficiency between the two. Cutting the stems with a knife/chert tool was overall faster than hand-pulling, especially for plants harvested in winter-time, when the stems were dried and hard. However, the main disadvantage was that the basal part of the stem remained attached to the top end of the tuber, and had to be removed in subsequent processing stages (see Fig. 3 "stem removal").

To test whether the microliths found in conjunction with the tuber assemblages could have been used to cut the stems, sickle B was used to cut green stems for 63 min in a longitudinal, unidirectional movement.

Table 3
Club-rush tuber processing activities, timings, products and by-products.

Experiment	Objetive	Method/tools	Materials	State	Amount of material processed (gr)	Number of people involved in processing	Total time spent processing	Product	By-product	Overall evaluation of the experiment
Processing experiment #1 (2017)	Separate aerial and underground parts	Cutting tool	Mature club-rush (Stem + USO)	air-dried	290	1	5 min	USO + basal part of the stem	Stems	Success
Processing experiment #2 (2018)		By hand	Adult and immature club-rush (Stem + USO)	fresh wet	23,693	3	330 min	clean USO	Stems	Success
Processing experiment #3 (2018)		Cutting tool	Adult and immature club-rush (Stem + USO)	fresh wet	9567	1	350 min	USO + basal part of the stem	Stems	Success
Processing experiment #4 (2019)		By hand and cutting tool	Adult and immature club-rush (Stem + USO)	fresh wet	18,478	4	193 min	clean USO + some with basal part of the stem still atached	Stems	Success
Processing experiment #5 (2018)	Peel the tubers: remove scale leaves, roots, rootlets and stem bases	By hand/ use of knife	USO: Primarily adult tubers, with some mature and immature tubers	fresh wet	15,876	5	5.5 h	Fresh peeled tubers	Scale leaves, roots, rhizomes, basal stems	Success
Processing experiment #6 (2019)		By hand	USO: Primarily adult tubers, with some mature and immature tubers	fresh wet	6258	2	5 h	Fresh peeled tubers	Scale leaves, roots, rhizomes, basal stems	Success
Procesing experiment #7 (2019)		Pounding in a basalt mortar	USO: Primarily adult tubers, with some mature and immature tubers	fresh wet	253	1	5–10 min	–	Smashed tubers, mixed with rhizomes/roots	Failure
Processing experiment #8 (2019)		Grinding in a slab	USO: Primarily adult tubers, with some mature and immature tubers	fresh wet	248	1	5–10 min	–	Both smashed and semi-peeled tubers, mixed with roots and rhizomes	Failure
Processing experiment #9 (2019)		Pounding in a basalt mortar	USO: Primarily adult tubers, with some mature and immature tubers	air-dried (12 h)	148	1	5–10 min	–	Cracked tubers, mixed with roots and rhizomes	Failure
Processing experiment #10 (2019)		Grinding in a slab	USO: Primarily adult tubers, with some mature and immature tubers	air-dried (12 h)	147	1	5–10 min	–	Slightly cracked, semi-processed tubers, mixed with roots and rhizomes	Failure
Processing experiment #11 (2018)	Roast the tubers	Roasting in aerobic conditions	USO: Primarily adult tubers, with some mature and immature tubers	air-dried (7 h)	168	1	15 min (c. 500-540°)	–	Carbonised tubers, roots, scale leaves, roots, basal stems	Failure
Processing experiment #12 (2018)		Roasting in aerobic conditions	USO: Primarily adult tubers, with some mature and immature tubers	air-dried (7 h)	75	1	15 min (c. 240-280°)	–	Semi-dry tubers, roots, scale leaves, roots, basal stems	Failure
Processing experient #13 (2019)		Roasting in anaerobic conditions	USO: Primarily adult tubers, with some mature and immature tubers	fresh wet	256	2	120 min (c. 340°)	–	Semi-dry tubers, roots, scale leaves, roots, basal stems	Failure
Processing experient #14 (2019)		Roasting in anaerobic conditions	USO: Primarily adult tubers, with some mature and immature tubers	air-dried (7 h)	80	2	120 min (c. 334°)	Roasted tubers	Carbonised tubers, fragmented roots, scale leaves, roots, basal stems	Success
Processing experiment #15 (2019)	Peel the tubers: remove scale leaves, roots, rootlets and stem bases	Pounding roasted tubers in a mortar	USO: Primarily adult tubers, with some mature and immature tubers	roasted	10	1	5 min	–	Cracked tubers, mixed with roots and rhizomes	Failure
Processing experiment #16 (2019)		Grinding roasted tubers in a slab	USO: Primarily adult tubers, with some mature and immature tubers	roasted	10	1	15 min	Peeled roasted tubers	Scale leaves, roots, rhizomes, basal stems	Success

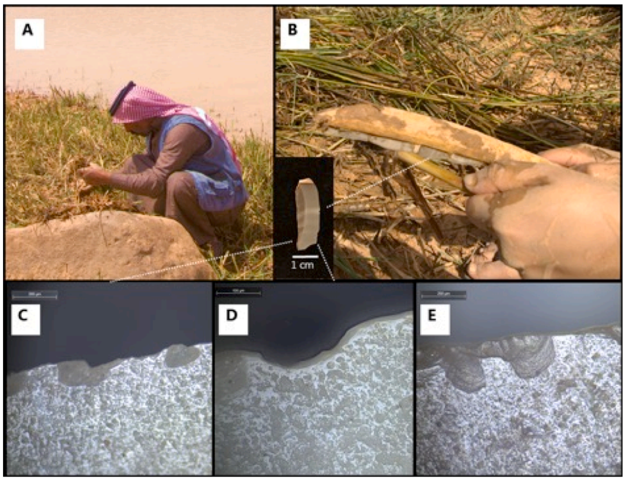

Fig. 6. A) Separating aerial and underground plant parts by hand. B) Sickle B used to cut and separate the stems approximately-one centimetre above the tuber; Use-wear traces from experimental tools EXLI67 showing C) scalar and trapezoidal scarring, silica gloss and longitudinal striae (scale 200 μm), and D) edge-rounding and silica gloss (scale 100 μm; E) Use-wear traces from an inversely retouched bladelet found in the fireplace A at Shubayqa 1 (ID004, scale 200 μm).

At this point, three out of the four sickle inserts had developed macroscopically visible silica gloss along the active edges as well as rather small scalar and trapezoidal scarring (Fig. 6C and D). The high power microscope confirmed the findings, and also made visible faint, longitudinal striations (Fig. 6C). The use-wear was generally more developed on the side of the tool facing the thumb (in this case the dorsal side). A comparison between the experimental and archaeological tools in Fig. 6C-E, shows similar wear-trace development in terms of scarring and gloss, suggesting that the archaeological implement could have been used in a similar fashion to the experimental ones. This is further indicated by laser scanning confocal microscope analyses of archaeological tools from Shubayqa 1 (Ibáñez-Estévez et al. 2021). Using this method, which allows assigning silica gloss to a specific plant type (Evans and Donahue 2008, Ibáñez, Lazuen and González-Urquijo 2018, Stemp and Chung 2011), it was possible to establish that four artefacts recovered from the site were used to cut silica rich plants (cereals, grasses and reeds), which could potentially include club-rush. However, the processing of other silica rich plants, such as cereals and other grasses, as well as soil digging could produce very similar wear-traces to those found on the archaeological tools from Shubayqa 1 (Anderson 1991, p. 525). Therefore, the interpretations from these initial experiments are to be considered suggestions until further analyses are carried out.

3.2.2. *Removing scale leaves, roots and rhizomes*

Club-rush rhizome tubers comprise tight scale leaves, rhizomes and rootlets that have to be removed in order to access the starch-rich parenchymatous tissue (Fig. 5D). For this purpose a number of different experiments were carried out, including the processing of tubers in different states (wet, air-dried, roasted), and using a number of tools (hands, knives, ground stone tools) and processing techniques (grinding, pounding, see details in Table 3).

Overall, the most suitable processing techniques for club-rush tubers depended on the season of collection and the state of maturity of the tubers: old/mature fibrous tubers, adult tubers, and young and/or immature tubers (Fig. 7A). Old tubers from autumn-winter time were dried at the time of collection, and due to their thick and fibrous epidermis, a cutting tool was necessary to remove the outer scale-leaves (Fig. 7B). In contrast, adult and immature tubers from spring-summer time could have been processed both whilst fresh (i.e. wet) and after drying. In the following lines we discuss the different processing techniques applied to these latter groups of tubers.

Fig. 7. A) Image of unpeeled spring-summer time adult and immature tubers (left) and autumn–winter time mature tuber (right); B) Peeling of tubers with knives/cutting tools; C) Fresh peeled tubers; D) Plant residues derived from tuber processing: scale leaves, roots and rhizomes; E) Tubers with cut marks made by cutting tools during peeling; F) Immature (left) and adult (right) tubers dried before processing, showing characteristic shrinkage and wrinkled epidermis.

3.2.2.1. *Peeling fresh and air-dried tubers by hand and using cutting and ground stone tools.*

Experiments #5–10 intended to evaluate the processing of the tubers straight after they were gathered, whilst the tubers were still fresh and wet, as well as after drying. For this purpose three main approaches were tested: 1) processing the tubers with bare hands; 2) using a cutting tool to remove the scale leaves and rhizomes; 3) and using ground stone tools, both grinding and pounding implements.

The first set of experiments (#5–8) was carried out with fresh tubers. To remove the scale leaves, rhizomes and rootlets we used bare hands, inserting the fingernails into the surface of the tuber and scraping (processing experiment #5 and 6). This process was time consuming (e.g. 5 h, 2 people for c. 600 g of unprocessed tubers), but successful. The resulting products were perfectly cleaned tubers (Fig. 7C), and a residue composed of scale leaves, roots and rhizomes (Fig. 7D). Some participants preferred the use of cutting tools like a knife, as the constant friction with the hard outer epidermis damaged the fingernails. Besides, a cutting tool was sometimes necessary to remove the hard rhizomes. Interestingly, the use of a cutting tool left clear-cut marks on the surface of the tubers that can be recognisable in the archaeological record (Fig. 7E).

Processing experiments #7–10 were carried out to evaluate whether the thousands of ground stone tools found at Shubayqa 1 could have been used, amongst other activities, to obtain peeled tubers (i.e. remove process club rush and). We tested the use of a basalt mortar and wooden pestle (experiment #7), as well as a grinding slab (experiment #8) as a means to separate the fresh tubers from the root and the rhizomes. However, the experiments failed. The tubers were overall too wet and sticky to be ground, and the resulting product was a mush of unprocessed tuber materials (see detailed description of these experiments in Supplementary Materials and Table 3).

These experiences led us to dry the tubers in the sun, and try to process them once the water content had evaporated (experiments #9 and 10). But these processing activities also failed. After c. 12 h in the sun, the tubers became too hard and none of the different types of tubers (i.e. mature, adult, immature) could be processed either by hand or with cutting tools. Besides, many of the adult and immature tubers had completely shrunken, showing wrinkles characteristic of dehydration (Fig. 7F). When trying to process them with pounding and grinding tools (experiments #9 and 10) air-dried tubers fragmented into small pieces, leaving a mix of cracked tubers, along with fragments of roots, rhizomes and scale leaves (see examples of cracked tubers in Fig. 9).

From these sets of experiments we learnt that the best strategy to remove the scale leaves, roots and rhizomes from club-rush tubers was to peel them soon after they were harvested, when they were still fresh and preserved their water content, either by hand or using cutting tools. However, tuber peeling was the most time-consuming aspect of the *chaîne opératoire*, as it required considerably more time and energy than the gathering of the plants itself (see Table 3). As such, we decided to test a final processing method that could optimise the exploitation of this plant food.

3.2.2.2. Roasting club-rush tubers. In this study we sought to test if roasting could facilitate the de-husking of club-rush tubers. To find out which was the best procedure to obtain roasted club-rush tubers four main experiments were carried out (see Table 3, experiments # 11–14). The step-by-step description of the different roasting experiments can be found in the Supplementary Materials.

Overall, roasting activities involved unprocessed fresh and air-dried club-rush tubers. In the study area, drying of tubers was relatively fast. For example, in late springtime, when day temperatures vary between 30 and 40°, a sub-sample of c. 3065 g was air-dried after c. 7 h (from 8 am to 3 pm). Additionally, the tubers were burnt in both aerobic conditions and anaerobic conditions. In experiments #11 and 12, the tubers were roasted in hot ashes, whereas in experiments #13 and 14 we used pit-ovens (also known as “earth oven” or “roasting pits” Fig. 8). These pit-ovens were made of: 1) a layer of wood charcoals and pre-heated basalt stones in the bottom; 2) followed by a layer of club-rush tubers wrapped in stems; 3) and a top layer of wood charcoal remains and soil, which after adding water became hardened and sealed the deposit (see detailed step-by-step description of the construction of the fire installations in the Supplementary Materials). The fuel used in all the

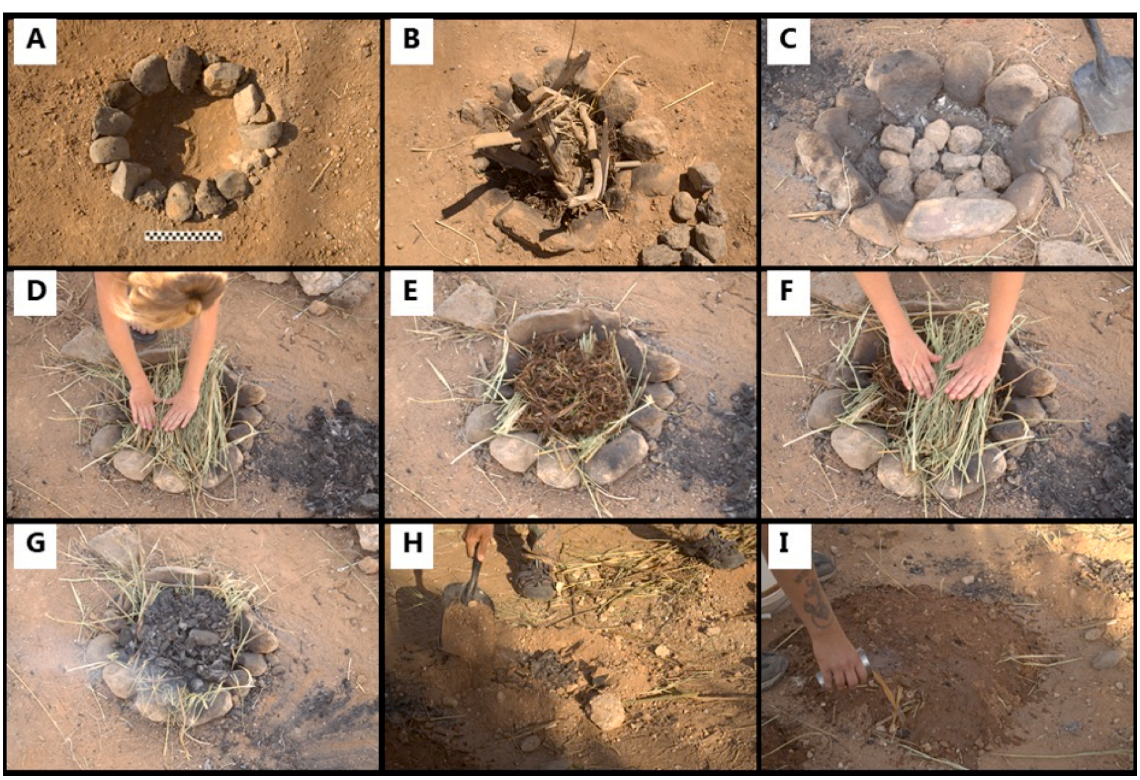

Fig. 8. Pit-oven construction, experiments #13 and 14. A) A c. 50 cm diameter wide and c. 30 cm deep pit with angular to sub-angular cobble-sized basalt stones; B) Fuel wood ready to be burnt; C) Burnt wood charcoal pieces and small cooking basalt stones (note thermal alteration in the pit lining stones); D) First layer of club-rush stems; E) Unprocessed club-rush tubers ready to be roasted; F) Second layer of club-rush stems; G) Remaining wood charcoal fragments; H) Covering of the pit with soil; and I) Addition of water to seal the deposit.

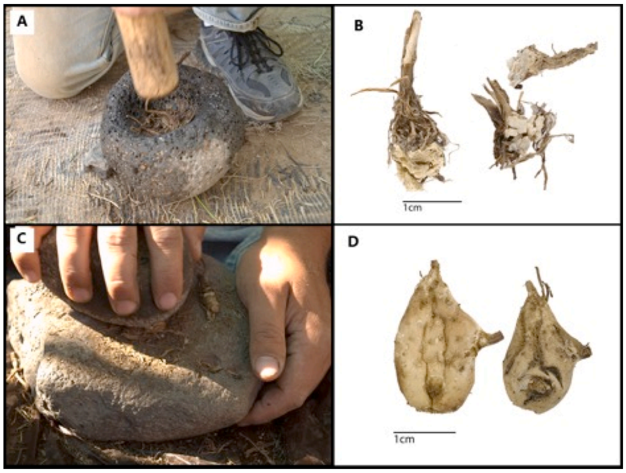

Fig. 9. Roasted tubers from experiment #14 A) being pounded in a mortar, leading to B) cracked tubers; C) being ground in a quern, leading to D) perfectly peeled tubers.

experiments was the same and included wheat straw and club-rush stems as starters, and fig and Chenopodiaceae (goosefoot family) wood. In experiments #13 and 14, commercial fuel wood (olive and oak) was additionally used. The amount of club rush tuber materials included in each of the roasting pits and the temperatures in the different stages of the process (initial lighting of the fire v. end), and burning elements (flames, soil, wood charcoals and the basalt stones) were individually recorded.

The results show important differences in the state of the tubers from experiments #11–14. Roasting of air-dried tubers in the hot ashes (aerobic or semi-aerobic conditions) for 15 min at temperatures of 500-540° resulted in completely carbonised tubers, whereas temperatures of 240-280° in the same conditions were instead insufficient, and resulted in semi-wet tubers. Whilst these two experiments failed, roasting of the tubers in anaerobic conditions proved successful. The tubers from experiment #14 were perfectly roasted, although by the time the pit-oven was opened, 1/5 of the tubers had been completely carbonised. The procedure was the same as in experiment #13 (i.e. 2 h of cooking at a starting temperature of c. 340), but the tubers from experiment #13 had been gathered from the lake and directly put into the pit-oven whilst wet, whereas those in experiment #14 had been air-dried first. This additional step reduced the humidity of the tubers, and allowed them to perfectly roast inside the pit-oven. However, the roasted tubers still preserved the scale leaves and root/rhizome remains, meaning that an additional step was necessary to peel them.

3.2.2.3. Peeling roasted tubers by pounding and grinding. Once the tubers were roasted, we intended to test whether the use of ground stone tools, in particular mortars and querns, could help remove the hard scale leaves that were still attached to the tubers (Experiments #15–16, Fig. 9, see detailed description in Supplementary Materials).

In experiment #15, we took the basalt mortar and wooden pestle to pound the roasted tubers from previous experiment #14, but failed in obtaining peeled tubers (Fig. 9A). After only 5 min of pounding, the tubers were completely fragmented and cracked, and the different parts of the plant, that is, the tuber, the scale leaves, and small fragments of semi-carbonised roots and rhizomes were mixed (Fig. 9B). Instead, in experiment #16, we used the quern and a stone basalt hand stone to process 10 gr of roasted tubers (Fig. 9C). This method proved successful, as the abrasion removed the roasted scale leaves efficiently, obtaining completely clean tubers (Fig. 9D). In addition, the peeling/grinding of the tubers in the quern allowed separating the clean tubers from the remaining residue, something that was not possible using the deeper-faced mortars.

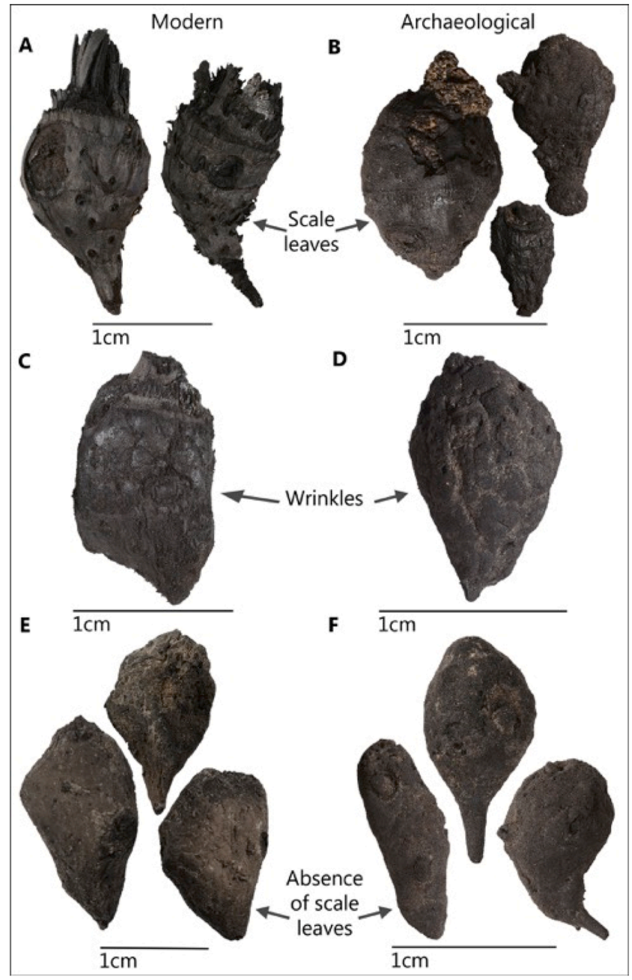

Fig. 10. Initial classification and comparison of the modern and archaeological carbonised club-rush tubers. A) Modern unpeeled carbonised tubers from experiment #11; B) Tubers from Shubayqa 1, sample 30 (2012), still showing scale leaves and the rhizome detachment scars; C) Modern wrinkled tuber from experiment #11; D) Wrinkled tuber from Shubayqa 1, sample 90 (2013); E) Modern peeled tubers from experiment #6; F) Archaeological tubers from Shubayqa 1, sample 90 (2013), interpreted as "peeled".

3.2.3. Initial comparison of the experimental and archaeological club-rush tubers

Whilst the full taphonomic study of the experimental and archaeological tubers has not yet been completed, the experimental club-rush tuber materials produced in this work allow us to start classifying and understanding the taphonomic history of the archaeological tuber remains recovered at Shubayqa 1. The initial qualitative comparison of the archaeological and experimental tubers shows clear equivalences in three main categories (Fig. 10):

- Tubers that still preserve scale leaves. Processing experiments #11 and #14 showed that if unpeeled tubers were placed into the fireplaces and carbonised, they would still preserve the scale leaves (Fig. 10A). In other words, carbonization allowed the breakage of the roots and rhizomes but did not remove the tough scale leaves. Interestingly, in the first report from Shubayqa 1 (Arranz-Otaegui et al. 2018a) a small number of the tubers that still preserved scale-leaves was recorded (Fig. 10B). This evidence, together with the presence in the fireplaces of other plants elements such as the stems, stem bases, roots and rhizomes (see Fig. 3A-R, in Arranz-Otaegui et al. 2018a) suggests that, at some pint in their use-life, Natufians must have placed unprocessed tubers in the fireplaces.

- Tubers with wrinkled epidermis. Processing experiment #11 showed that if club-rush tubers were first air-dried and then carbonised, the resulting tubers would exhibit a very characteristic wrinkled epidermis, resulting from the gradual loss of humidity (Fig. 10C). An initial evaluation of the archaeological tuber assemblage shows that this club-rush tuber category was also attested in the fireplaces from Shubayqa 1 (Fig. 10 D), indicating that some of the tubers were dry by the time they were carbonised.

- Peeled tubers. To produce comparative experimental materials, the hand-peeled tubers from processing experiments #5 and #6 were carbonised under both aerobic and anaerobic conditions (see description of the procedures in Supplementary Materials experiments #11 and #14). In both cases, the resulting tubers were characterised by the absence of scale leaves, rhizome detachment scars, and stem bases, and removal of most of the rhizome detachment scars (Fig. 10E). The comparison with the archaeological tubers reported in Arranz-Otaegui et al. (2018a) is in this sense revealing, as it shows that the largest amount of tubers belonged to this category (Fig. 10F). We can therefore hypothesise that most of the tubers found in the fireplaces were peeled by the time they were put into the fireplaces and become carbonised, as otherwise they would have still preserved the tough scale leaves (as observed in experiments #11 and #14, Fig. 10A and 10B).

4. Final conclusions: First insights into club-rush tuber exploitation at Shubayqa 1

Based on the experimental work and the material found at Shubayqa 1 we can start to draw some initial conclusions about how club-rush tuber exploitation activities could have taken place during the Early Natufian period.

In terms of gathering methods, we consider that uprooting was the most efficient method to harvest club-rush plants in the Black Desert, whilst digging sticks could have been useful specifically to harvest specimens that remain stuck in the mud or that were not growing underwater (i.e. like those available during autumn–winter time). If we accept that the rainy season at the end of the Late Pleistocene took place at the same time as today (i.e. October-November), it is most likely that the harvesting of club-rush tubers was carried out during spring-early summer time (May-June).

At this stage, before the plants started to flower, the tubers are most succulent, before the plants started to flower, at the time the tubers were most succulent. An interesting aspect that emerged from the comparison of the size of the archaeological and modern tuber assemblages is that the archaeological specimens were overall more rounded in shape and slightly larger in width than tubers that derive from modern unmanaged stands. Future studies will aim at evaluating the possible factors behind these differences, both in terms of environmental conditions, selective gathering as well as possible management practices.

After gathering the plants, the Natufian communities would need to separate the aerial and underground parts. This activity was most likely carried out immediately after the harvesting, before the stems become dry and hard to remove, either by hand or using chipped stone tools. The on-going use-wear analyses of the chipped stone tools found at Shubayqa 1 and the application of confocal microscopy are expected to provide additional insights into which procedure was potentially used during the Early Natufian period. Yet so far, the gathered data suggests that chipped stone tools were not crucial at any stage of tuber gathering and processing.

The final and most-time consuming stage of the processing was the peeling of the club-rush tubers. We consider that individual peeling of club-rush tubers, either by hand or using chipped-stone tools, could have been an option during the Natufian, especially if the tuber assemblages harvested were small (e.g. up to 2,000 tubers). But, for large assemblages (e.g. more than 15,000), as those recorded in Shubayqa 1, more efficient processing methods were available. Indeed, our experiments for the first time show that air-drying, roasting and subsequent grinding would have been less demanding, both in terms of time and effort, than peeling the tubers one-by-one. When it comes to the use of groundstone tools, we can conclude that the mortars and querns attested at Shubayqa 1, did not serve to process fresh tubers, as the gestures to pound and grind did not remove the scale leaves, roots and rhizomes. Nevertheless, previous studies did succeed in peeling club-rush tubers using deep-conical wooden mortars (i.e. Hillman), and as such, further experiments are necessary to evaluate how the depth of the mortars (i.e. 5, 10 or 20 cm or larger) and the raw material used (wood opposite to stone) could affect the overall efficiency of the method.

Finally, one of the most interesting conclusions we can extract from this work derives from the initial comparison of the experimental and archaeological tuber assemblages. The results show that the largest part of the tubers found in the fireplaces from Shubayqa 1 were probably peeled by the time they were placed on them. In other words, the tubers were carbonised after the processing stage, probably during cooking. As such, the final step in our experimental program will be to evaluate how the club-rush tubers were transformed into plant foods, and as well to identify the specific cooking practices and the types of foodstuffs produced with them. In particular we will ask: why were the club-rush tubers peeled and subsequently put into the fireplaces? And what types of cooking techniques were used in their transformation?. Ultimately, this detailed interdisciplinary experimental approach will enable us not only to reconstruct the complete sequence for club-rush tuber gathering, processing and cooking during the Early Natufian; but also, to start identifying some of the social, economic and cultural practices associated with the routine exploitation of wild plant resources in the past.

CRediT authorship contribution statement

Amaia Arranz-Otaegui: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Resources, Writing – review & editing, Visualization, Funding acquisition. **Patrick Nørskov Pedersen:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Resources, Writing – review & editing, Visualization. **Ann Frijda Schmidt:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Resources, Writing – review & editing, Visualization. **Anne Jörgensen-Lindahl:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Resources, Writing – review & editing, Visualization. **Joe Roe:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Johan Villemoes:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **George Alexis Pantos:** Visualization, Investigation, Writing – review & editing. **Kathryn Killackey:** Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2022.103677.

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