Comp. by: ISAAC PANDIAN Stage: Revises1 Chapter No.: 21 Title Name: Mithen&Black
Page Number: 0 Date:28/1/11 Time:05:17:46

21 Irrigation and phytolith formation: an experimental study

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ABSTRACT

It has been proposed that phytoliths from archaeological sites can be indicators of water availability and hence inform about past agricultural practices (Rosen and Weiner, 1994; Madella *et al*., 2009). Rosen and Weiner (1994) found that the number of conjoined phytoliths from cereal husks increased with irrigation while Madella *et al*. (2009) demonstrated that the ratio of long-celled phytoliths to short-celled phytoliths increased with irrigation. In order to further explore these hypotheses, wheat and barley were experimentally grown from 2005 to 2008 in three different crop growing stations in Jordan. Four different irrigation regimes were initially employed: 0% (rainfall only), 80%, 100% and 120% of the optimum crop water requirements, with a 40% plot being added in the second and third growing seasons. Each plot measured 5 m × 5 m and a drip irrigation system was used. Environmental variables were measured on a daily basis, and soil and water samples were taken and analysed at the University of Reading. Phytoliths from the husks of these experimentally grown plants were extracted using the dry ashing method. Results demonstrate that although the number of conjoined cells increases with irrigation, there were considerable inter-site and inter-year differences suggesting that environmental variables other than water availability affect phytolith uptake and deposition. Furthermore, analytical experiments demonstrated that conjoined phytoliths are subject to change or breakage by external factors, making this methodology problematic to apply to archaeological phytolith assemblages that have an unknown taphonomic history. The ratio of long cells to short cells also responded to increased irrigation, and these forms are not subject to break up as are conjoined forms. Our results from the modern samples of durum wheat and six-row barley show that if an assemblage of single-celled phytoliths consists of over 60% dendritic long cells then this strongly suggests that the crop received optimum levels of water. Further research is needed to determine if this finding is consistent in phytolith samples from the leaves and stems, as suggested by Madella *et al*. (2009), and in other species of cereals. If this is the case then phytoliths are a valuble tool for assessing the level of past water availability and, potentially, past irrigation.

21.1 INTRODUCTION

21.1.1 Archaeology, irrigation and phytoliths

The development of water management systems in southwest Asia has long been recognised as important for understanding socio-economic change. Although Wittfogel's 'hydraulic hypothesis' (Wittfogel, 1957) of irrigation management as the prime mover for the emergence of early states may no longer be tenable, the management requirements of irrigation systems and the potential increase in surplus that can arise from their use remain key issues for understanding the emergence of social complexity (Scarborough, 2003). Direct archaeological evidence for water management in Jordan takes numerous forms, including wells, cisterns, field systems and irrigation ditches (Chapter 14, this volume; Oleson, 2001). Such evidence is often substantial for proto-historic and historic periods, such as the sophisticated Nabataean modifications to the siq at Petra (Bellwald and al-Huneidi, 2003) or the Roman/Byzantine reservoir, aqueduct and field system in Wadi Faynan (Barker, 2000). Structural evidence for water management is both more elusive and more difficult to interpret for the prehistoric periods, when it is likely that water management, including the irrigation of cereals, began.

The earliest known structural evidence in the Water, Life and Civilisation study region has been summarised in Chapter 14 of

Water, Life and Civilisation: Climate, Environment and Society in the Jordan Valley, ed. Steven Mithen and Emily Black. Published by Cambridge University Press.

this volume: the PPNB wadi barriers and cistern in the Jafr Basin; the Pottery Neolithic well at Sha'ar Hagolan, Israel (Garfinkel *et al*., 2006); and the set of small terrace walls at the Neolithic site of Dhra', Jordan, which have been interpreted as functioning to minimise soil erosion, controlling water runoff during wet periods of the year, and as field systems for growing wild and domesticated plants.

Whether or not the Dhra' walls functioned to provide additional water to crops remains unclear. Indeed, such uncertainty often exists even when a complex water management system is evident. At the Early Bronze Age site of Jawa, for instance, there appears to have been a system of channels, dams and pools to collect and store winter flood water from the adjacent Wadi Rajil (Helms, 1981; Helms, 1989). Hydrological models have been developed to estimate the size of the animal and human populations that could be sustained by such water storage (Whitehead *et al*., 2008). But the estimates are highly dependent upon whether the stored water had also been used to irrigate surrounding fields for the growth of cereals, for which there is no direct evidence.

At other archaeological sites there may be circumstantial evidence for agricultural intensification requiring irrigation, but a complete absence of any structural evidence for water management. At the Chalcolithic site of Ghassul, for instance, Bourke (2001, p. 119) proposes that there had been 'elite-regulated exploitation of flood-water irrigation systems', but has no evidence for ditches, walls or dams. Such structures may not have been necessary or simply insufficiently substantial to have survived in the archaeological record. Indeed, in some cases effective water management requires no more than minor and ephemeral adjustments to water courses, as we have observed among the Bedouin in Wadi Faynan (Figure 15.2, this volume). They use small walls of pebbles and mud to divert seasonal streams and create substantial pools of water; these are constructed in a few minutes, frequently modified and then simply washed away leaving no archaeological trace. Far more substantial evidence may have been destroyed: Philip (2001) notes that the down-cutting of wadis and the deposition of colluvium in the Jordan Valley may have removed or buried structural evidence for water management of the Early Bronze Age, for which there is only direct evidence from Tall Handaquq (Mabry, 1989) and Jawa (Helms, 1981, 1989).

As the structural evidence for water management is difficult to interpret and may simply not exist, it would be of considerable value to have a methodology for the inference of crop irrigation directly from archaeobotanical remains. Helback (1960) proposed that the size of charred flax seeds could be used to this end, while Mabry *et al*. (1996) suggested that the size of wheat grains from Tall Handaquq implied irrigation agriculture. Such arguments are problematic because of the impact that charring itself may have on the size of seed grains, and the numerous other factors that may also influence grain size. Studies by Jones *et al*. (1995) and Charles *et al*. (2003) demonstrated that when modern-day fields and crops are available for study, their weed floras can be indicators of past water availability. Unfortunately, sufficiently well-preserved assemblages of charred plant remains from prehistoric sites for such studies are rarely recovered from the archaeological record.

Carbon isotope analysis is another method which has been proposed for identifying irrigation in arid regions (Araus *et al*., 1997, 1999). Studies of carbon isotopes from cereal grains and rachises have demonstrated that ratios change as a result of increased water availability. However, there are problems in applying this method to archaeological remains. Firstly, as with the method proposed by Jones *et al*. (1995) and Charles *et al*. (2003) it is often impossible to recover a large enough sample from an archaeological site to use this method. Secondly, there are unknown environmental variables that could have affected the carbon isotope signature such as climate and soil chemistry. Thirdly, the impacts of charring and diagenesis on carbon isotope ratios are poorly understood (Tieszen, 1991; Heaton, 1999; Codron *et al*., 2005). Finally, a highly specialised laboratory is needed in order to conduct analysis. However, despite these problems this method has potential for identifying past water availability, and research into the effect of irrigation and taphonomy on carbon isotope ratio in cereal grains is being conducted as part of the Water, Life and Civilisation project (Chapter 22, this volume).

Another proposed method for identifying irrigation is phytolith analysis. Rosen and Weiner (1994) found that the number of conjoined phytoliths from cereal husks increased with irrigation while Madella *et al*. (2009) demonstrated that the ratio of long-celled phytoliths to short-celled phytoliths increased with irrigation. If phytoliths could be used to identify ancient irrigation, this would be a very valuable tool for archaeologists; phytoliths are often abundant on archaeological sites, samples are easy to take and processing is straightforward and relatively inexpensive compared with the hours of flotation time needed to recover macroscopic remains or the cost involved in setting up a stable isotope laboratory.

In order to further explore the hypothesis that phytoliths can be indictators of water availability, wheat and barley were experimentally grown from 2005 to 2008 in three different crop growing stations in Jordan under different irrigation regimes. The phytoliths from the husks of these plants were then extracted for analysis. This chapter outlines the methodology used in the experiment and discusses the results in light of their implications for the use of phytoliths as indicators of past water availability.

21.1.2 Phytoliths and their formation

Phytoliths are composed of opaline silica which is taken up as monosilicic acid by plants through their roots into the vascular system during transpiration and deposited in a solid state as silicon dioxide in inter- and intra-cellular spaces. The reasons that plants produce phytoliths are only partially understood. One reason appears to be protection from disease (Williams and Vlamis, 1957; Yoshida *et al*., 1959), herbivory, pathogenic fungi and insect attack (Takijima *et al*., 1949; Djamin and Pathak, 1967; Heath, 1979). Phytoliths also protect plants from the harmful impacts of trace elements such as aluminium and manganese (Jones and Handreck, 1967; Horiguchi, 1988; Hodson and Evans, 1995; Hodson and Sangster, 1999). It has also been demonstrated that phytoliths slow down the rate of transpiration in cuticular and epidermal cells (Mitsui and Takatoh, 1959; Yoshida *et al*., 1959; Okuda and Takahashi, 1965; Raeside, 1970), inhibit the plant's uptake and translocation of sodium in saline conditions (Ahmad *et al*., 1992; Liang *et al*., 1996) and increase the oxidising power of roots (Okuda and Takahashi, 1965). Phytoliths also increase the strength and yield capabilities of plants and even the fertility of pollen in certain species (Mitsui and Takatoh, 1959; Yoshida *et al*., 1959; Vlamis and Williams, 1967; Raeside, 1970; Miyake and Takahashi, 1983, 1986; Ahmad *et al*., 1992). In Japan, silica from slag has been used as a form of fertiliser for rice plants since the 1950s because it increases dry matter production and grain yield (Agarie *et al*., 1996).

Two modes – passive and active – of silicon uptake in plants have been proposed, while some species have also been identified as silicon rejectors (Richmond and Sussman, 2003). Jones and Handreck (1965) were able to predict the weight percent of phytoliths to original plant matter processed (phytolith weight % = weight of phytoliths/weight of plant matter processed $\times$ 100) if they knew the concentration of silicon in the soil solution and the amount of water transpired, suggesting that the uptake of silicon was passive (Jones and Handreck, 1965). Okuda and Takahashi (1965) demonstrated that silicon uptake can occur against a concentration gradient in rice, suggesting that uptake can also be active. Barber and Shone (1966) argued that while passive uptake explained the entry of silicon into the roots of barley it did not adequately explain its uptake into the transpiration stream (Barber and Shone, 1966). It has also been suggested that some plants such as tomato and faba bean are silicon excluders or rejecters and actively prohibit the uptake of silicon (Liang *et al*., 2006). Generally the evidence for silicon uptake in grasses and sedges now suggests that both passive and active components coexist in many species (Jarvis, 1987; Walker and Lance, 1991; Mayland *et al*., 1993; Ernst *et al*., 1995; Liang *et al*., 2006) but, unlike diatoms, a suite of genes responsible for the transportation of silicon has not yet been identified in plants (Richmond and Sussman, 2003).

Phytolith research is a relatively new topic within archaeology, the potential of which is still being explored (see Chapter 23, this volume). One role that they may play is as a proxy for past water availability and possible irrigation (Rosen and Weiner, 1994; Rosen, 1999). This is because silicon uptake and hence deposition is influenced by the rate of transpiration, which in turn is dependent on water availability. Richardson found a correlation between water transpired by barley grown in controlled greenhouse conditions and the silicon content of the plant (Richardson's results reported in Hutton and Norrish, 1974, p. 204). Jones and co-workers (Jones and Milne, 1963; Jones *et al*., 1963; Jones and Handreck, 1965) demonstrated that water transpiration affected silicon uptake in oats, while Hutton and Norrish (1974) showed that the amount of silica found in the husks of wheat was proportional to water transpired.

Additional variables also affect silicon uptake and deposition. One important factor is the amount of silicon available to the plant in the growing medium (Parry and Smithson, 1958, 1964, 1966; Yoshida *et al*., 1959; Blackman, 1968a, 1968b; Blackman and Parry, 1969). This can come from two different sources, the soil and the water. Rain water contains little silicon, with silicon accretion and input from rain water being ≤ 1 kg ha^{-1} yr^{-1} (Alexandre *et al*., 1997). The level of silicon in the water used for irrigation can vary according to the source of water used; if a form of rainwater harvesting is employed, then the water will contain little silicon, whereas if the water comes from a wadi or river, the silicon level is likely to be higher (Imaizumi and Yoshida, 1958; Meybeck, 1987; Bluth and Kump, 1994; White and Blum, 1995). The amount of silicon in the soil varies according to geology and land use (Alexandre *et al*., 1997). If land is under cultivation, silicon levels in soils can be reduced by plant uptake. If plants remain *in situ*, silicon will eventually be released back into the soil through phytolith dissolution. However, if plants are harvested, and thus removed from the growing site, then silicon levels will be reduced. The level to which this occurs is partly dependent on plant species: monocots produce between 14 and 20 times as much weight percent of phytolith as dicots, thus leaving less silicon available in the growing medium (Albert *et al*., 2003).

Another variable which affects the uptake and deposition of silicon is the transpiration rate. This is climatically dependent, being much faster in arid and semi-arid regions than in temperate and humid climes (Jones and Handreck, 1965; Barber and Shone, 1966; Raeside, 1970; Hutton and Norrish, 1974; Rosen and Weiner, 1994; Webb and Longstaffe, 2002). It has been suggested, however, that one of the roles of silicon in plants is to slow down transpiration rates: in both rice and (to a lesser extent) barley, the transpiration rate is faster in silicon-deprived plants than in the non-silicon-deprived control samples (Yoshida *et al*., 1959; Okuda and Takahashi, 1965). Lewin and Reimann (1969) suggest this increased transpiration rate in silicon-deficient plants could be due to a lack of silica gel associated with the cellulose in the cell walls of epidermal cells which helps reduce water loss (Lewin and Reimann, 1969).

Soil texture and chemistry also affect phytolith production. For example, a clay-rich soil will retain more water than other soil types, while aluminium oxides, iron oxides and alkaline soils are adsorbers of silicon, making less available to the plant

(Okamoto *et al*., 1957; Parry and Smithson, 1958, 1964, 1966; McKeague and Cline, 1963). When nitrogen is added to soil, the percentage of silicon in wheat decreases (Hutton and Norrish, 1974), while sodium fluoride inhibits silicon uptake in rice (Mitsui and Takatoh, 1959; Okuda and Takahashi, 1965). Other variables that affect silicon uptake are species (Parry and Smithson, 1958, 1964, 1966; for a review of silicon uptake in different species see Lewin and Reimann, 1969, p. 294) and plant age (Sangster, 1970; Bartoli and Souchier, 1978; Perry *et al*., 1984).

21.1.3 Phytoliths as a proxy for water availability

Rosen and Weiner (1994) explored the possibility of using phytoliths as a proxy for past irrigation by analysing dry-farmed and irrigated samples of emmer wheat (*Triticum turgidum* subsp. *dicoccum*) and bread wheat (*T. aestivum*). They hypothesised that the increased level of transpiration in arid and semi-arid regions would affect silicon uptake and deposition to such an extent that it would be discernible in the archaeological record. They set up a field experiment at the Gilat Agricultural Research Station, Israel, where emmer wheat was planted in two plots, one irrigated, the other non-irrigated, each measuring approximately 3 m × 1 m. The topography was flat and the growing medium was a light loessial soil. Rainfall for the growing season was 224 mm and the irrigated plot received an additional 200 mm of water. In addition, samples of bread wheat (*T. aestivum*) were collected from irrigated and dry-farmed fields in Gilat and northern and central Israel as well as from dry-farmed fields in Germany and eastern Washington State, USA. A limited number of wild (*Hordeum vulgare* subsp. *spontaneum*) and domestic (*H. vulgare* subsp. *vulgare*) barley samples were also collected. Phytoliths were isolated from the samples using acid extraction following the methodology of Piperno (1988) (Rosen and Weiner, 1994, p. 127).

The results showed that the samples grown under irrigation not only had a greater yield of phytoliths but also a greater number of conjoined cells. The percentage of phytoliths with 10 or more conjoined cells was only 2.1% for the non-irrigated plants but 13% in the irrigated plants (Rosen and Weiner, 1994). A similar pattern was evident from bread wheat, with the yield from irrigated wheat collected from Germany and the USA consisting almost entirely of single-celled phytoliths, whereas the irrigated Israeli-grown wheat contained a greater number of conjoined forms. Owing to the limited number of barley samples counted, it was not possible to obtain a statistically viable result, but preliminary findings suggested that barley may respond to irrigation in a similar way, with irrigated barley having a greater number of conjoined cells than the dry-farmed barley (Rosen and Weiner, 1994). Rosen and Weiner (1994) propose that when dealing with archaeological samples from arid and semi-arid regions, the presence of at least 10% of phytoliths with 10 or more conjoined cells, or any phytoliths with 100 or more conjoined cells, provides an indication of past irrigation. This was used to infer that irrigation had been used for growing emmer wheat at two Chalcolithic sites in the northern Negev: Gilat and Shiqmim (Rosen and Weiner, 1994).

Although the work of Rosen and Weiner was pioneering, experimentation was on a small scale in order to establish whether the methodology had potential. As such, many variables such as soil chemistry and climate were not accounted for. In addition, only two irrigation regimes were employed, irrigated and non-irrigated, and as such they were not able to determine whether the size and number of conjoined phytoliths increases linearly with irrigation or whether there is an exponential relationship between conjoined phytoliths and water availability.

Webb and Longstaffe (2002) reported that the weight percent of phytoliths in Prairie grass (*Calamovilfa longifolia*) was higher in plants grown in arid conditions than those grown in regions with a high relative humidity (Webb and Longstaffe, 2002; Madella *et al*., 2009). A recent study by Madella *et al*. (2009) also explored the possibility of using phytoliths as indictors of past water availability. Their study involved five different cereals: bread wheat (*Triticum aestivum)*, emmer wheat (*T. dicoccum*), spelt wheat (*T. spelta*), two-row barley (*Hordeum vulgare*) and six-row barley (*H. distichon*). These were grown under two different climatic regimes: Middle East climatic conditions, which were simulated using a growing chamber, and a North European climatic condition, i.e. open fields in Cambridge, UK. The plants in the Middle Eastern climatic conditions were grown under two different irrigation regimes: wet and dry. The wet regime involved keeping the pots at water-holding capacity, with water being administered on a daily basis, and the dry regime was irrigated to 50% of the water-holding capacity.

Madella *et al*. (2009) classified phytoliths according to their method of silicification as either fixed forms or sensitive forms. Fixed forms were defined as cells whose silicification is under genetic control (presumably equivalent to the passive silicon uptake described above) and would therefore be less influenced by water availability; these comprise all short cells e.g. dumbbell/bilobate, rondel, trapezoid, crenate trapezoids, cross, keeled, conical etc. (Madella *et al*., 2009, p. 35). The sensitive forms are phytoliths formed in cells whose silicification is assumed to be under environmental control (or active silicon uptake) and which would, therefore, be indicative of past water and other climatic variables; these consist of all grass long cells. Phytoliths from the leaves of all plants were analysed, while phytoliths from the stems were analysed for emmer and spelt wheat. Madella *et al*. also used X-ray micro-chemical analysis on bread wheat to measure the elemental concentration of silicon and oxygen in the silica to help gain an understanding of water availability versus evapo-transpiration by detecting differences in the ratios of oxygen and silicon in the plant (Madella *et al*., 2009).

Madella *et al*. (2009) compared the ratios of fixed to sensitive forms from both the dry and wet regimes grown under Middle Eastern climatic conditions. In the leaves, they found an increase in the number of sensitive forms relative to fixed forms under the wet regime for bread wheat, emmer wheat and two-row barley, while an overlap was seen in the values between fixed and sensitive forms in spelt wheat and six-row barley. The analysis of phytoliths from plant stems showed that the mean for sensitive forms from the dry regime was higher than for the wet regime, although the error bars indicate that there was considerable overlap in the values between the two regimes. Results from the X-ray micro-analysis of phytoliths from bread wheat found that the level of oxygen was higher in the wet grown samples than in the dry regime samples (Madella *et al*., 2009).

While these results are valuable for the potential use of phytoliths as indicators of past water availability, they are not without their limitations.

The first concern is that the plants grown under the Middle Eastern climatic regime were cultivated in pots in a greenhouse rather than in open fields and thus natural growing conditions would not have been emulated. These plants would have received little competition for water and nutrients from other plants because of the restricted growing area and would presumably have been weed-free, all of which could affect silicon uptake. In addition, greenhouses increase humidity levels and, unless dehumidifiers were used (which is not stated in the paper), it is probable that the humidity would have been higher than natural for a Middle Eastern arid environment, affecting transpiration rates. A second issue is that the amount of water given to the plants, and how this relates to their known crop water requirements, is not stated and so it is unclear how these irrigation systems relate to plant water requirements. For example, what percentage of the crop water requirements is represented by the 50% of the pot holding capacity, and would results have differed if a regime supplying 25% of the pot holding capacity been included in the experiment? A third concern is that the soil silicon levels were not measured and so we do not know if they were higher in the soils used for the pot experiments than in the open fields.

21.2 AIMS OF THE EXPERIMENTAL CROP GROWING STUDY

To explore in more detail the hypothesis that phytoliths can be indicators of past water availability, crop growing experiments were established in Jordan as part of the Water, Life and Civilisation project in collaboration with the National Centre for Agricultural Research and Extension (NCARE), Jordan. The aims of the experiment were threefold: (1) to determine whether the differences in irrigated and non-irrigated phytoliths observed by Rosen and Weiner (1994) are apparent in other species of wheat; (2) to determine if these differences are also observable in other cereals (barley); and (3) to assess whether variables such as climate and soil and water chemistry affect silica deposition.

21.3 MATERIALS AND METHODS

21.3.1 Experimental conditions

Two crops were grown for phytolith analysis, both of which were native land races: durum wheat (*T. durum*) (ASCAD 65) and six-row hulled barley (*H. vulgare*) (ASCAD 176). These were grown at three different NCARE crop growing stations: (1) Khirbet as Samra, which is on the Jordanian Plateau to the northeast of Amman, (2) Ramtha, which is in the north of Jordan, 5 km from the Syrian border and (3) Deir ‘Alla, which is in the Jordan Valley (see Figure 21.1 and Table 21.1). The experiment involved three growing seasons. Each experimental plot measured 5 m by 5 m and was surrounded by a soil bund with a 1.5 m

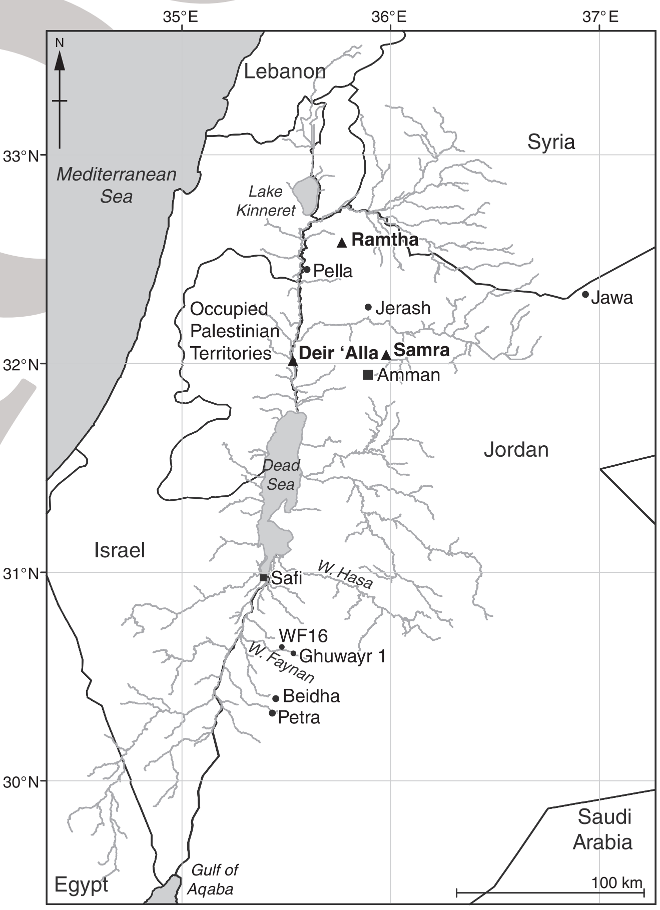

Figure 21.1. Map showing location of crop growing sites.

Table 21.1 *Description of crop growing sites*

	Khirbet as Samra	Ramtha	Deir 'Alla
Location (latitude and longitude)	N 32° 08.890′	N 32° 34′	N 32° 11.483′
	E 36°08.710′	E 36° 1′	E 035° 37.167′
Altitude (metres)	567 m above sea level	500–600 m above sea level	−192 m below sea level
Slope (at soil sampling localities)	<3°	<3°	<3°
Precipitation average (mm year^{-1})	150	300–350	250

After Carr (2009)

separation from the adjacent plot. In the first season, four different irrigation regimes were employed: (1) no irrigation (0% of crop water requirements); (2) under-irrigated (80% of crop water requirements); (3) irrigated (100% of crop water requirements); and (4) over-irrigated (120% of crop water requirements). In the second and third seasons an additional under-irrigated plot was added which was given 40% of crop water requirements. The calculations for irrigation levels were based on knowledge of crop water requirements estimated by using Class A – Pan evaporation readings (Allen *et al*., 1998). Daily rainfall and evaporation were taken into account and allowed for when irrigation was calculated, with less irrigation water being applied during periods of higher rainfall and low evaporation. The total amount of irrigation water applied to each of the experimental plots is shown in Table 21.2, and total rainfall and evaporation for all three sites by plant growth over the three growing seasons is shown in Figure 21.2 (for more information on crop growth stages see Allen *et al*., 1998). Water was provided by a drip irrigation system with a 60 cm spacing between water pipes and a 40 cm spacing between the drippers on each pipe. Each irrigation plot had eight lines, with reclaimed wastewater being used for irrigation. The water used for irrigation was treated wastewater at Khirbet as Samra and Ramtha and a mixture of treated wastewater and fresh water at Deir 'Alla. The water used was within the Jordanian standards for the irrigation of restricted crops. Samples of irrigation water from all three crop growing stations were collected and analysed at the Department of Soil Science, University of Reading. Table 21.3 provides a list of the analyses undertaken (see chapter 3 of Carr, 2009, for methodologies).

Crops were planted in November of each year and harvested in May. Figure 21.3 shows the harvesting of barley from the third growing season at Khirbet as Samra. All plots, including the non-irrigated ones, were given 25 mm of water after sowing to encourage germination. No pesticides or fertilisers were employed and the plots were not weeded. Bird attack was an ongoing problem at Deir 'Alla and Ramtha, with some

Table 21.2 *Amount of applied irrigation (mm per year) by crop, year and growing site*

Irrigation regime	Deir 'Alla	Ramtha	Khirbet as Samra
Year 1 (2005–6)	barley		
0%	25.0	25.0	25.0
80%	74.1	101.5	124.2
100%	92.6	126.8	155.2
120%	111.1	152.2	186.3
Year 1 (2005–6)	wheat		
0%	25.0	25.0	25.0
80%	91.2	150.7	176.0
100%	114.0	188.4	220.1
120%	136.8	226.1	264.1
Year 2 (2006–7)	wheat and barley		
0%	25.0	25.0	25.0
40%	28.4	41.0	41.3
80%	56.8	82.0	82.5
100%	71.0	102.5	103.2
120%	85.2	123.0	123.8
Year 3 (2007–8)	wheat and barley		
0%	25.0	25.0	25.0
40%	88.9	60.2	79.2
80%	177.8	120.4	158.4
100%	222.3	150.5	198.1
120%	266.7	180.6	237.7

plots having to be entirely covered with mesh for protection (Table 21.4), although this was not applied until the plants were reaching maturity.

A grid system was used to collect the plants. This involved running a tape measure diagonally across the plot and collecting the plants along the diagonal transect from six 50 cm intervals: 0–50 cm, 50–100 cm, 100–150 cm, 150–200 cm, 200–250 cm and 250–300 cm. This was done to avoid edge effect. Plants were placed inside paper bags after collection. In addition to the plants taken for phytolith analysis a 1 m × 1 m square was sampled for

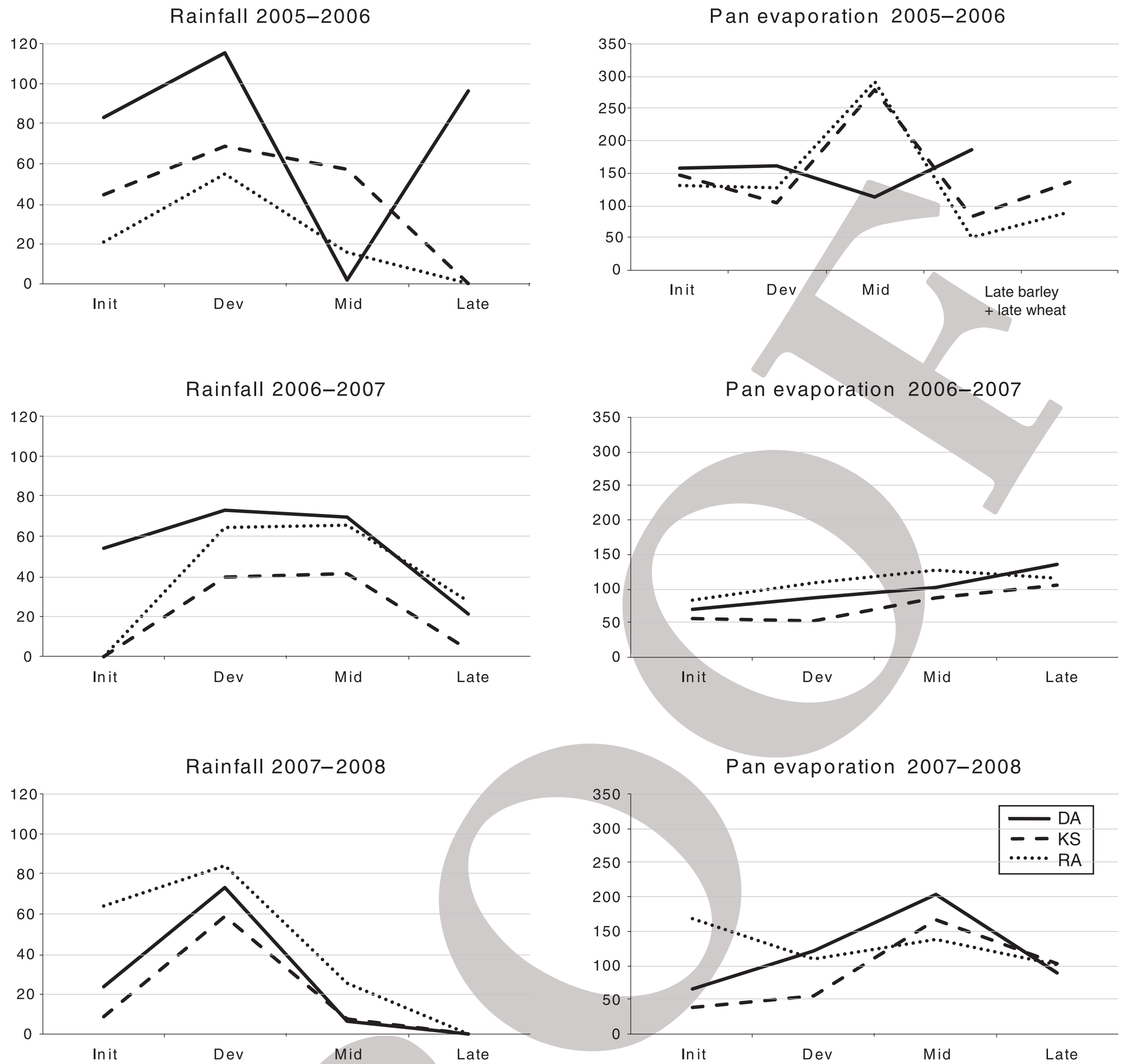

Figure 21.2. Irrigation and evaporation (both in mm) by crop development stage. Crop development stages (given on the *x* axis) follow the Food and Agricultural Organisation convention of Initial (Init.), Crop development (Dev.), Mid-Season (Mid.) and Late. Late barley and late wheat are shown separately, reflecting differences in their development. DA, Deir ‘Alla; KS, Khirbet as Samra; RA, Ramtha.

yield for each of the irrigation plots which was analysed by the scientists at the NCARE crop growing stations. The area sampled for yield was selected at random by throwing a 1 m $\times$ 1 m square into the 5 m $\times$ 5 m plot. The only occasions when this procedure was not observed were when parts of the plot had been eaten by birds. In these instances the square was placed into an uneaten area to avoid biasing results.

21.3.2 Soil analysis

Soil samples were taken from each plot at three different depths: 0–5 cm, 5–25 cm and >25 cm, and characterised and analysed at the Department of Soil Science, University of Reading (Carr, 2009). Table 21.5 provides a list of the analyses undertaken (see chapters 4 and 5 of Carr, 2009, for methodologies). Soil samples were also taken after the first and last years of experimentation to test for plant-available silicon. The extraction was done using 0.025M citric acid (details of this methodology are provided in Table 21.6). Analysis was conducted using a PE Optima ICP-OES in the Department of Soil Science, University of Reading.

21.3.3 Phytolith processing and counting

Before the processing of the modern plants began, an experiment was conducted to compare the impact that analytical methods have on conjoined phytoliths (Jenkins, 2009). This was undertaken using the husks from the 100% irrigated wheat from the first season of crop growing at Khirbet as Samra. Two different

Table 21.3 *Selected water quality parameters for reclaimed water from the crop growing stations based on samples collected in the field and available data*

Location	Potentially plant-beneficial ions in the irrigation water (mg L^{-1})					Potentially plant-toxic ions in the irrigation water (mg L^{-1})			Additional parameters			
	Sulphate (SO_4)	Calcium (Ca)	Potassium (K)	Magnesium (Mg)	Phosphate (PO_4)	Chloride (Cl)	Sodium (Na)	Boron (B)	EC (dS m^{-1})[a]	pH	Total organic carbon (TOC) (ppm)	Sodium adsorption ratio (SAR)
Khirbet as Samra measured data (May 2006 and May 2007)	65.09	44.55	31.32	27.22	14.41	374.81	261.14	0.94	1.82	8.14	12.11	7.67
Khirbet as Samra average (based on measured and published data) (1995–2007)	65.09	44.55	31.32	27.22	35.63	364.61	261.14	0.91	2.14	7.86		7.67
Ramtha measured data (May 2007)	104.66	44.16	27.25	31.12	6.80	398.76	195.53	0.73	1.50	8.49	10.73	5.69
Ramtha average (based on measured and published data) (2005–2007)	104.66	49.71	32.97	34.19	6.80	398.76	232.46	0.73	1.71	8.21		6.30
King Talal Reservoir measured at Deir ‘Alla (May 2007)	15.47	19.21	4.11	3.68	8.07	47.55	35.13	0.16	1.49	7.67	7.18	1.92
King Talal Reservoir average for Deir ‘Alla (based on measured and published data) (1995–2007)	90.78	50.09	15.74	31.39	21.74	276.66	125.67	0.54	1.91	7.85		

After Carr (2009); other data GTZ (2005); Al-Zu’bi (2007); Ammary (2007); Bashabsheh (2007).
[a] EC, electrical conductivity

Table 21.4 *Record of plots covered with mesh*

		Year 1	Year 2	Year 3
Deir 'Alla	barley	not covered	covered	not covered
	wheat	covered	covered	covered
Ramtha	barley	covered	covered	covered
	wheat	covered	covered	not covered
Khirbet as Samra	barley	not covered	not covered	not covered
	wheat	not covered	not covered	not covered

Figure 21.3. Harvesting barley at Khirbet as Samra after the third growing season.

processing methods were employed: dry ashing and acid extraction. The former method involves burning the plant samples in a muffle furnace to remove organic matter while the latter uses nitric acid to remove organic matter.

The results demonstrated that dry ashing produces a higher weight percent of phytoliths to original plant matter and a far greater number of conjoined cells than the acid extraction method. This is in agreement with earlier studies, such as those by Jones and Milne (1963) and Raeside (1970), both of which reported a greater number of conjoined cells with dry ashing than acid extraction. Two explanations are proposed for this. The first is that the oxidation of the organic matter during acid extraction forces the phytoliths apart and causes a mechanical breakdown of conjoined forms that does not occur with dry ashing or that acid extraction destroys the silica gel holding the phytoliths together (Hayward and Parry, 1980). The second is that dry ashing causes the silica to dehydrate, as proposed by Jones and Milne (1963), causing fusion between forms resulting in a stronger structure (Jenkins, 2009).

The finding that the analytical procedure employed can change the structure of the phytoliths has implications for analysis of archaeological assemblages. Frequently phytoliths are recovered from ashy deposits or hearths and are the product of plants that have been burnt in the past. It is presumed that such phytoliths would resemble modern plants that have been dry ashed. Samples are often taken, however, that do not appear to have been burnt. These samples could either resemble those that have been wet ashed based on the premise that dry ashing causes fusion, or resemble those that have been dry ashed based on the premise that acid extraction forces phytoliths apart. For the purpose of this experiment it was decided to process the modern plants using the dry ashing method. This is because phytoliths are frequently recovered from ashy deposits and these can be sampled in isolation for the application of the proposed methodology; given that it is still unclear why the morphology of the phytoliths changes with processing, it is most reliable to compare archaeological samples that are presumed to have been heated with modern samples that have also been heated. Until the exact cause of the differences resulting from processing can be pinpointed, there is limited value in proceeding with wet ashing and employing this methodology to unburnt deposits. The methodology employed for extracting phytoliths from modern plants is provided in Table 21.7. Only husks were analysed because they have been found to have a higher silica content than other parts of the plant. Hutton and Norrish (1974) have suggested that the percentage of silica in the husks is closely related to the amount of water transpired in wheat and hence more accurately reflects water availability during growth.

Slides were counted using a Leica DME at $\times 400$. Phytoliths were counted according to the number of dendritic long cells in each conjoined form and the following broad counting categories were used: single cell, 2 to 5, 6 to 10, 11 to 15, 16 to 20, 21 to 30, 31 to 50, 51 to 70, 71 to 100, 101 to 150, 151 to 200, 201 to 250, 251 to 300, 301 or over. Frequently, forms were found that were not properly silicified. In these forms the cork-silica cells and papillae were silicified but the dendritic long cells were either poorly silicified or unsilicified. Examples of well silicified and poorly silicified forms are shown in Figure 21.4. In these cases the same counting categories were used as above, but they were classified as unclear/poorly silicified forms and the number of dendritics was estimated by counting their outlines between the silicified cork-silica cells and papillae. In addition, single cork-silica cells were counted.

Ten slides were counted from the samples from the first growing season and five from the second and third seasons. Occasionally it was not possible to count the total target number of slides, for example when the crop had failed to grow successfully or if it had been eaten by birds. Many of the barley samples contained a large number of fused phytolith forms, even when the ashing temperature was reduced to 400 °C, making it impossible to count these slides. It is assumed that the phytolith forms

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Table 21.5 *Soil physical and chemical properties at the crop growing stations*

	Khirbet As Samra – non-irrigated soil			Ramtha – non-irrigated soil			Deir ‘Alla – irrigated soil (100% of the crop water demand for 1 year)		
	Surface (0–5 cm)	Middle (5–25 cm)	Bottom (>25 cm)	Surface (0–5 cm)	Middle (5–25 cm)	Bottom (>25 cm)	Surface (0–5 cm)	Middle (5–25 cm)	Bottom (>25 cm)
Soil classification (World Reference base)	Calcisol			Calcisol			Cambisol		
Soil texture	Silty clay loam			Silty clay loam			Silty clay loam		
Soil colour	Hue 7.5YR 6/6 – reddish yellow			Hue 2.5YR 4/8 – red			Hue 2.5YR 6/4 – light yellowish brown		
Parent material	Limestone			Limestone			Quaternary sediments		
Sand (%)	16.1	16.1	18.5	19.9	19.9	13.8	17.1	17.1	20.9
Silt (%)	60.2	60.2	64.9	66.4	66.4	74.0	64.6	64.6	64.4
Clay (%)	23.8	23.8	16.6	13.7	13.7	12.2	18.3	18.3	14.7
CEC to clay ratio (CCR)	0.86			4.34			1.28		
Clay mineralogy	Smectite, kaolinite, illite (Khresat and Taimeh, 1998)			Smectite, kaolinite, illite (Khresat, 2001)			Smectite, kaolinite (Neamen *et al*., 1999)		
pHe	8.30	8.16	7.96	8.27	8.21	8.20	8.41	8.63	8.63
ECe (dS m^{-1})	0.77	1.49	6.48	0.77	0.59	0.73	1.89	1.28	1.21
Organic carbon (%)	1.18	0.53	0.14	0.77	0.65	n/a	0.68	0.57	0.49
Organic matter (%) (assuming OM contains 0.58 g C per g organic matter)	2.03	0.91	0.24	1.33	1.12	n/a	1.17	0.97	0.84
CEC ($cmol_c$ kg^{-1})	20.50			59.50			23.50		
Ex Ca ($cmol_c$ kg^{-1})	9.76			32.82			9.89		
Ex Mg ($cmol_c$ kg^{-1})	2.99			6.94			6.49		
Ex Na ($cmol_c$ kg^{-1})	0.67			0.66			1.66		
Ex K ($cmol_c$ kg^{-1})	1.23			1.79			2.76		
ESP (%)	3.26			1.10			7.08		

After Carr (2009)

CEC = Cation exchange ratio; ECe = electrical conductivity of a saturation paste extract; pHe = pH of extract; Ex Ca = Exchangeable calcium; Ex Na = Exchangeable sodium; Ex Mg = Exchangeable magnesium; Ex K = Exchangeable potassium.

in these samples were only weakly silicified and were not robust enough to withstand the ashing process. Over 250 forms were counted per slide and in total, 90,855 barley phytolith forms were counted from 245 slides and 104,360 wheat forms from 264 slides.

21.4 RESULTS

21.4.1 Soil and water

All three growing sites had silty clay loam soils and a pH in excess of 8.1 with Deir ‘Alla resulting in the highest reading with 8.63, indicating that the soil was alkaline (Table 21.5; see Carr, 2009, for the analyses). The organic carbon and organic matter levels are low at all sites. Salinity levels and exchangeable sodium percentage are highest at Deir ‘Alla, probably because the soil had been irrigated with a mixture of treated wastewater and fresh water for a year.

Results for extractable silicon are presented in Figure 21.5. The greatest difference in levels of extractable silicon was between sites, with Ramtha having the greatest amount of extractable silicon and Khirbet as Samra the lowest. The levels of silicon increased throughout experimentation at Ramtha and Khirbet as Samra but remained the same at Deir ‘Alla. Results from the water analysis demonstrate that the water from Khirbet as Samra and Ramtha has a higher concentration of both plant-beneficial ions and potentially plant-toxic ions than the water used for irrigation at Deir ‘Alla. However, solutes of toxic metals such as arsenic, lead, zinc, nickel, cadmium and copper were below detection limits in the water at all sites (Carr, 2009).

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Table 21.6 *Methodology used for analysis of extractable silicon*

Stage	Procedures followed for available plant Si analysis
1	Air dry soils
2	Grind and pass through 2 mm mesh
3	Weigh 3 g into a 50 ml polypropylene centrifuge tube
4	Add 30 ml, 0.025M citric acid by pipette
5	Shake samples end over end at 14 rpm for 6 hours at 30 °C
6	Centrifuge samples at 3,000 rpm for 15 minutes (a Mistral 3000i machine was used)
7	Filter samples through filter paper (Whatman no 1 papers were used)
8	Store extracts at 4 °C until measurement
9	Dilute extracts 1:20 with water before measurement
10	Measurements of Si concentrations were obtained using a PE Optima ICP-OES
	All storage, measuring and dispensing of solutions was carried out with plastic ware

Table 21.7 *Dry ashing methodology employed for extracting phytoliths from modern plants*

	Procedure followed for dry ashing
1	Weigh empty crucibles
2	Put dried plant samples in crucibles and weigh them
3	Ash samples in muffle furnace for 3 hr at 500 °C
4	Transfer ashed samples into centrifuge tube
5	Add HCl 10% (up to 6 ml) and shake tube
6	Wait ~5 min
7	Level samples with distilled water (up to 10 ml), tighten lid and shake tubes
8	Centrifuge 5 min at 2,000 rpm
9	Discard supernatant
10	Repeat three times
11	Transfer into weighed beakers
12	Put in drying cupboard at less than 50 °C until dry
13	Remove samples, allow to cool and weigh beakers and sample
14	Zero a balance with a labelled slide
15	Weigh 1 mg ± 0.1 mg of sample on the slide
16	Add mounting agent (we used *Entellan*) and mix thoroughly before covering with cover slip

21.4.2 Crop yield

Crop yield could not be recorded for wheat from Ramtha for the third growing season because the crop had been decimated by birds. Also, it should be noted that although more water was given to wheat than barley in the first growing season, to meet the higher water requirements of wheat, the levels of irrigation for both crops was the same for the second and third growing seasons (see Table 21.2). However, a corresponding decrease in

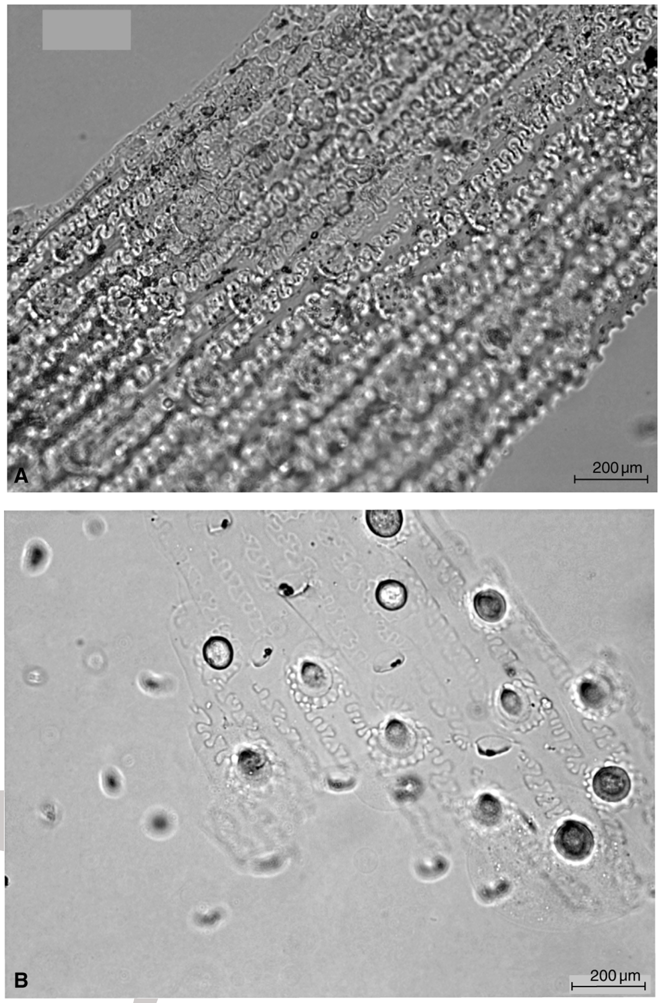

Figure 21.4. (A) Well silicified conjoined phytolith. (B) Poorly silicified conjoined phytolith.

yield from the first to the second season is not found as a result of this, as shown in Figure 21.6. The most substantial difference in the wheat yields was between the non-irrigated and 40% irrigated plots, which had low yields, and the other irrigation regimes which had higher yields. The lowest yields were from the non-irrigated plots at Khirbet as Samra which failed to produce any grains. This is probably attributable to the low rainfall at this site which, in total, was less than 100 mm in all three years.

A more significant increase in yield was observable between the non-irrigated barley and the 40% irrigated barley than was seen in wheat, as illustrated in Figure 21.7. A similar result to wheat was found with the non-irrigated barley from Khirbet as Samra, which produced neither grains nor inflorescences, preventing any phytolith analysis. It is interesting that non-irrigated wheat produced inflorescences when non-irrigated barley did not, because barley has a lower water requirement than wheat. The non-irrigated plot from the third growing season at Deir ‘Alla also had a low grain yield with only 0.2 tonnes per hectare.

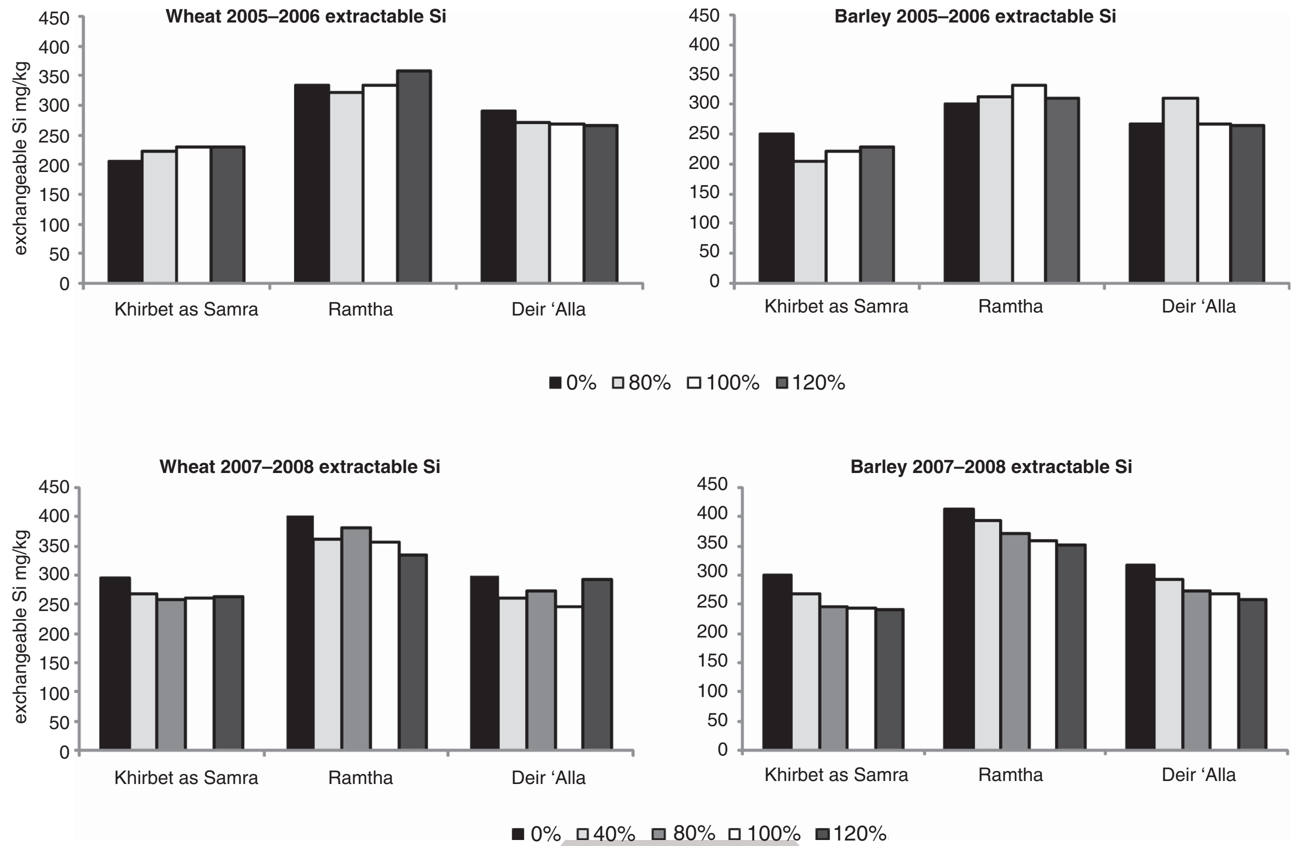

Figure 21.5. Extractable silicon from soil samples taken before and after experimentation.

The total rainfall at Deir ʻAlla was less in the third growing season than in the previous two seasons and it is notable that a similarly low yield was not observed for wheat as for barley. The barley yields from Ramtha in the irrigated plots were less than for the other two sites but this may be a product of bird attack which, as stated above, severely damaged the wheat. Field notes record that the non-irrigated barley was least affected by bird attack, probably because it ripened after the irrigated plots; this would also explain why the yield from Ramtha was higher in comparison to the other two sites for the non-irrigated plot than for the irrigated ones.

21.4.3 Phytolith analysis

Weight percent was calculated by expressing the weight of phytoliths to original plant matter processed (phytolith weight % = weight of phytoliths/weight of plant matter processed × 100). This is useful for determining the level of silicon uptake and resulting phytoliths in the plant. A comparison of the results from plants grown in irrigated and non-irrigated conditions can establish if the uptake is increased with irrigation. Figure 21.8 shows the mean weight percent of phytoliths for the wheat samples and illustrates that the non-irrigated plot has the lowest weight percent and that the highest values are from the samples from the 80% irrigated plot. Deir ʻAlla has a greater mean weight percent of phytoliths than the other two sites for the first and third growing season but not for the second growing season. The exception is the 40% plot. Generally Deir ʻAlla has greater weight percents than the other two sites.

The most striking observation that can be made for the results of the mean weight percent of phytoliths from barley is that the values are much lower than for wheat (see Figure 21.9), Deir ʻAlla has the greatest weight percent for the non-irrigated barley samples in all three years, followed by Ramtha and lastly Khirbet as Samra. Values also rise in all of the non-irrigated plots with each growing season. When this is plotted against rainfall it is apparent that the increase in weight percent for non-irrigated barley correlates with increased rainfall, with the exception of the third year at Deir ʻAlla (see Figure 21.10). The results of the samples from the irrigated plots show that the mean of those from Ramtha is the highest, and that there is an increase in weight percent of phytoliths in each growing season. This correlates with the results of the extractable silicon analysis which demonstrated that at Ramtha and Khirbet as Samra the level of silicon in the soil increased from the beginning to the end of the experiment. Figure 21.11 shows the mean value of extractable silicon from all three sites plotted against phytolith weight percent which demonstrates that barley has a positive correlation, while wheat has a negative one. This increase in silicon levels is

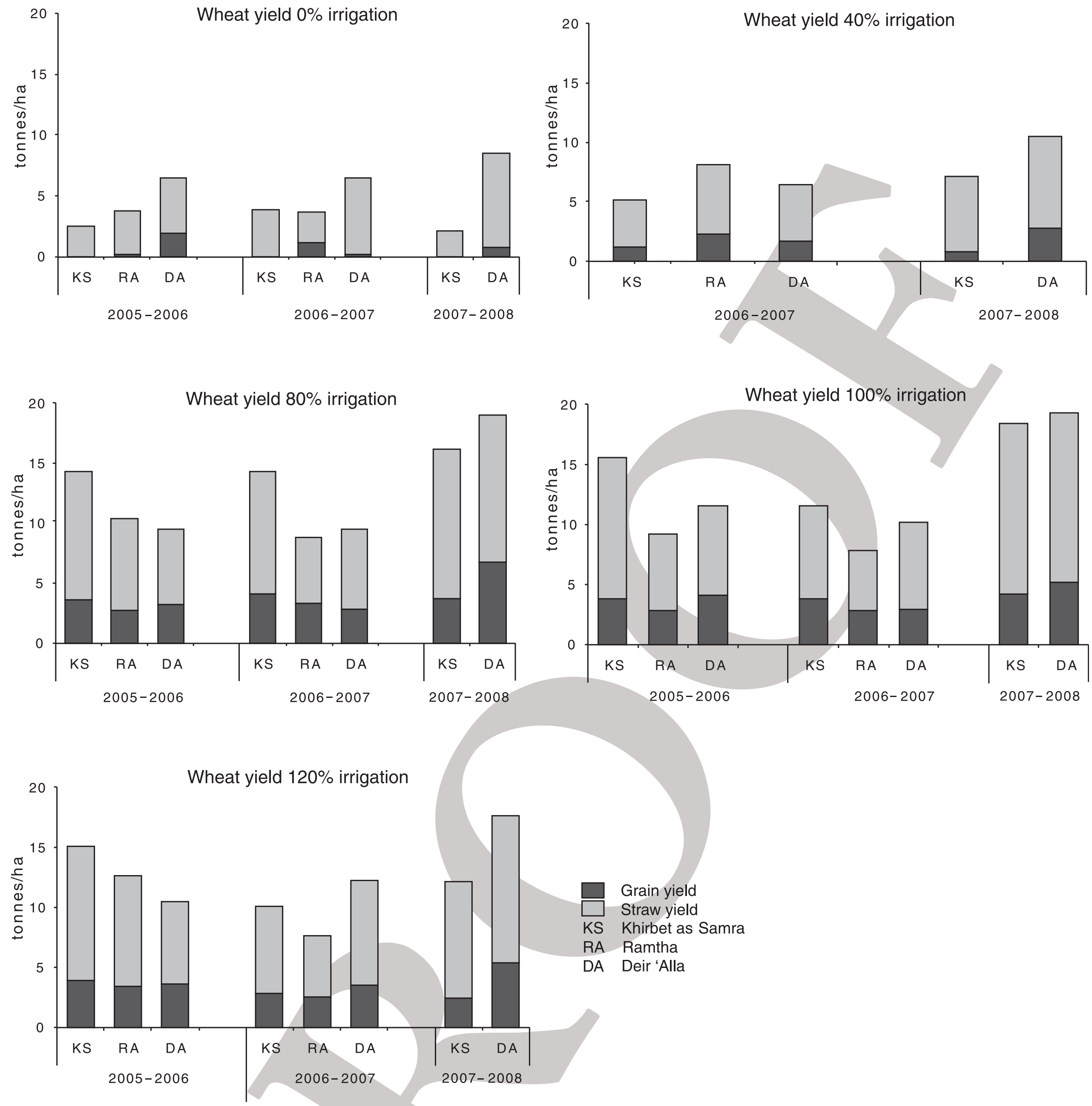

Figure 21.6. Crop yield for wheat.

unexpected because the plants are taking up silicon from the soil which is not being returned in phytolith form because the crops are harvested and removed from the sites. Silicon is not entering the soil through the irrigation water because the results show that the greatest rise in silicon levels was in the non-irrigated plots. Further tests are needed to check if other changes occurred in the soil through time. For example, it is possible that the pH or cation exchange capacity of the soil changed through time in a manner that resulted in more available silicon. For example, the soil may have become more alkaline which would have caused greater dissolution of silicates in the soil. It is also possible that the clay mineral fraction was being washed down through the soil profile by the irrigation water, removing the clay silicates from the rooting zone of the plants. This would explain why the non-irrigated samples have more available silicon than the irrigated ones.

A comparison was made between long dendritic cells, those termed by Madella *et al*. (2009) as *sensitive forms*, and cork-silica cells or *fixed forms* (Madella *et al*., 2009). Silica cells and cork cells form in pairs and for the purposes of this study are grouped together as one category (Kaufman *et al*., 1970). These cells are known by a variety of names; for example Blackman and Parry (1968) refer to them as silico-suberous couples. Images

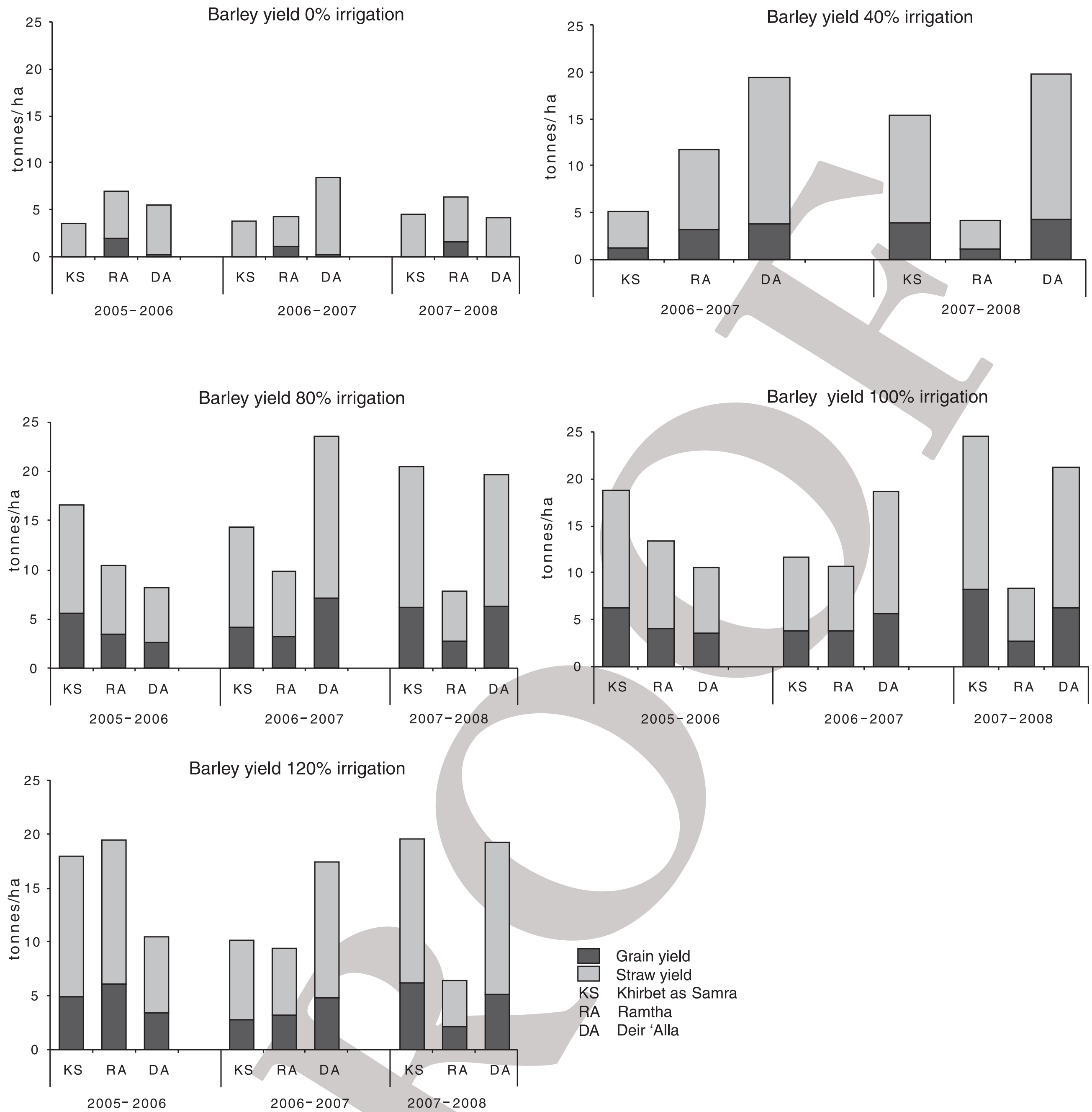

Figure 21.7. Crop yield for barley.

of both these phytolith types are shown in Figure 21.12. Results of the comparison of long dendritic cells to cork-silica cells from the wheat samples are shown in Figure 21.13. Only samples with a combined total of over 200 cork-silica cells and dendritics were used in this analysis. The results demonstrate that, with the exception of the first growing season at Ramtha, the mean percent of dendritics in the irrigated samples is always higher than the percent for the non-irrigated ones. Despite this trend, it is also apparent that there is often a significant overlap between the values for the irrigated and non-irrigated samples, with the exception of Khirbet as Samra where the percent of dendritics in the non-irrigated samples is always lower than in the irrigated ones. This correlates with rainfall which is significantly lower at Khirbet as Samra than the other two sites. This negates the claim of Rosen and Weiner (1994) that changes in phytolith assemblages reflect irrigation and not rainfall. It is also clear from Figure 21.13 that there is a decrease in the mean percent of dendritics from both the irrigated and non-irrigated samples through time: the first growing season has an average of 48%, the second season 28%, and the third season only 15%. This

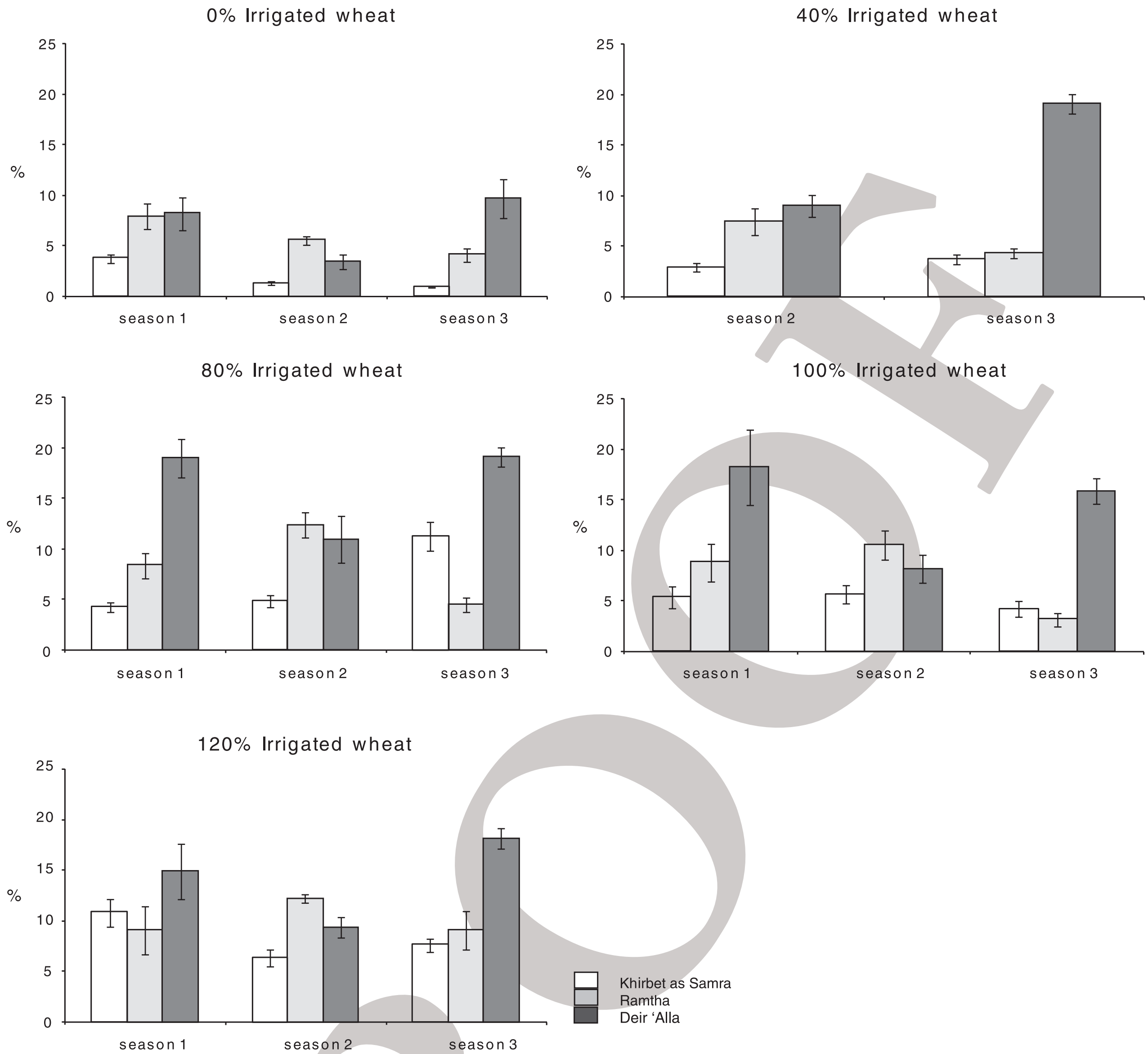

Figure 21.8. Weight percent of phytoliths to original plant matter processed for wheat.

correlates with weight percent of phytoliths which also decreases, but not with the results of the extractable silicon analysis which increases throughout experimentation.

The results from the barley analysis are provided in Figure 21.14. These show that the mean percent of dendritics in the irrigated samples is always greater than the percent for the non-irrigated ones. There is also a decrease through time in the percent of dendritics to cork-silica cells for barley, but the main decrease happens between the second and third growing seasons. In the samples from the first growing season, dendritics make up 50% of the total single cells. This decreases to 49% in the second season and to 25% in the third growing season. This result, however, could partly be influenced by sample size which was reduced in the third growing season because many of the samples fused during ashing. As with the wheat, the non-irrigated samples from Khirbet as Samra have low percentages of dendritics, although this is based on results from only one slide in the third growing season because the phytoliths from the other four samples were all fused and could not be counted. However, the levels of dendritics in the irrigated barley are also lower at Khirbet as Samra than in the samples from the other two sites.

A comparison of the number of well silicified to poorly silicified conjoined wheat phytoliths can be found in Figure 21.15 and the absolute counts with standard deviations are shown in Table 21.8. A difference can be seen between the sites in the first growing season; the non-irrigated samples from Khirbet as Samra produced far fewer well-silicified conjoined phytoliths than the non-irrigated samples from the other two crop growing

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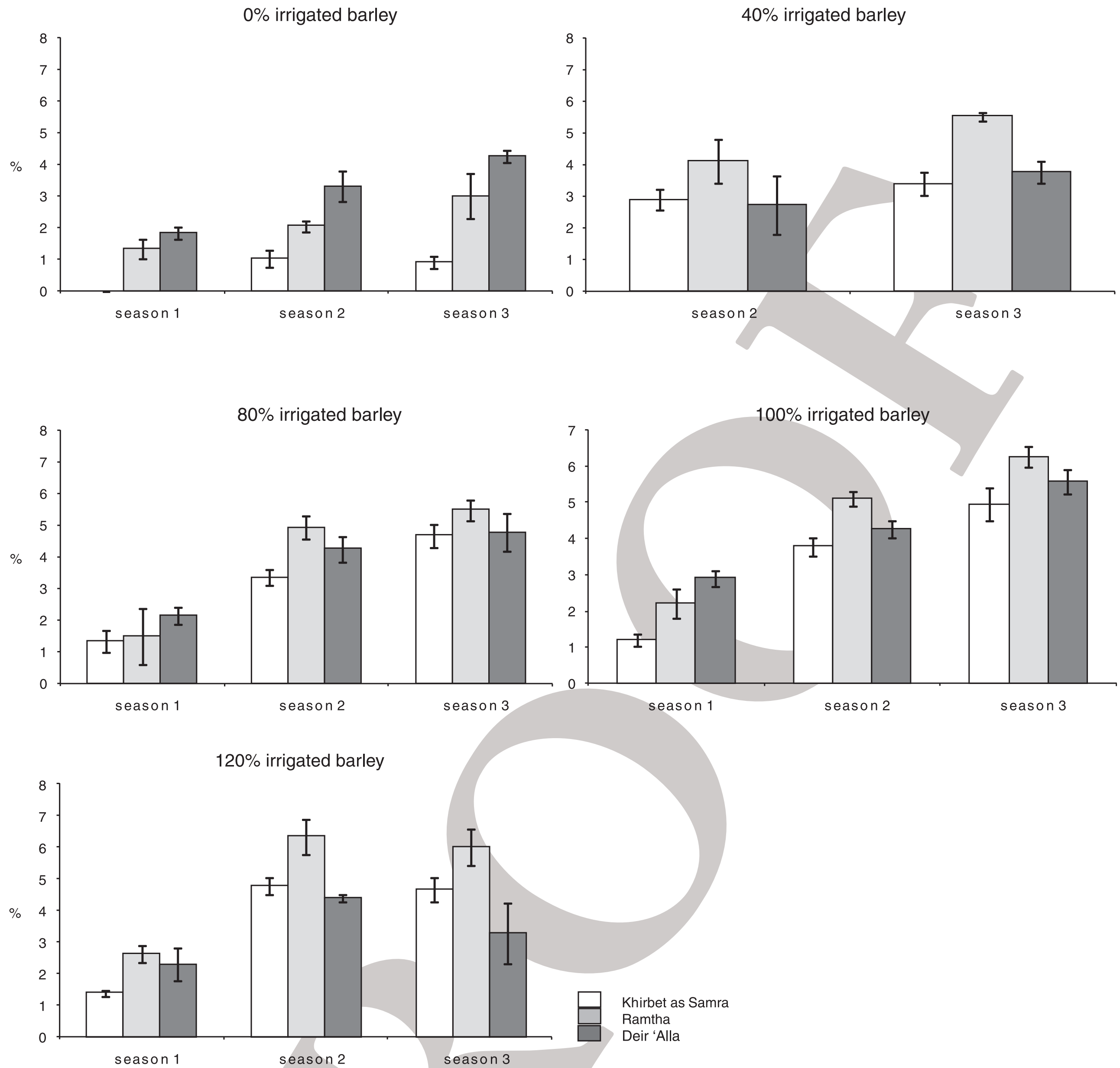

Figure 21.9. Weight percent of phytoliths to original plant matter processed for barley.

stations, while Deir ‘Alla had a greater percent of well silicified forms in the non-irrigated samples (63%) than in the mean of the irrigated samples (60%). However, in all other seasons at the three sites the irrigated samples had a greater mean of well silicified conjoined forms than the non-irrigated ones. There is an increase in the number of conjoined forms in the Khirbet as Samra non-irrigated samples in the second year which reaches 32% but falls in the third year to 16%. A decrease in well silicified forms is apparent in the third year in the irrigated samples from both Khirbet as Samra and Ramtha. Figure 21.16 shows the comparison of well silicified and poorly silicified forms for the barley samples with Table 21.9 showing the absolute counts and standard deviations. From these it is clear that there is a gradual decline in the number of well silicified forms over time. It is also apparent that, unlike wheat, the non-irrigated samples from Deir ‘Alla have far fewer well silicified forms than the irrigated ones and that there is a decrease in the number of well silicified forms from the second to the third growing season in the non-irrigated samples from Khirbet as Samra.

Figure 21.17 shows the percent of conjoined dendritics for the wheat samples by four different categories: 2–15 cells, 15–50 cells, 51–100 cells and 100 cells and over. It is clear that in all of the plots the 2–15 cell category has the highest percent of phytoliths. However, it is also apparent that this varies between both sites and years. The most consistent site over the three years was Khirbet as Samra. Here the phytoliths from the

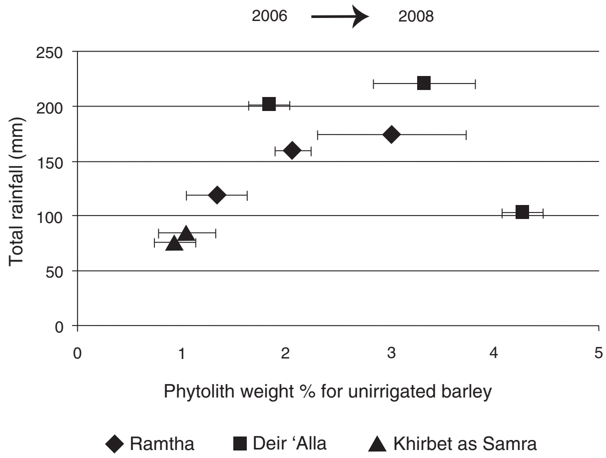

Figure 21.10. Correlation between non-irrigated barley and rainfall.

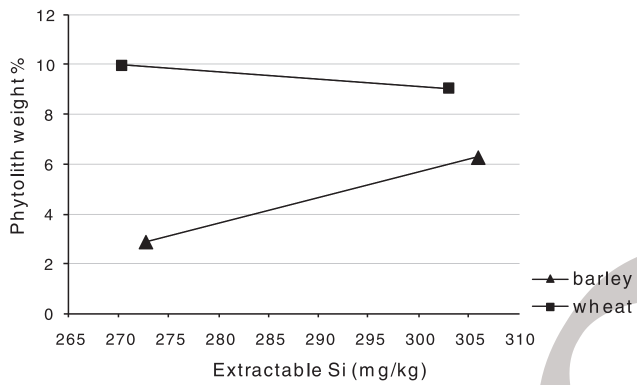

Figure 21.11. Correlation between mean weight percent of phytoliths and levels of extractable silicon.

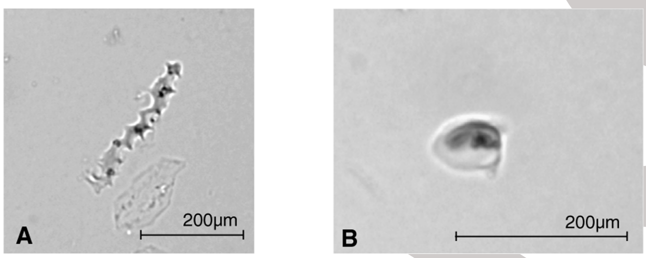

Figure 21.12. (A) Single dendritic long cell. (B) Single cork-silica cell.

non-irrigated plots are largely dominated by forms that consist of between 2 and 15 cells, with the first season having 80%, the second season 79% and the third season 78%. Khirbet as Samra also has the lowest percent of forms from the non-irrigated plots in the over 100 cells category. The greatest variation between years is found in the samples from Ramtha which has a more even distribution of numbers of phytoliths over all four counting categories than in the previous two years. Both Ramtha and Deir ‘Alla have an increase in the percent of forms in the 2–15 cell category in the second growing season which then decreases in the third season, and in the third growing season both Ramtha

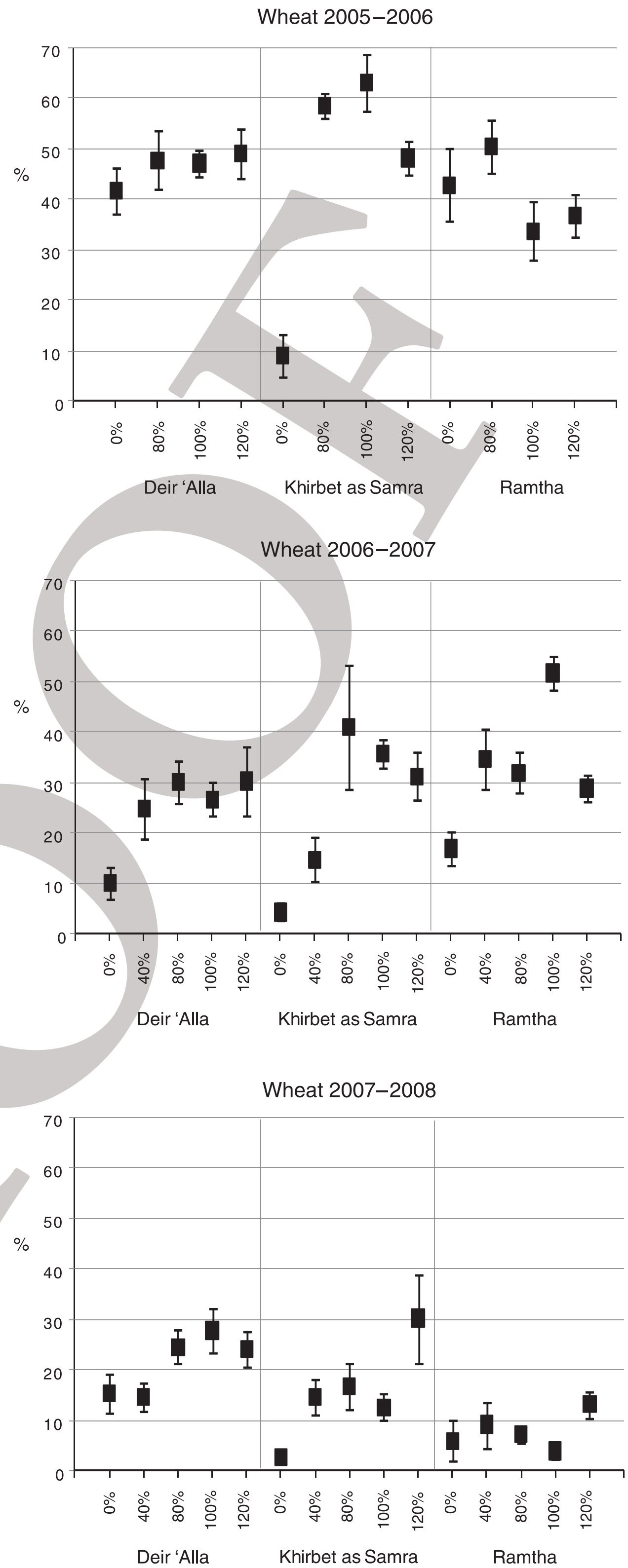

Figure 21.13. Comparison of the percent of cork-silica cells and dendritic long cells for the wheat samples.

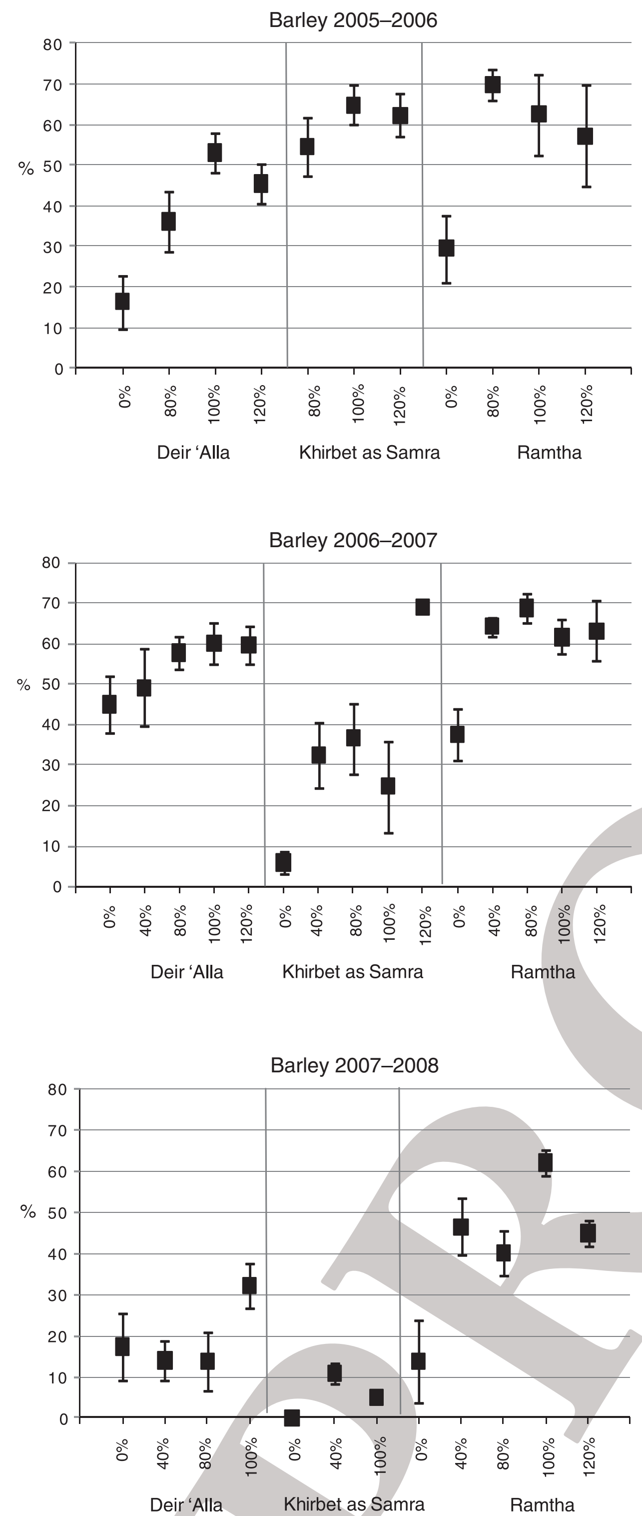

Figure 21.14. Comparison of cork/silica cells and dendritic long cells for the barley samples.

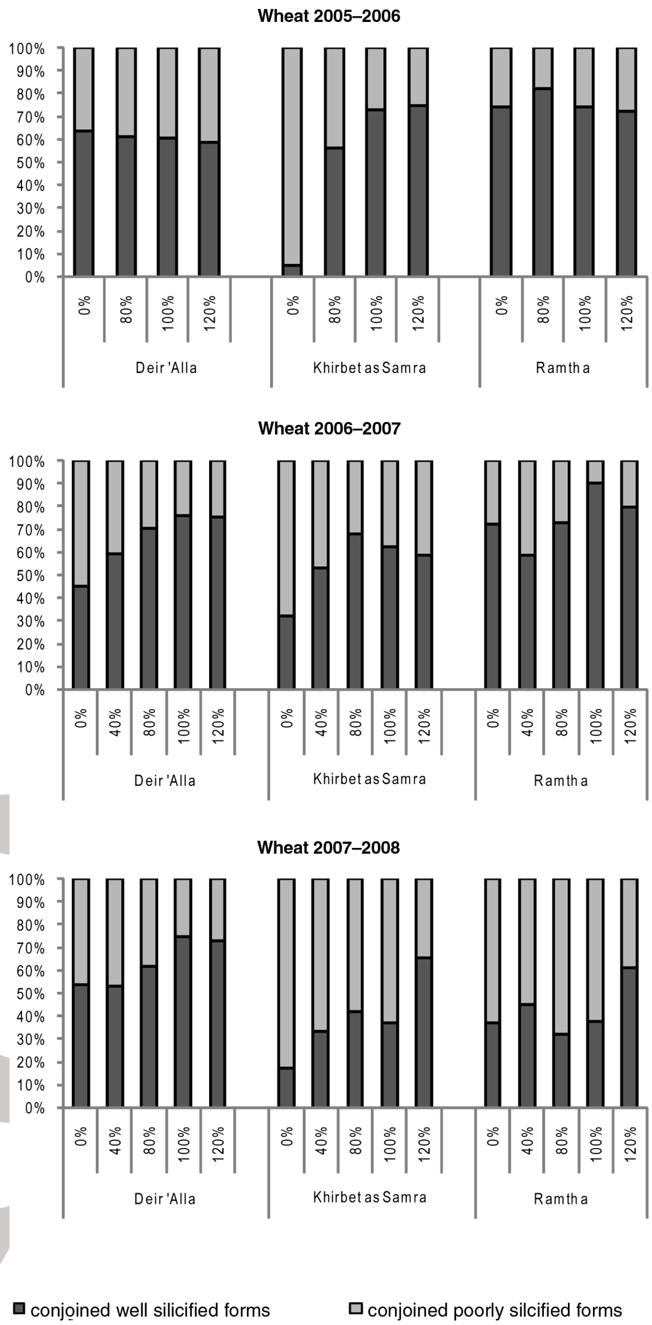

Figure 21.15. Comparison of well silicified to poorly silicified conjoined forms from the wheat samples.

and Deir ‘Alla have a greater percent of non-irrigated samples in the over 15 conjoined cell categories than irrigated ones. However, overall the number of conjoined cells increases with irrigation; the average number of forms with over 15 conjoined cells from the irrigated samples is 47% but is only 41% for the non-irrigated samples.

Figure 21.18 shows the same comparison for barley. As with wheat, there is an increase in the number of forms falling in the 2–15 cell category at Ramtha and Deir ‘Alla in 2006 to 2007 which decreases again in the third season. Unfortunately, there was no sample for barley from the first year of crop growing at Khirbet as Samra, and in the third season only one replicate was analysed because, as stated above, the phytoliths in the other four

Table 21.8 *Absolute numbers of well silicified and poorly silicified conjoined phytoliths counted with standard deviations from the wheat samples (all standard deviations were calculated using the STDEV function in Excel 2007). DA, KS, RA = Deir 'Alla, Khirbet as Samra and Ramtha, respectively*

Site/ regime	Phytolith type	*n* phytos counted	Mean	*n* slides	Standard deviation	Phytolith type	*n* phytos counted	Mean	*n* slides	Standard deviation
Wheat 2005–2006										
DA 0%	poorly silicified	562	56	10	35.24	well silicified	1,498	150	10	47.66
DA 80%	poorly silicified	880	88	10	25.24	well silicified	1,373	137	10	27.46
DA 100%	poorly silicified	942	94	10	36.34	well silicified	1,436	144	10	33.13
DA 120%	poorly silicified	953	95	10	43.29	well silicified	1,356	136	10	32.57
KS 0%	poorly silicified	1,189	119	10	72.13	well silicified	59	6	10	6.56
KS 80%	poorly silicified	746	75	10	33.15	well silicified	957	96	10	24.91
KS 100%	poorly silicified	562	56	10	35.24	well silicified	1,498	150	10	47.66
KS 120%	poorly silicified	571	57	10	25.37	well silicified	1,668	167	10	42.15
RA 0%	poorly silicified	558	56	10	21.21	well silicified	1,574	157	10	20.08
RA 80%	poorly silicified	378	38	10	14.19	well silicified	1,760	176	10	16.44
RA 100%	poorly silicified	541	54	10	18.51	well silicified	1,532	153	10	45.66
RA 120%	poorly silicified	634	63	10	27.28	well silicified	1,666	167	10	23.02
Wheat 2006–2007										
DA 0%	poorly silicified	173	35	5	22.53	well silicified	142	28	5	17.52
DA 40%	poorly silicified	237	47	5	17.56	well silicified	349	70	5	18.32
DA 80%	poorly silicified	197	39	5	6.50	well silicified	470	94	5	18.25
DA 100%	poorly silicified	146	29	5	7.22	well silicified	463	93	5	23.36
DA 120%	poorly silicified	171	34	5	14.96	well silicified	528	106	5	15.90
KS 0%	poorly silicified	106	21	5	9.44	well silicified	50	10	5	7.00
KS 40%	poorly silicified	347	69	5	27.48	well silicified	394	79	5	16.32
KS 80%	poorly silicified	186	37	5	9.26	well silicified	392	78	5	21.22
KS 100%	poorly silicified	216	43	5	11.03	well silicified	361	72	5	20.39
KS 120%	poorly silicified	272	54	5	14.52	well silicified	390	78	5	13.34
RA 0%	poorly silicified	186	37	5	5.89	well silicified	481	96	5	19.61
RA 40%	poorly silicified	217	43	5	13.87	well silicified	304	61	5	14.69
RA 80%	poorly silicified	222	44	5	19.73	well silicified	593	119	5	25.51
RA 100%	poorly silicified	78	16	5	12.10	well silicified	701	140	5	39.32
RA 120%	poorly silicified	166	33	5	3.56	well silicified	637	127	5	25.75
Wheat 2007–2008										
DA 0%	poorly silicified	252	50	5	13.90	well silicified	293	59	5	18.68
DA 40%	poorly silicified	299	60	5	20.73	well silicified	336	67	5	12.83
DA 80%	poorly silicified	274	55	5	12.56	well silicified	441	88	5	24.99
DA 100%	poorly silicified	194	39	5	8.47	well silicified	566	113	5	18.31
DA 120%	poorly silicified	218	44	5	16.88	well silicified	591	118	5	16.84
KS 0%	poorly silicified	44	N/A	1	N/A	well silicified	9	N/A	1	N/A
KS 40%	poorly silicified	366	73	5	18.29	well silicified	185	37	5	23.31
KS 80%	poorly silicified	292	58	5	21.79	well silicified	212	42	5	37.11
KS 100%	poorly silicified	304	61	5	26.11	well silicified	178	36	5	18.61
KS 120%	poorly silicified	319	64	5	15.51	well silicified	495	99	5	23.99
RA 0%	poorly silicified	219	44	5	10.99	well silicified	129	26	5	8.93
RA 40%	poorly silicified	312	62	5	18.60	well silicified	256	51	5	31.75
RA 80%	poorly silicified	392	78	5	18.98	well silicified	187	37	5	10.57
RA 100%	poorly silicified	185	37	5	23.66	well silicified	113	23	5	18.39
RA 120%	poorly silicified	140	47	3	10.79	well silicified	218	73	3	22.68

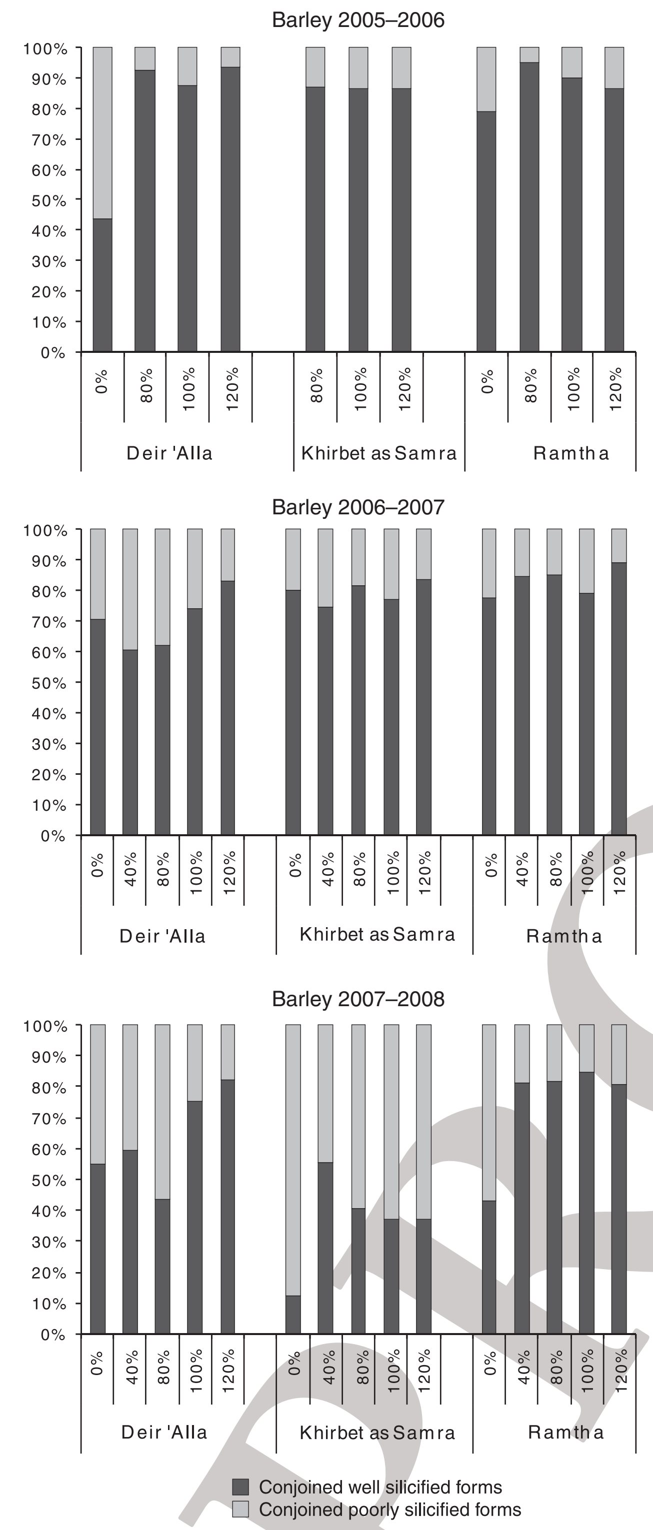

Figure 21.16. Comparison of well silicified to poorly silicified conjoined forms from the barley samples.

samples all fused during processing. Khirbet as Samra has the highest percent of forms with over 100 cells while Deir ‘Alla has the most variation in results over time. Overall, the number of conjoined cells does increase with irrigation, with the number of phytolith forms with over 15 conjoined cells increasing from 33% for non-irrigated samples to 39% for the mean of the irrigated ones.

21.5 DISCUSSION

21.5.1 Water availability and phytolith formation

Results from the crop yield analysis demonstrate that the yield capability of the crops grown in this experiment were, as would be expected, positively affected by irrigation but were not affected by the increasing levels of salinity that were found to have built up in the soil over the three years of experimentation (Carr, 2009).

The results from the analysis of the available silicon and weight percent of phytoliths produced interesting results. For barley it is clear that, with the exception of the non-irrigated plots, the results correlate with those from the extractable silicon analysis, with Ramtha having both the greatest silicon levels and highest phytolith yields. Wheat, however, does not respond in the same way. In the second growing season the wheat from Ramtha produced the highest weight percent of phytoliths in all plots except the 40% plot, but in the first and third seasons, Deir ‘Alla has the highest weight percent. It is also notable that, with the exception of the third growing season at Deir ‘Alla, the phytolith weight percent and soil silicon levels increase linearly with barley, but the weight percent of phytoliths from wheat decrease as silicon levels increase. These results, coupled with the significantly lower weight percent for barley, suggest that the processes that govern silica uptake and deposition differ between the two crops. It appears that while wheat is more efficient in its uptake of silicon than barley, there are factors other than available silicon in the growing medium that affect phytolith production and deposition in wheat.

Deir ‘Alla is located in the Jordan Valley, is below sea level and, as such, records higher temperatures than either of the other two crop growing stations. However, records of evaporation show that Ramtha has the highest rates of evaporation, because Deir ‘Alla is more humid owing to its proximity to the Dead Sea. This greater phytolith weight percent from Ramtha for wheat is not due to the use of mesh to cover the crops during maturation because the wheat crops at both Deir ‘Alla and Ramtha were covered in the first two growing seasons. Furthermore, the use of mesh would increase humidity resulting in slower transpiration rates and presumably decreased silicon uptake. Similarly there is no correlation with this result and rainfall because while Deir ‘Alla had the highest rainfall in the first and second seasons Ramtha recorded the greatest amount in the third growing season. Another factor which could affect silicon uptake is high concentrations of nitrogen in the soil. Unfortunately nitrogen was

Table 21.9 *Absolute numbers of well silicified and poorly silicified conjoined phytoliths counted with standard deviations from the barley samples*

Site/regime	Phytolith type: poorly silicified				Phytolith type: well silicified			
	n phytos counted	Mean	*n* slides	Standard deviation	*n* phytos counted	Mean	*n* slides	Standard deviation
Barley 2005–2006								
DA 0%	1,372	137	10	56.70	1,069	107	10	22.46
DA 80%	239	24	10	10.57	1,638	164	10	36.76
DA 100%	158	16	10	13.37	1,105	111	10	9.86
DA 120%	89	9	10	10.56	1,323	132	10	34.35
KS 80%	168	17	10	11.48	1,123	112	10	47.57
KS 100%	105	11	10	9.66	661	66	10	31.09
KS 120%	133	13	10	8.33	840	84	10	29.54
RA 0%	393	44	9	30.55	1,488	165	9	38.32
RA 80%	48	5	10	2.82	913	91	10	26.17
RA 100%	135	14	10	18.40	1,232	123	10	43.30
RA 120%	162	18	9	32.49	1,021	113	9	40.69
Barley 2006–2007								
DA 0%	64	13	5	6.69	153	31	5	8.91
DA 40%	50	17	3	10.02	84	28	3	13.86
DA 80%	74	15	5	9.15	121	24	5	5.93
DA 100%	31	6	5	4.82	89	18	5	8.70
DA 120%	41	8	5	5.50	199	40	5	5.85
KS 0%	31	6	5	3.11	124	25	5	13.22
KS 40%	66	13	5	6.69	195	39	5	8.94
KS 80%	77	15	5	13.90	344	69	5	14.31
KS 100%	125	25	5	15.03	413	83	5	31.61
KS 120%	35	7	5	2.92	179	36	5	17.14
RA 0%	72	14	5	5.77	246	49	5	10.33
RA 40%	33	7	5	3.21	180	36	5	7.07
RA 80%	28	6	5	3.36	157	31	5	5.27
RA 100%	42	8	5	7.02	158	32	5	5.94
RA 120%	24	5	5	0.84	194	39	5	10.08
Barley 2007–2008								
DA 0%	156	31	5	12.52	190	38	5	21.95
DA 40%	115	29	4	10.47	169	42	4	13.82
DA 80%	335	67	5	25.80	261	52	5	16.50
DA 100%	102	26	4	9.29	306	77	4	16.34
DA 120%	16	N/A	1	N/A	75	N/A	1	N/A
KS 0%	14	N/A	1	N/A	2	N/A	1	N/A
KS 40%	327	65	5	21.56	405	81	5	15.15
KS 80%	366	92	4	28.72	251	63	4	35.35
KS 100%	285	95	3	11.31	170	57	3	36.77
KS 120%	442	88	5	37.04	262	52	5	32.67
RA 0%	242	48	5	19.37	184	37	5	21.99
RA 40%	96	19	5	5.54	411	82	5	12.40
RA 80%	111	22	5	5.76	493	99	5	15.98
RA 100%	76	15	5	5.17	416	83	5	15.74
RA 120%	73	15	5	7.23	308	62	5	9.71

not tested for during soil analysis. However, after the first growing season plant samples of both wheat and barley were taken, oven dried and crushed and then tested for nitrogen, potassium and phosphorus by NCARE. The results for both wheat and barley found that the level of nitrogen was lower for the plants from Ramtha than plants grown at the other two stations,

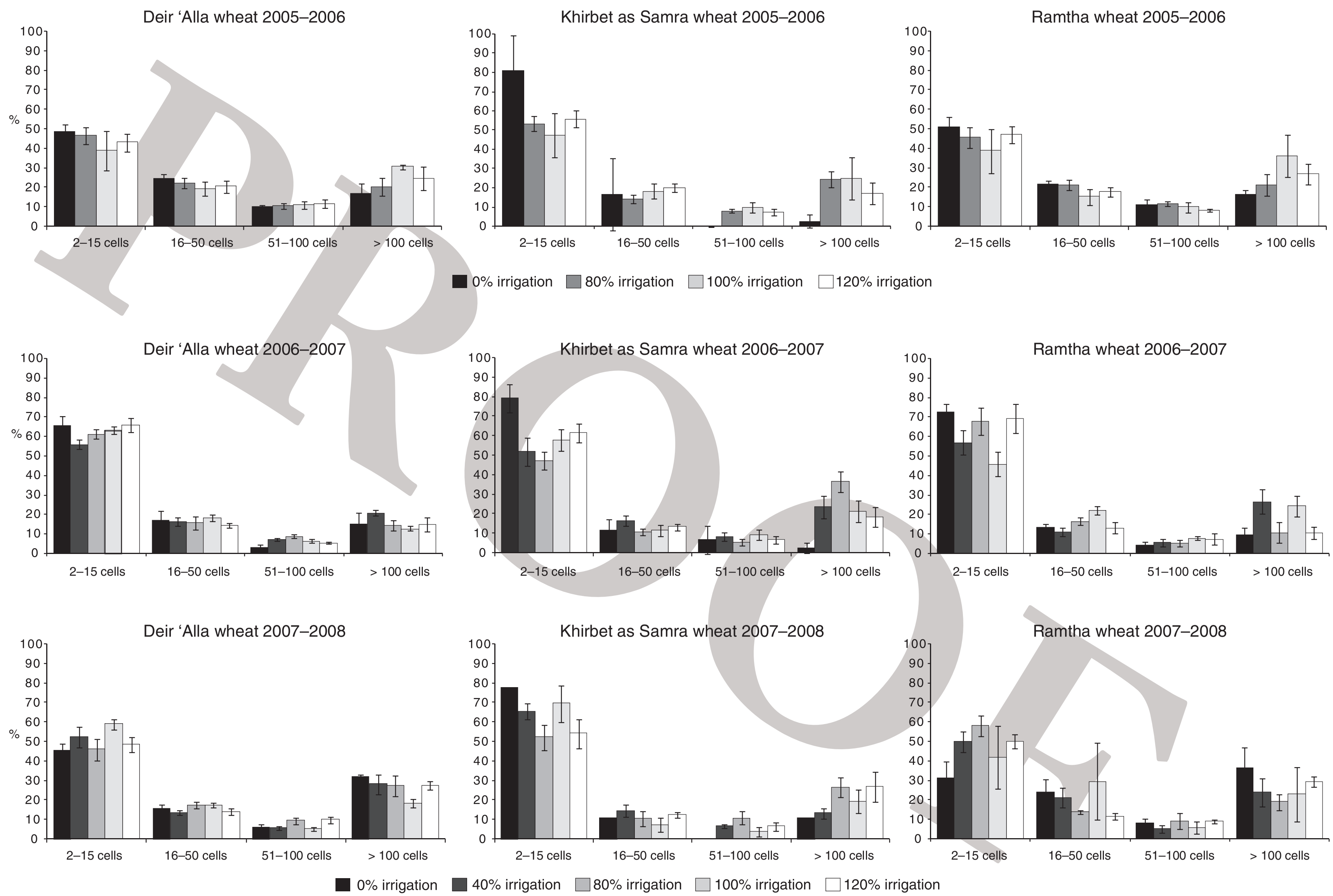

Figure 21.17. Percent of conjoined cells in the wheat samples for all sites, years and irrigation regimes.

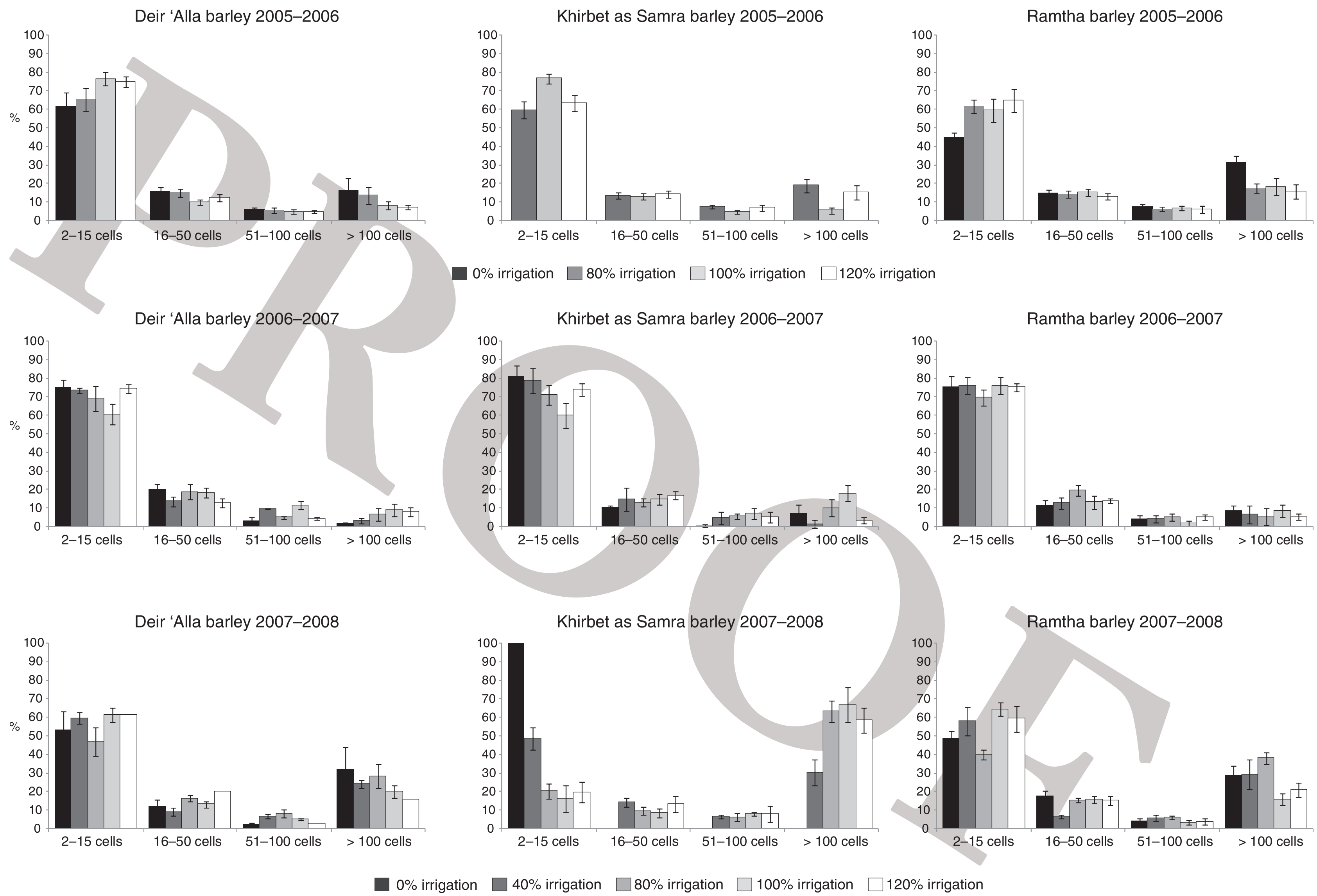

Figure 21.18. Percent of conjoined cells in the barley samples for all sites, years and irrigation regimes.

suggesting that the plants from Ramtha did not take higher levels of nitrogen from the growing medium than plants from Deir ‘Alla and Khirbet as Samra.

Results from the comparison of the cork-silica cells to dendritic long cells, and from the comparison of well silicified conjoined forms to the poorly silicified conjoined forms, show a decrease in indicators of water availability (dendritic long cells and well silicified conjoined forms) over time. This is interesting because an increase in sensitive forms due to irrigation was not found in the six-row barley analysed by Madella *et al*. (2009). With wheat, the lowest percent of both these forms is found in the non-irrigated plots from Khirbet as Samra. As this is the site with the least rainfall, it confirms that the production of dendritic long cells is governed by water availability.

While this study found that the ratio of dendritic long cells to cork-silica cells is an indicator of water availability for both wheat and barley, there were significant inter-site and, more notably, inter-year differences. This demonstrates that local climatic and environmental conditions affect results. However, the decrease in dendritics over time is the biggest difference seen in the results and affects all three sites. It is possible that this is due to a build up of salinity in the soil caused by the use of treated wastewater for irrigation, as demonstrated by the work of Carr (2009). Ahmad *et al*. (1992) showed that silicon increases the tolerance of bread wheat to salinity while Liang *et al*. (1996) report similar findings for common barley, though they found that barley was more salt-tolerant than bread wheat. Ahmad *et al*. (1992) suggest that this tolerance occurs because there is an interaction between freely available sodium and silicon ions which reduces their uptake into the plants, as observed in the roots of the wheat they studied. The fact that common barley exhibits a greater tolerance for salt stress than wheat could explain why in our experiments the percent of dendritics decreased after one growing season for wheat but only after two seasons for barley. It may also explain why phytolith weight percent increases over time in barley samples but decreases in wheat.

21.5.2 Implications for archaeological study

The results from this research demonstrate that phytolith assemblages are altered by increased water availability. The most effective method for identifying water availability is the ratio of long cells to short cells. This is because these forms are single celled and not subject to break up, a problem with the conjoined phytolith method proposed by Rosen and Weiner (1994). Analytical experiments conducted by Jenkins (2009) demonstrated that conjoined phytolith forms do not remain stable from the time of formation to the time of analysis, and using this method to indicate water availability in assemblages with unknown taphonomic pathways is problematic.

Although the proportion of dendritic long cells to cork-silica cells is a more reliable indicator of water availability than changes in the number of conjoined cells, this method is not without its pitfalls. It is clear that the inter-year differences found in the percent of dendritics are sometimes greater than that found between the irrigated and non-irrigated samples. Further work is planned to establish if the decrease in dendritics from the second to the third growing season is the result of smaller sample size or a real change in phytolith ratios. Work is also needed to determine if this method is applicable to the leaves and stems as well as the husks as suggested in the work of Madella *et al*. (2009). This is important because while the types of long cells found in the leaves and stems have smooth edges and so are distinct from the wavy edged dendritics found in husks, the corresponding short cells formed in leaves (rondels) are morphologically very similar to cork-silica cells. This means that in an archaeological assemblage derived from a mixture of plant parts, it would be difficult to isolate short cells formed in husks from those formed in leaves.

Results from this study also show that the source of water, i.e. rainfall or irrigation, is unimportant in its effects on changes in phytolith formation and deposition. It is possible that the greater amount of available silica coming from wadi water may increase the level of silicon uptake, but our results found that the important factor for affecting changes to phytolith formation was water availability. This inability to detect the difference between rainfall and irrigation is of course true for many methodologies which claim to be able to identify irrigation, such as the FIBS method (Charles *et al*., 2003). The changes they identify occur as a result of increased water availability and not necessarily as a result of rainfall. However, if other proxies, such as carbonate deposits or stable isotopes, indicate that the site under excavation was occupied during an arid period, then phytoliths can potentially be used to infer past irrigation. Results from this experiment suggest that an archaeological phytolith assemblage consisting of 60% dendritics would indicate that water was abundant. Chapter 22 shows an example of the application of this methodology to archaeological and modern phytolith assemblages with encouraging results.

21.6 CONCLUSION

This study has confirmed that the uptake and deposition of phytoliths is affected by water availability, as suggested by Rosen and Weiner (1994) and Madella *et al*. (2009). But it also demonstrates that these changes reflect increased water availability which could be from precipitation or irrigation, a claim previously refuted by Rosen and Weiner (1994). The change in phytolith composition is discernible in an increase in the ratio of dendritic long cells to cork-silica cells in the husks of durum wheat and six-row barley, supplementing the work of Madella *et al*. (2009). However, results for six-row barley contrast with those of Madella *et al*. (2009) who found that six-row barley responded negatively to increased irrigation, with the percent of long cells in leaves decreasing, not increasing. The method proposed by Rosen and Weiner (1994) which suggested that the number of conjoined phytoliths increased with irrigation was found to be less reliable for identifying past water availability. Our results suggest that an assemblage consisting of over 60% dendritic long cells indicates a level of water availability sufficient to meet the crop requirements of cereals. If this method is found to be consistent in all plant parts, as suggested by the work of Madella *et al*. (2009), phytoliths could be a valuable tool for estimating past water availability and, potentially, irrigation.

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