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Effect of dung, ash and runoff water on wheat and barley grain sizes and stable isotope ratios: Experimental studies in ancient desert agriculture (Negev, Israel)

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A R T I C L E   I N F O

Keywords:
Ancient runoff farming
Arid desert climate
Manuring experiments
Triticum aestivum
Hordeum distichum
Grain size variations
Stable isotope ratios

A B S T R A C T

Archaeological excavations in the central Negev desert in terraced wadi fields at Horvat Haluqim revealed remains of two ancient fertilizers: charred plant ash and animal dung. Average annual rainfall in the area is 94 mm. Runoff rainwater from natural hillside catchments, captured by terrace walls, augmented soil moisture in valleys to enable agriculture. Some terraced fields are farmed by Bedouin, who grow wheat and barley. Using these cereal varieties, we conducted novel investigations in this arid desert environment about the effect of plant ash, sheep dung and runoff water on grain sizes, δ13C, Δ13C, and δ15N. Our study included both controlled pot experiments and traditional runoff farming by Bedouin. The pots were filled with local desert loess soil to investigate the effect of four different fertilizer treatments – (1) “None” for baseline data, (2) “Ash”, (3) “Dung”, (4) “Ash & Dung combined” – on the above cereal varieties. The largest cereal grains were produced by treatment 4 (ash & dung), which is a remarkable result, because it independently corroborates the archaeological findings. The pots received equal amounts of tap water, totalling 240 mm for barley and 325 mm for wheat. The Δ13C values of cereal grains in the pot experiments ranged from 15.62 to 17.47‰. Concerning δ15N, sheep dung produced a small increase, as compared to the baseline data, but plant ash fertilizer caused a decrease. Ash and dung together (treatment 4) yielded variable δ15N results. Stable isotopes of the same cereal varieties were also studied in the context of traditional runoff farming by Bedouin in terraced wadi fields in the area. Runoff water reception by terraced fields is by nature highly variable. A negative correlation was found between δ15N of cereal grains and runoff soil moisture. The Δ13C values ranged from 12.59 to 17.44‰. Concerning δ15N, cereal grains from the drier fields had comparatively high values, while the wetter fields yielded the two lowest δ15N values. Nevertheless, other δ15N values from weter fields were quite high, indicating the effect of additional factors besides runoff water. Though the Bedouin do not add fertilizers to the terraced fields, their sheep and goats graze the cereal stubble after the harvest. This leads to a spatially random and spotty distribution of manure, which may explain the diverging δ15N values.

1. Introduction

Ancient agriculture developed in different climatic regions and environments. The archaeological history of field manuring, the ancient fertilizers involved, as well as their respective effect on crops involve complex investigations (Wilkinson, 1982, 1989; Bakels, 1997; Miller and Gleason, 1994; Nicosia et al., 2013; Paz et al., 2017). Studies about the effect of animal manure on the stable isotope ratios δ15N and δ13C of cereal grains yielded new insights in recent years. Several pioneering studies were conducted in north-western Europe, a region characterized by rain-fed farming in a temperate humid climate. The research results in this environment showed that animal manure (dung) significantly

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Sea, all of them situated in the large desert zone of the Southern Levant. Fig. 1.

raises $\delta^{15}$N in cereal grains (Bogaard et al., 2007; Fraser et al., 2011; Kanstrup et al., 2011; Kanstrup, 2012). Thus, $\delta^{15}$N measurements of ancient grains uncovered in archaeological excavations may indicate whether manure was applied during their cultivation (Fraser et al., 2011; Kanstrup et al., 2012; Bogaard et al., 2013; Kanstrup et al., 2014).

However, animal dung is only one of the factors involved, as climate and soil properties also influence stable isotope values in cereal grains. Bakels (2019) emphasized the importance of regional baseline studies concerning $\delta^{13}$N values in cereals on unmanured soils in order to evaluate the effect of manuring. She pointed out that the soil substrate used in such experiments should resemble as far as possible the original soil at the onset of farming prior to manuring (Bakels, 2019).

Concerning the eastern Mediterranean region, experimental studies in the semi-arid region of Aleppo in Syria gave complex non-uniform results regarding the effect of animal manure on stable isotope data of cereal grains. Bakels (2019) emphasized the importance of regional baseline studies concerning $\delta^{13}$N values in cereals on unmanured soils in order to evaluate the effect of manuring. She pointed out that the soil substrate used in such experiments should resemble as far as possible the original soil at the onset of farming prior to manuring (Bakels, 2019).

Stable isotope studies of natural vegetation in Israel, growing in climatic regions ranging from dry sub-humid to arid desert conditions, showed that water availability is the primary factor controlling C and N isotope variability in C3 plant communities (Hartman and Danin, 2010). Investigations in Jordan (Flohr et al., 2011; 2019) focussed on $^{13}$C contents of wheat and barley in relation to rainfall and/or irrigation. Three areas were studied, having different amounts of average annual rainfall during the rainy season: Deir ‘Alla (281 mm), Khirbet as-Samra (150 mm), and Ramtha (220 mm). The results showed a large variation in carbon stable isotope values of crops that received similar amounts of water. Evidently, additional site-specific factors, besides water, affect $\delta^{13}$C and $\Delta^{13}$C values. Nevertheless, Flohr et al. (2019) concluded that $^{13}$C isotopic studies of crops can be very useful for investigating past agricultural practices and water availability.

Here we present experimental investigations from an even drier region, located in the central Negev desert in Israel. An ingenious form of farming developed in this hilly region based on runoff rainwater from natural catchments, captured by stone terrace walls built in ephemeral stream valleys, ‘wadi’ in Arabic, ‘nahal’ in Hebrew (Evenari et al., 1982; Bruins, 1986, 2012; Bruins et al., 2019).

The meteorological station at Kibbutz Sede Boker, located in the area of our experiments, recorded an average annual rainfall of 94.1 mm for the period 1970–2020 (data from the Israel Meteorological Service). Hence the area is significantly more arid than the Aleppo region in Syria. The wettest year at Sede Boker in this 50-year period was 1991–92 with 187.8 mm, while the most severe drought year was 1998–99 with just 34.0 mm rainfall. The central Negev highlands have an average temperature ranging from 8°C in January to 26°C in August. Light frost may occur in winter. Maximum temperatures in summer may reach 40°C (Goldreich, 2003).

Climatic classification based on the numerical P/PET ratio (P = annual precipitation; PET = annual potential evapotranspiration) is useful for agricultural studies (Middleton and Thomas, 1997). The method also facilitates detailed time-series analyses, which showed that in Israel the climate has become drier during the period 1970–2002 in the inland regions east of the coastal plain (Kafle and Bruins, 2009). A detailed P/PET classification of the Negev (Bruins, 2012) showed the Sede Boker area to have an average P/PET index of only 0.07. Hence the area of our research lies in the arid zone (P/PET range of 0.05–0.20), but close to the boundary with the hyper-arid zone, which has P/PET values below 0.05. For comparison, the semi-arid zone, in which farming based on rainfall is feasible, has a P/PET range of 0.20–0.50.

The arid central Negev desert is obviously too dry for rain-fed farming. Yet the region contains thousands of ancient agricultural fields with stone terrace walls in ephemeral valleys. These walls captured runoff water during significant local rainfall events, leading to storage of additional amounts of water in the silty loam soils of these terraced fields, thus enabling agriculture in the past and in modern times (Evenari et al., 1982; Bruins et al., 2019).

1.1. Related historical and archaeological findings

An ancient literary archive containing Greek, Latin, and Arabic documents, dating to the Late Byzantine and Early Islamic periods (6th to 7th centuries CE) was discovered at Nizzana in the western central Negev desert (Kraemer, 1958). Ancient terraced wadi fields used for runoff farming occur in the area. Several Nizzana papyri mention the cultivation of wheat and barley, providing even data about the volume amounts sown and harvested (Kraemer, 1958; Mayerson, 1961).

Archaeological excavations of ancient agricultural terraced wadi fields at Horvat Haluqim in the central Negev desert yielded evidence of ancient manuring practices (Bruins, 2007, 2012:37; Bruins and Jongmans, 2012; van Asperen et al. 2014; Bruins and van der Plicht, 2017a, 2017b). Significantly darker layers were uncovered at various depth levels below the surface in several terraced wadi fields. These darker soil layers were dated by radiocarbon to different archaeological periods, including the Late Bronze Age, the Iron Age (Bruins and van der Plicht, 2017a, 2017b), and the Early Islamic period (Bruins et al., 2020).

Micromorphological investigations (Bruins and Jongmans, 2012) showed the presence of very fine charred organic particles dispersed through the soil matrix, which give the soil a darker colour than usual for the central Negev desert. Also, animal bone fragments (usually sheep/goat) occur in these darker layers, besides worked flint and pottery sherds, all varying from the microscopic scale to larger pieces. Therefore, the source of these materials was interpreted (Bruins, 2007) to have been derived from household kitchen ash/refuse, which was purposefully added to the (former) surfaces of the terraced field to enhance soil fertility (Bruins et al., 2019, 2020).

In addition, microscopic investigations showed the presence of non-charred dung pellets and faecal spherulites (Bruins and van der Plicht, 2017a) in these darker soil layers. These globular spherulites are radially crystallised bodies of calcium carbonate produced in the intestines of ruminants, including sheep, goats, cattle and camels (Canti (1997,
They show a characteristic extinction cross under the microscope, when viewed in crossed polarized light (Canti, 1998:438; Bruins and Van der Plicht, 2017a:13). Both the dung pellets and the spherulites indicate that animal manure was purposefully added by the ancient farmers to former surface levels of terraced fields to increase soil fertility (Bruins 2007; Bruins and van der Plicht, 2017a).

1.2. Runoff farming by Bedouin in terraced wadi fields in the central Negev

Bedouin living at present in the central Negev desert grow wheat and barley in some ancient terraced wadi fields. Comparative anthropology may elucidate ‘silent’ archaeological findings. The very fact that the Bedouin do engage at present in the farming of wheat and barley, based
on runoff water, underlines the feasibility of this form of desert agriculture regarding the past. Though climatic conditions fluctuated during the past 4000 years, as shown by lake level changes of the Dead Sea (Bookman (Ken-Tor) et al., 2004; Kagan et al., 2015) and records revealed in speleothems (Bar-Matthews and Ayalon, 2004), the arid zone seems to have persisted in the central Negev highlands (Bruins, 2012).

Inter-annual variability of rainfall in the Sede Boker area is large (Fig. 3), even beyond the typically 50–100 % of the arid zone (Middleton and Thomas, 1997), underlining its position near the climatic boundary with the hyper-arid zone. Consequently, the Bedouin will not sow cereal crops every year, but only if runoff floodwater has wetted the ancient fields sufficiently during the beginning of the rainy season. Such decision making concerning the sowing of annual food crops may also have been practised in the past.

The Bedouin today surprisingly do not manure the terraced wadi fields they use for farming (Bruins, 1986:145; 2007). This rather astonishing fact is apparently related to their nomadic and semi-nomadic background, in which extensive livestock production of sheep and goats used to be the traditional basis of their rural economy (Marx, 1967; Kressel et al., 1991). Farming was adopted relatively late by the Bedouin, apparently in the 19th century (Kressel et al., 1991), as an auxiliary economic branch in addition to pastoralism. When the cereal crops fail, i.e., no filling of the grains due to drought, the plants can still be eaten as pasture by their sheep and goats.

2. Research objectives

Ancient inhabitants at Horvat Haluqim did manure terraced wadi fields, used for runoff farming, with household kitchen ash and animal dung, as described above (Bruins, 2007; van Asperen et al., 2014; Bruins and van der Plicht, 2017a, 2017b; Bruins et al., 2020). Therefore, we became motivated to investigate experimentally the effect of plant ash and animal dung on wheat and barley grain size and stable isotope values in the desert environment of the central Negev. Previous investigations regarding stable isotope ratios of cereal crops in a semi-arid region of Syria (Fraser et al., 2011) and in semi-arid to arid regions of Jordan (Floh et al., 2019) showed complex results. More research is necessary in arid climatic zones. Our investigations in the Negev desert of Israel took place in the driest environment so far investigated regarding stable isotope ratios of cereal grains, in order to obtain regional baseline data (Bakels, 2019) of δ15N and δ13C, and to study the effect of “ancient” fertilizers (plant ash and sheep dung) on grain size and stable isotope values. It also seems the first time that the effect of desert farming by Bedouin with natural runoff water on δ15N and δ13C values of wheat and barley grains has been investigated.

Within the regional context of ancient runoff farming in the central Negev desert, in an area situated at the border of the arid and hyper-arid zones (Bruins, 2012), the research questions can be summarized as follows:

(1) What is the effect of two “ancient” fertilizers, animal dung and plant ash, on grain dimensions, mass, delta 15N, delta 13C, and delta 13C of wheat and barley plants grown in pots, filled with local desert loess soil, irrigated with tap water in known quantities?

(2) What is the effect of capricious natural runoff water variability in terraced wadi fields with alluvial desert loess soils farmed by Bedouin, who did not apply manure, on grain dimensions, mass, delta 15N, delta 13C, and delta 13C of the same wheat and barley varieties?

3. Materials and methods

The fieldwork was carried out during the growing season 2014–2015 and involved (1) controlled pot experiments at the Sede Boker Campus of the Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev and (2) runoff farming by Bedouin in ancient terraced wadi fields of Nahal Divshon, about 3.5 km south of the Sede Boker Campus (Figs. 1, 2). The same wheat and barley varieties were used in both investigations.

3.1. Proxies for ancient animal dung and ancient household ash refuse

Considering the arid desert climate in the region, domesticated herds of sheep and goats were the most likely sources of animal dung remains detected at Horvat Haluqim as fertilizer in soil layers of terraced agricultural wadi fields. For our pot experiments we used sheep dung from the modern Haroa Farm, located in the vicinity of Horvat Haluqim, as a reasonable proxy.

Regarding the other type of ancient fertilizer, plant ash refuse, Bedouin families living in the region still use vegetation and wood as the traditional fuel for cooking, for making tea and coffee, and heating in winter. The Bedouin regularly clean the ash from the fireplace, a shallow hole in the soil, and move it to an ash waste dump near the tent or home. We received a few buckets of such ash refuse for our investigation. The material contained ash, small charcoal fragments, and some pieces of household refuse, including nails, fragments of metal, glass and cigaretes. Such items ended up in the ash of the fireplace, a process somewhat reminiscent of pottery sherd s in ancient household refuse used as manure on agricultural fields (Wilkinson, 1982, 1989). The above pieces of refuse were of course removed in our investigation, as only the plant ash charcoal mix was added to the pots in our experiment.

3.2. Selection of wheat and barley varieties used in the investigation

The cereal grains we selected have been used in runoff farming by a Bedouin family for about four decades (two generations, father and son) in terraced wadi fields of Nahal Divshon. Following a successful harvest, the family stored seeds for their own household usage and for sowing in the next rainy season, thus continuing with these varieties. The second author (Bruins) has been in contact with this family for many years and purchased a large bag of these cereal grains. The mixture was found to be composed of two naked bread wheat varieties (Triticum aestivum) and a hulled two-row barley variety (Hordeum vulgare var. distichum). The two bread wheat varieties were separated according to grain colour: white or brown. The local Bedouin classified both wheat varieties in Arabic as “qamah”, which refers to flour for making bread, i.e., free-threshing soft bread wheat.

The respective frequency distribution of the three cereal types in the bag of grains we received from the Bedouin family is as follows: brown wheat 69 %, white wheat 29 % and two-row barley 2%. Evidently the Bedouin sow and harvest these seeds together. Apparently, a small amount of two-row barley became mixed with the wheat in the recent past. Today the Bedouin family continues to sow this seed mixture, dominated by wheat, in terraced wadi fields of Nahal Divshon. In addition, they also sow six-row barley separately in additional terraced fields.

3.3. Pot experiments

Plant growth from germination to harvest of the two wheat varieties and the two-row barley variety was monitored in 60 pots, situated in a greenhouse at the Sede Boker Campus of the Jacob Blaustein Institutes for Desert Research (Ben-Gurion University of the Negev). The round pots used for the experiments are 29 cm in diameter and 30 cm high. All the pots were filled with about 21 kg of local desert loess soil, which originated from the salt-free upper 30 cm of the natural profile of the southern Sede Zin synclinal valley (Dan et al., 1973; Issar et al., 1984), where the Sede Boker Campus is located. The soil is a Loessial Serozem in the Israel classification system, correlating with Aridisols in the system of the United States Department of Agriculture (Singer, 2007:262). The soil has a texture of silt loam, being calcareous throughout, and saline below 30 cm depth, the current depth of leaching by rainfall. Natural soil organic matter content is extremely low, typical for a desert...
environment. Gypsum and calcic horizons often occur at greater depth; the latter formed during the Late Pleistocene (Issar et al., 1984).

The measured average bulk density of the soil in all the 60 pots was 1.33 g/cm³, which is in the range of natural values of loess soil in the area. For example, alluvial loess soils in various ancient terraced wadi fields at Horvat Haluqim have bulk densities ranging from 1.12 to 1.59 g/cm³ (van Asperen et al., 2014).

A tube and a bucket were installed underneath each pot to facilitate proper drainage (Ben-Gal and Shani, 2002). Both the bottom of the pot and the tube were filled with rock-wool, in order to prevent loss of soil into the drainage system. The pots were equally irrigated with tap water having a low electrical conductivity of 0.2 DSm⁻¹ in controlled amounts, so that the different fertilizer treatments (see below) constitute the principal variable to evaluate their effect on cereal grain size and stable isotope ratios.

Subsequently, the two selected fertilizers were added and mixed with the upper half of soil in the pots (down to ca 13 cm depth) in a specific pattern to facilitate four different treatments: (1) None, i.e., baseline data without fertilizers; (2) Ash - 150 ml plant ash per pot; (3) Dung – 150 ml sheep dung per pot; and (4) Mix - a mixture of 75 ml sheep dung and 75 ml ash per pot.

Concerning the fertilizer amount, 150 ml per pot, the rationale is based on writings by ancient Roman agronomists. For example, Columella instructed manuring with “12 loads of 80 modii per jugerum” for average weather conditions (Semple, 1928). Such an amount would correspond to 223 ml per pot in our investigation. However, Theophrastus wrote concerning manure that “in arid districts or in thin dry soil a moderate application was the wise course” (Semple, 1928).

Concerning our fertilizer experiments in pots. The Bedouin did not apply any type of manure to the terraced fields. Herbicides or pesticides were not used. Weeding is not practised. Their type of farming involves only ploughing and sowing without additional inputs. Farming is an auxiliary economic activity. If the cereal crops fail, as a result of drought, the wheat and barley plants are considered as pasture and grazed by their flocks of sheep and goats.

When most of the cereal plants had reached maturity, we selected four different sites in the terraced wadi fields to harvest wheat and barley plants of the three above varieties on 13 May 2015, to investigate the respective seeds. The four sites were visibly selected in relation to either dry or wet fields, as natural runoff water flows in the landscape are highly variable. Two comparatively dry fields (Sites 1 and 4) were located in small tributary wadis and two comparatively wet fields (Sites 2 and 3) were situated in the main wadi bed of Nahal Divshon.

### 3.5. Stable isotopes of nitrogen (δ¹⁵N) and carbon (δ¹³C)

Ancient farmers apparently selected comparatively large grains for cultivation in the next growing season, as a gradual increase in grain size has often been observed through time by archaeo-botanical research (Willcox, 2004; Fuller, 2007; Zohary et al., 2012). Concerning our stable isotope measurements 15 cereal grains larger than the average length were selected from each of the three different cereal varieties, from each of the four different fertilizer treatments in the pot experiments. Likewise, 15 large cereal grains were selected of the same three cereal varieties from each of the four sampled fields that received runoff water at Nahal Divshon and adjacent tributary wadis cultivated by Bedouin.

For comparison, also 15 cereal grains were selected of small cereal grains of each of the three varieties in the “Dung” fertilizer treatment of the pot experiment. Thus, the effect of animal dung on δ¹⁵N values of both large and small cereal grains could be studied in a comparative manner.

The δ¹³C and δ¹⁵N isotopic composition of the samples was measured at the Centre for Isotope Research, University of Groningen. The samples were cleaned by washing with demineralized (and decarbonized) water. Only the inner part of the cereal grains was selected, but not the outer skin. Next the samples were combusted and purified by an Elemental Analyzer (EA), coupled on-line with a stable isotope Mass Spectrometer (IRMS), which measures the ¹³C/¹²C and ¹⁵N/¹⁴N ratios of the CO₂ and N₂ gas, respectively.

The stable isotope ratios, as deviations from the internationally agreed reference material, are expressed in permil:

\[
\delta^{13}C = \frac{^{13}C_{sample} - ^{13}C_{ref}}{^{13}C_{ref}} \times 1000,
\]

\[
\delta^{15}N = \frac{^{15}N_{sample} - ^{15}N_{ref}}{^{15}N_{ref}} \times 1000.
\]
Fig. 4. The pot experiments showing cereal plants with their first two leaves after germination (left) and the production of tillers (right), by which a single cereal plant increases the number of ears and seeds (Photographs by Danielle van Bommel).

Table 2
Number of plants of each cereal variety investigated in the pot experiments with respect to the four different treatments.

<table>
<thead>
<tr>
<th>Fertilizer Treatment</th>
<th>White Wheat</th>
<th>Brown Wheat</th>
<th>Two-row Barley</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (no fertilizers)</td>
<td>27</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Ash</td>
<td>24</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Dung</td>
<td>15</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Mix (Ash &amp; Dung)</td>
<td>20</td>
<td>22</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 3
Effect of fertilizer treatment on the average number of tillers per plant (standard deviation is listed between brackets). A star * indicates a significant statistical difference.

<table>
<thead>
<tr>
<th>Fertilizer Treatment</th>
<th>White Wheat</th>
<th>Brown Wheat</th>
<th>Two-row Barley</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (baseline)</td>
<td>3.0 (0.5)</td>
<td>3.2 (0.6)</td>
<td>6.9 (3.7)</td>
</tr>
<tr>
<td>Ash</td>
<td>2.3* (1.1)</td>
<td>2.4* (0.8)</td>
<td>7.8 (2.5)</td>
</tr>
<tr>
<td>Dung</td>
<td>3.8 (1.9)</td>
<td>3.4 (1.3)</td>
<td>13.0* (4.9)</td>
</tr>
<tr>
<td>Mix (Ash &amp; Dung)</td>
<td>3.5 (1.4)</td>
<td>3.1 (1.2)</td>
<td>8.6 (0.7)</td>
</tr>
</tbody>
</table>

4. Results of the fertilizer experiments in pots

The number of cereal plants investigated in the pot experiments (Fig. 4) is shown in Table 2. A total of 77 plants were investigated in the baseline study “None”, 68 plants received fertilizer treatment “Ash”, 65 plants received fertilizer treatment “Dung”, and 60 plants received the combined addition of both ash and dung (treatment ‘Mix’).

4.1. Plant height in relation to fertilizer treatment

The final plant height of the three cereal varieties was measured in each of the four treatments (Fig. 5). Though differences in average final plant length are not statistically significant, the results are nevertheless valuable. Manuring with sheep dung and/or ash resulted in all cases in taller plants as compared to the baseline treatment “None” without any fertilizers. The combined addition of ash and sheep dung (treatment ‘Mix’) resulted in the tallest barley plants, which is a remarkable result of our pot experiments, independently fitting geoarchaeological findings of both ash and dung in ancient agricultural soil layers at the central Negev site of Horvat Haluqim (Bruins and Van der Plicht 2017a).

4.2. Number of tillers per plant

The average number of tillers for each cereal variety was determined (Table 3). The absolute number of tillers in the pot experiments comprised 189 tillers of white wheat, 166 tillers of brown wheat, and 545 tillers of two-row barley. However, for all further analysis of the grains (mass, dimensions, stable isotopes), only pots were included, in which the same number of plants made it from sowing to harvesting throughout the growing season: 5 plants for pots with white wheat, 5 plants for pots with brown wheat, and 4 plants for pots with barley. The reason is of course to have equal plant density per pot, respectively, for each of the three cereal varieties. Thus, 40 plants of white wheat with 126 tillers were included, 50 plants of brown wheat with 154 tillers, and 32 plants of barley with 279 tillers.

Differences between the white and brown wheat varieties were

with $^{13}R = \frac{[^{13}CO_2]/[^{12}CO_2]}{}$ and $^{15}R = \frac{[^{15}N]/[^{14}N]}{}$.

The reference material for $^{13}C$ is Vienna PeeDee Belemnite (VPDB), and for $^{15}N$ ambient inhalable reservoir (AIR), see Mook (2006) and references therein. The delta values are measured at a precision level of 0.1–0.2‰.

In addition, the quantity $\Delta^{13}C$ was calculated using the formula $\Delta^{13}C = (\delta^{13}C_{air} - \delta^{13}C_{sample}) / (1 + \delta^{13}C_{sample}/1000)$.

It represents the actual isotope discrimination of the plant sample relative to the air (Flohr et al., 2011). For air we have chosen the value $\delta^{13}C_{air} = -8.5$‰, which is representative for the period covered by our cereal plant studies from sowing to harvesting during the year 2014–2015 (autumn, winter, spring). The $\delta^{13}C_{air}$ of −8.5‰ for this period is the annual global value shown by Graven et al. (2020), their Fig. 3.
found to be small. Evaluating the wheat results in relation to the four different treatments, it is noteworthy that the addition of “Ash” to the soil resulted in the smallest number of tillers. However, two-row barley consistently produced many more tillers than wheat in each of the four fertilizer treatments. The record average of 13 tillers per barley plant (Table 3) relates to the addition of sheep dung to the soil.

4.3. Cereal grain mass in relation to fertilizer treatments

Harvesting took place when all the cereal varieties had reached physical maturity, which occurred during the month of May 2015. The tillers were winnowed and the number of grains per ear were counted in relation to each cereal variety and each fertilizer treatment (Table 4). In

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Table 5
Effect of fertilizer treatments on the average grain dimensions (mm) of white wheat, brown wheat, and barley. The standard deviation in mm is shown between brackets. A star * indicates a significant statistical difference in comparison with the baseline treatment “None”.

<table>
<thead>
<tr>
<th>Cereal Variety</th>
<th>Fertilizer Treatment</th>
<th>Cereal Grain Dimensions in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
<td>Width</td>
</tr>
<tr>
<td>White Wheat</td>
<td>None</td>
<td>6.21 (0.38)</td>
</tr>
<tr>
<td></td>
<td>Ash</td>
<td>6.27 (0.46)</td>
</tr>
<tr>
<td></td>
<td>Dung</td>
<td>6.10 (0.50)</td>
</tr>
<tr>
<td></td>
<td>Mix (Ash &amp; Dung)</td>
<td>6.31 (0.46)</td>
</tr>
<tr>
<td>Brown Wheat</td>
<td>None</td>
<td>6.23 (0.43)</td>
</tr>
<tr>
<td></td>
<td>Ash</td>
<td>6.29 (0.51)</td>
</tr>
<tr>
<td></td>
<td>Dung</td>
<td>6.21 (0.37)</td>
</tr>
<tr>
<td></td>
<td>Mix (Ash &amp; Dung)</td>
<td>6.35 (0.40)</td>
</tr>
<tr>
<td>Barley</td>
<td>None</td>
<td>8.92 (0.51)</td>
</tr>
<tr>
<td></td>
<td>Ash</td>
<td>8.97 (0.48)</td>
</tr>
<tr>
<td></td>
<td>Dung</td>
<td>8.95 (0.61)</td>
</tr>
<tr>
<td></td>
<td>Mix (Ash &amp; Dung)</td>
<td>9.18* (0.47)</td>
</tr>
</tbody>
</table>

Fig. 6. The wadi of Nahal Divshon with terraced fields farmed by Bedouin, looking northward. The first author is harvesting selected wheat and two-row barley plants in Site 1, a field located in a tributary wadi that received less runoff water, as all cereal plants are brown. Site 2, situated in the main wadi, received more runoff water, as some wheat plants are still partly green (Photo by H.J. Bruins, 13-05-2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
order to establish the average grain weight (mass), 20 grains were randomly selected of each cereal variety from each fertilizer treatment and measured separately (Table 4). The barley grains, surrounded by a hull, are slightly heavier than the two naked wheat varieties. The average weight results (mass) in grams are displayed in Table 4; the standard deviation is smaller than 0.011.

The fertilizer treatment “Mix” (both ash & dung) resulted in the largest grain mass for all three cereal varieties, which is a most significant result. Thus, the pot experiments corroborate independently the archaeological findings, in which charred ash, non-charred dung and non-charred phytoliths were uncovered in darker soil layers of ancient agricultural terraced wadi fields at Horvat Haluqim (Bruins, 2007; Bruins and Jongmans, 2012; Bruins and Van der Plicht, 2017a). A rather surprising outcome is that the lowest grain mass in both wheat varieties resulted from the fertilizer treatment “Dung”, i.e., only sheep dung without ash, resulted in the smallest grains for both wheat varieties, though not for barley. Even the baseline treatment “None” yielded larger wheat grains.

4.4. Cereal grain dimensions in relation to fertilizer treatments

The length, width and thickness of the cereal grains were measured (Table 5). The two-row barley grains are surrounded by a hull (not free-threshing) and hence bigger than the wheat grains. Again, the most remarkable result is that the fertilizer treatment “Mix” (both ash and dung) produced the largest grains in all dimensions (length, width, and thickness) for each of the three cereal varieties. Surprisingly, the fertilizer treatment “Dung”, i.e., only sheep dung without ash, resulted in the smallest grains for both wheat varieties, though not for barley. Even the baseline treatment “None” yielded larger wheat grains.

5. Results of runoff farming by Bedouin in terraced wadi fields at Nahal Divshon

The Bedouin farmer cultivated wheat and barley but did not apply fertilizers to the terraced wadi fields at Nahal Divshon. Therefore, water seems to be the main variable growth factor. The capricious nature of runoff water flows in the landscape resulted in significant soil moisture differences of agricultural fields. The soils consist of alluvial desert loess, which accumulated gradually in the course of time in the terraced wadi fields. These soils are younger than the Serozem loess soils in the...
Synclinal valley of Sede Zin where the Jacob Blaustein Institutes for Desert Research are located. Soils in terraced wadi fields in the central Negev desert usually have an AC profile with a very weakly developed A horizon (Bruins et al., 2020).

Site 1. A small field situated in a tributary wadi next to Nahal Divshon (Fig. 6). It was clear from the dry mature state of all cereal plants in this field, dominated by wheat, that comparatively less runoff water had been received in this particular area. We collected for our investigation a two-row barley plant, composed of 11 tillers, and a wheat plant, having 7 tillers.

Site 2. A terraced field within the main wadi bed of Nahal Divshon, situated adjacent to Site 1 (Fig. 6). The cereal plants were taller than in Site 1 and some were still slightly green (Fig. 7), indicating that Site 2 had received more runoff water. We collected for our investigation five brown wheat plants, of which two plants consisted of one tiller and three plants had two tillers each. Three white wheat plants were sampled, consisting respectively of one, two and four tillers. In addition, a two-row barley plant with four tillers was collected.

Site 3. Another terraced field within the main wadi bed of Nahal Divshon, dominated by six-row barley (Fig. 8). Though barley has a shorter growing cycle than wheat, reaching maturity a few weeks earlier, the density and height of the standing barley crop indicated that also this field had been comparatively well watered by natural runoff flows. A few plants of two-row barley were also found in this field, indicating that the barley seed stock of the Bedouin family is slightly mixed, as was also noticed for the wheat fields, in which also some two-row barley plants occur. We collected a two-row barley plant with 7 tillers for our investigation.

Site 4. A small field in a tributary wadi next to Nahal Divshon (Fig. 9), situated west of the main wadi bed in the vicinity of Site 3. This field is dominated by wheat and, in addition, contains some two-row barley. All plants had reached full maturity, having a yellow–brown colour. On the other hand, a neighbouring wheat field in the main wadi bed of Nahal Divshon is still largely green (Fig. 9). Obviously, less runoff floodwater had reached Site 4, similarly as for Site 1 (Fig. 6). We collected for our investigation one brown wheat plant with 9 tillers and one two-row barley plant with 10 tillers.

5.1. Average plant height of cereal varieties in Bedouin runoff farming at Nahal Divshon

Our measurements show a clear correlation between runoff water differences in selected fields and plant height of the three cereal varieties (Table 6). Most data show the cereal crops to be lower in height at Sites 1 and 4, situated in small tributary wadis, which received comparatively less runoff water. On the other hand, the cereal plants tend to be taller in Sites 2 and 3, situated in the main wadi bed of Nahal Divshon, which received more runoff water (Table 6).
5.2. Average size and mass of cereal grains in Bedouin runoff farming at Nahal Divshon

The length, width, thickness, and mass of wheat and barley grains harvested from the selected four Bedouin runoff farming sites at Nahal Divshon were measured. The average results are presented in Table 7. A distinct relationship can be noted of grain size & mass vis-à-vis runoff water reception of the related fields, as determined by their geomorphological position in the landscape. Cereal crops in the small tributary wadis, sites 1 and 4, which received less runoff water, tend to have a smaller grain size and lower mass (Table 7). On the other hand, the cereal crops in sites 2 and 3, situated in the main wadi bed of Nahal Divshon, which has a much larger natural watershed, tend to have a larger grain size and mass (Table 7).

6. Stable isotope results of the cereal grains

6.1. Stable isotope results of cereal grains from the fertilizer pot experiments at the Sede Boker Campus

Measurements of $\delta^{13}$C in C$_3$ plants were found by various researchers to be related to rainfall or soil moisture. For example, a large variety of C$_3$ plants in Israel were investigated by Hartman and Danin (2010) in different climatic regions with average annual precipitation ranging from about 990 mm to 75 mm. Their results showed an overall trend that $\delta^{13}$C values become smaller (more negative) with increasing rainfall; the $\delta^{13}$C values they obtained range from $-22.6\%$ to $-28.6\%$ (Hartman and Danin, 2010).

Our results of the three cereal varieties in the four fertilizer treatments range from $-23.75\%$ to $-25.52\%$ (Table 8). The pots received regular irrigation with tap water until the plants reached full maturity, when irrigation was halted. Barley, having a growing season of about 4

![Site 4](image_url)

Fig. 9. Site 4 is dominated by fully mature wheat and some two-row barley plants, farmed by Bedouin. This small field has received less runoff water than the adjacent green wheat field situated in the main wadi of Nahal Divshon. A few plants of wheat and two-row barley were harvested in Site 4 for our investigation (Photo by H.J. Bruins, 13-05-2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6

<table>
<thead>
<tr>
<th>Site</th>
<th>Geomorphic Position of Field</th>
<th>Relative Runoff Water Supply</th>
<th>Cereal Variety</th>
<th>Average Plant Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tributary wadi</td>
<td>Less</td>
<td>Brown Wheat</td>
<td>41.9</td>
</tr>
<tr>
<td>2</td>
<td>Main wadi</td>
<td>More</td>
<td>Brown Wheat</td>
<td>63.0</td>
</tr>
<tr>
<td>3</td>
<td>Main wadi</td>
<td>More</td>
<td>Brown Wheat</td>
<td>58.0</td>
</tr>
<tr>
<td>4</td>
<td>Tributary wadi</td>
<td>Less</td>
<td>Brown Wheat</td>
<td>71.5</td>
</tr>
</tbody>
</table>

Table 7

<table>
<thead>
<tr>
<th>Site</th>
<th>Geomorphic Position of Field</th>
<th>Relative Runoff Water Supply</th>
<th>Cereal Variety</th>
<th>Average Plant Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tributary wadi</td>
<td>Less</td>
<td>Brown Wheat</td>
<td>41.9</td>
</tr>
<tr>
<td>2</td>
<td>Main wadi</td>
<td>More</td>
<td>Brown Wheat</td>
<td>63.0</td>
</tr>
<tr>
<td>3</td>
<td>Main wadi</td>
<td>More</td>
<td>Brown Wheat</td>
<td>58.0</td>
</tr>
<tr>
<td>4</td>
<td>Tributary wadi</td>
<td>Less</td>
<td>Brown Wheat</td>
<td>71.5</td>
</tr>
</tbody>
</table>
months, received 240 mm. Wheat, having a longer growing season of about 5 months, received 325 mm.

Barley yielded in all four fertilizer treatments consistently the lowest (most negative) values of δ¹³C in comparison to the two wheat varieties. Fertilization with ash resulted in slightly less negative δ¹³C values for the three cereals, as compared to the baseline treatment “None” without any fertilizer. Treatment “Dung”, as well as the combined fertilization “Mix” with both ash and dung did not produce an overall trend, whilst the differences are small anyway, also considering the standard deviation.

The Δ¹⁵N values of barley grains (Table 8) are consistently larger than for both wheat varieties in each of the four treatments. All pots with barley plants received equal amounts of water, i.e., 240 mm. The differences between the Δ¹⁵N values in the four treatments range from a high of 17.47‰ (baseline “None”) to a low of 16.83‰ (“Mix Dung & Ash”). These figures compare reasonably well with the Δ¹³C values around 200 mm rainfall/irrigation obtained by Fraser et al. (2011), their Fig. 4) for barley in Jordan.

Concerning δ¹⁵N, the results obtained by Hartman and Danin (2010) for natural C₃ vegetation in Israel showed that δ¹⁵N tends to become larger with increasing aridity. Our baseline values of δ¹⁵N in the pot experiments (Table 8) are about 7.3‰ for wheat and 6.9‰ for barley. The addition of ash slightly lowered the values for the three cereal varieties. Somewhat higher values of δ¹⁵N were obtained, as expected, in the pots that received sheep dung: 7.7‰ for white wheat, 7.7‰ for brown wheat, and 7.3‰ for two-row barley. However, the increase is rather small, which may be due to the short-term (single year) effect of adding sheep manure to soil in pots. The research by Fraser et al. (2011) also found the increase of δ¹⁵N to be significantly smaller in newly established agricultural plots, as compared to long-term manuring of fields. Interestingly, even our baseline δ¹⁵N values of cereal grains from the none-manured pots with desert loess soil have significantly larger values than the results from semi-arid Aleppo in Syria (Fraser et al., 2011). The addition of both ash and dung in our pot experiments gave diverse δ¹⁵N results with one inexplicable low value of 3.90 ± 0.10‰ for brown wheat.

We also checked possible differences between large cereal grains and small cereal grains of the three cereal varieties in relation to the fertilizer treatment with sheep dung (Table 9). Concerning δ¹⁵N, the large grains of both wheat varieties have slightly higher values in comparison to small grains. Barley does not show this trend, as δ¹⁵N of large and small grains are exactly the same. Concerning δ¹³C, the small cereal grains of the wheat and barley varieties consistently show lower values (more negative) than the large grains. The differences are more significant for wheat than for barley. In terms of Δ¹⁵C, this trend is of course reversed, as smaller grains have higher values than larger grains.

### Table 7

Average dimensions of cereal grains (length, width, thickness) in mm and their average mass (g), grown by Bedouin in ancient terraced wadi fields at Nahal Divshon. The respective standard deviation is presented between brackets.

<table>
<thead>
<tr>
<th>Site</th>
<th>Geomorphic Position of Field</th>
<th>Relative Runoff Water Supply</th>
<th>Cereal variety</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Tributary wadi</td>
<td>Less</td>
<td></td>
<td>Brown Wheat</td>
<td>6.11 (0.3)</td>
<td>2.94 (0.2)</td>
<td>2.57 (0.2)</td>
<td>0.034 (0.007)</td>
</tr>
<tr>
<td>1 Tributary wadi</td>
<td>Less</td>
<td></td>
<td>Two-row Barley</td>
<td>9.07 (0.5)</td>
<td>2.97 (0.2)</td>
<td>2.25 (0.2)</td>
<td>0.035 (0.009)</td>
</tr>
<tr>
<td>2 Main wadi</td>
<td>More</td>
<td></td>
<td>Brown Wheat</td>
<td>6.17 (0.5)</td>
<td>3.07 (0.3)</td>
<td>2.75 (0.3)</td>
<td>0.038 (0.008)</td>
</tr>
<tr>
<td>2 Main wadi</td>
<td>More</td>
<td></td>
<td>White Wheat</td>
<td>6.25 (0.3)</td>
<td>3.26 (0.2)</td>
<td>2.75 (0.2)</td>
<td>0.043 (0.009)</td>
</tr>
<tr>
<td>2 Main wadi</td>
<td>More</td>
<td></td>
<td>Two-row Barley</td>
<td>9.60 (0.6)</td>
<td>3.27 (0.1)</td>
<td>2.50 (0.2)</td>
<td>0.059 (0.015)</td>
</tr>
<tr>
<td>3 Main wadi</td>
<td>More</td>
<td></td>
<td>Two-row Barley</td>
<td>9.39 (1.0)</td>
<td>3.77 (0.4)</td>
<td>2.73 (0.3)</td>
<td>0.053 (0.013)</td>
</tr>
<tr>
<td>4 Tributary wadi</td>
<td>Less</td>
<td></td>
<td>Brown Wheat</td>
<td>6.08 (0.3)</td>
<td>2.96 (0.3)</td>
<td>2.57 (0.2)</td>
<td>0.033 (0.007)</td>
</tr>
<tr>
<td>4 Tributary wadi</td>
<td>Less</td>
<td></td>
<td>Two-row Barley</td>
<td>9.86 (0.7)</td>
<td>3.61 (0.2)</td>
<td>2.70 (0.2)</td>
<td>0.057 (0.014)</td>
</tr>
</tbody>
</table>

### Table 8

Stable isotope results of wheat and barley grains from the four controlled manuring treatments in pots. Cereal grains larger than the average were selected for these measurements, which also include percentages of C and N.

<table>
<thead>
<tr>
<th>Manuring Treatment</th>
<th>Cereal type</th>
<th>Lab #</th>
<th>%C</th>
<th>%N</th>
<th>δ¹³C</th>
<th>Δ¹³C</th>
<th>δ¹⁵N</th>
<th>Δ¹⁵N</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>White Wheat</td>
<td>64,760</td>
<td>42.1</td>
<td>2.7</td>
<td>-24.66</td>
<td>16.57</td>
<td>7.26</td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>Brown Wheat</td>
<td>64,751</td>
<td>42.2</td>
<td>2.7</td>
<td>-23.99</td>
<td>15.87</td>
<td>7.32</td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>Barley</td>
<td>64,752</td>
<td>41.8</td>
<td>1.9</td>
<td>-25.52</td>
<td>17.47</td>
<td>6.85</td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>White Wheat</td>
<td>64,756</td>
<td>42.3</td>
<td>2.5</td>
<td>-24.13</td>
<td>16.02</td>
<td>6.91</td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>Brown Wheat</td>
<td>64,757</td>
<td>42.0</td>
<td>2.4</td>
<td>-23.83</td>
<td>15.70</td>
<td>7.25</td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>Barley</td>
<td>64,758</td>
<td>42.1</td>
<td>1.8</td>
<td>-25.07</td>
<td>17.00</td>
<td>6.75</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>White Wheat</td>
<td>64,753</td>
<td>42.6</td>
<td>3.1</td>
<td>-23.75</td>
<td>15.62</td>
<td>7.72</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>Brown Wheat</td>
<td>64,754</td>
<td>42.5</td>
<td>2.8</td>
<td>-24.06</td>
<td>15.94</td>
<td>7.71</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>Barley</td>
<td>64,755</td>
<td>42.0</td>
<td>2.4</td>
<td>-25.01</td>
<td>16.93</td>
<td>7.28</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>White Wheat</td>
<td>64,759</td>
<td>42.3</td>
<td>2.9</td>
<td>-24.29</td>
<td>16.18</td>
<td>7.74</td>
<td></td>
</tr>
<tr>
<td>Mix (Dung &amp; Ash)</td>
<td>White Wheat</td>
<td>64,760</td>
<td>41.6</td>
<td>1.7</td>
<td>-24.53</td>
<td>16.43</td>
<td>3.90</td>
<td></td>
</tr>
<tr>
<td>Mix (Dung &amp; Ash)</td>
<td>Barley</td>
<td>64,761</td>
<td>42.5</td>
<td>2.0</td>
<td>-24.91</td>
<td>16.83</td>
<td>7.11</td>
<td></td>
</tr>
</tbody>
</table>

### Table 9

Average stable isotope values of small and large grains of the three cereal varieties resulting from the manuring treatment with sheep dung. The respective C and N percentages are also presented.

<table>
<thead>
<tr>
<th>Manuring Treatment</th>
<th>Cereal type and Grain Size</th>
<th>Lab #</th>
<th>%C</th>
<th>%N</th>
<th>δ¹³C</th>
<th>Δ¹³C</th>
<th>δ¹⁵N</th>
<th>Δ¹⁵N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dung</td>
<td>White Wheat - Small</td>
<td>64,762</td>
<td>42.0</td>
<td>3.0</td>
<td>-24.27</td>
<td>16.16</td>
<td>7.53</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>White Wheat - Large</td>
<td>64,753</td>
<td>42.6</td>
<td>3.1</td>
<td>-23.75</td>
<td>15.62</td>
<td>7.72</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>Brown Wheat - Small</td>
<td>64,763</td>
<td>42.3</td>
<td>2.8</td>
<td>-24.98</td>
<td>16.90</td>
<td>7.14</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>Brown Wheat - Large</td>
<td>64,754</td>
<td>42.5</td>
<td>2.8</td>
<td>-24.06</td>
<td>15.94</td>
<td>7.71</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>Barley - Small</td>
<td>64,764</td>
<td>42.1</td>
<td>2.2</td>
<td>-25.08</td>
<td>17.01</td>
<td>7.28</td>
<td></td>
</tr>
<tr>
<td>Dung</td>
<td>Barley - Large</td>
<td>64,755</td>
<td>42.0</td>
<td>2.4</td>
<td>-25.01</td>
<td>16.93</td>
<td>7.28</td>
<td></td>
</tr>
</tbody>
</table>
From among the terraced wadi fields farmed by the Bedouin in the 2014/15 season in the Nahal Divshon area, we selected four different fields. Sites 1 and 4 (Table 10, Figs. 6 and 9) are situated in fields, related to small tributary wadis next to Nahal Divshon, which received comparatively less runoff water. Sites 2 and 3 (Table 10, Figs. 6, 7, 8) are situated in fields within the main wadi of Nahal Divshon, which received comparatively more runoff water. The stable isotope results of the cereal crops at the four sites reflect remarkably well these hydrological differences.

Concerning $\delta^{13}C$ (Table 10), it is indeed very clear that sites 2 and 3, which received more runoff water, have the lowest values (most negative), ranging from $-24.34\%$ to $-25.50\%$. Various investigations in different parts of the world have shown that lower $\delta^{13}C$ values (more negative) relate to more rainfall or more soil moisture, see Hartman and Danin (2010) and their references. Site 3 in Nahal Divshon is located more upstream than site 2 and, therefore, received probably somewhat more runoff water, as suggested by a GIS hydrological study in other terraced wadis in the area (Bruins et al., 2019). Anyhow, cereal grains from Site 3 produced the overall lowest $\delta^{13}C$ value ($-25.50\%$) in our investigation and also the lowest $\delta^{15}N$ value (2.16‰), both of which support comparatively wetter soil moisture conditions (Table 10).

Sites 1 and 4, which received less runoff water, have the highest (least negative) $\delta^{13}C$ values, ranging from $-20.83\%$ to $-23.94\%$. The grains from these cereal crops suffered apparently more from drought stress, which caused increased closure of the stomata. This physiological process leads to relative enrichment of heavier $^{13}\text{C}$ with respect to the lighter $^{12}\text{C}$ isotope (Ferrio et al., 2005; Riehl et al., 2014). The corresponding $\Delta^{13}C$ values are listed in Table 10.

Evaluating $\delta^{15}N$ in relation to the degree of soil moisture, Hartman and Danin (2010) reported results from natural $C_3$ vegetation in Israel. Drier conditions tend to result in higher $\delta^{15}N$ values (on average about 3 to 7‰), while wetter environments give lower $\delta^{15}N$ values (on average about 1 to 3‰).

The drier field sites 1 and 4 in our study (Table 10), which received less runoff water, show indeed relatively high $\delta^{15}N$ values, respectively 8.77‰ (wheat), 6.92‰ (barley), and 7.37‰ (wheat), 3.60‰ (barley). Our data show that barley tends to have lower $\delta^{15}N$ values than wheat in each of the four field sites (Table 10). The wetter terraced field sites 2 and 3 exhibit the lowest $\delta^{15}N$ values in our results: 3.23‰ (wheat) and 2.16‰ (barley). Yet the results are not uniform, as two other $\delta^{15}N$ values in field site 2 are quite high: 7.27‰ (wheat) and 5.27‰ (barley). It seems, therefore, that factors other than soil moisture are also involved.

Though the Bedouin do not manure their wadi fields, they allow their flocks of sheep and goats to graze the stubble after the harvest during the dry summer and autumn months until they sow again. While grazing, the animals will drop randomly manure in some spots of the terraced fields. Here, the $\delta^{15}N$ values of cereal plants, growing in these spots after sowing during the next season, may be higher as a result.

### 7. Conclusions

An outstanding result of our research is the independent corroboration by experimental fertilizer studies of archaeological findings in ancient agricultural terraced fields at Horvat Haluqim in the central Negev desert (Bruins, 1986, 2007; Bruins and Jongmans, 2012; Bruins and Van der Plicht, 2017a, 2017b). This concerns the presence of plant ash and animal dung, interpreted as fertilizers, in ancient soil layers of terraced wadi fields. Our controlled pot experiments with four fertilizer variations (Table 1) showed that the combination of plant ash and sheep dung produced the largest cereal grains in terms of mass (Table 4) and overall dimensions (length, width, thickness; Table 5).

The addition of ash alone caused an increase in the number of grains per ear for both wheat varieties, as well as increased grain mass (Table 4). However, this effect was not noticed for barley. Concerning the number of tillers per plant, treatment ash resulted in the lowest number of tillers for white wheat and brown wheat, 2.3 and 2.4, respectively. On the other hand, treatment dung resulted in the largest numbers of tillers per plant, 3.8 for white wheat, 3.4 for brown wheat, and particularly for barley with a record average of 13.0 tillers per plant.

The effect of plant ash from a Bedouin fireplace on $\delta^{15}N$ values of cereal grains represents another novel element in our research. The addition of ash to the desert loess soil in the pot experiments resulted in lower $\delta^{15}N$ values than the baseline treatment “None” without fertilizers. The addition of sheep dung caused a systematic, albeit small, increase in $\delta^{15}N$ values. Large grains yielded a slightly higher $\delta^{15}N$ value than small grains in both wheat varieties, but two-row barley gave exactly the same $\delta^{15}N$ result for both large and small grains (Table 9). The combined addition of both “Ash & Dung” was found to have an irregular impact on $\delta^{15}N$ values of cereal grains (Table 8). A third novel element in our research is the effect of runoff water on the stable isotopes of cereal grains grown by Bedouin in terraced wadi fields at Nahal Divshon. Unlike the pot experiments, in which tap-water supply to all pots was similar, the terraced wadi fields received variable amounts of natural runoff rainwater. The three cereal varieties in our investigation were the same in both the pot experiments and the terraced wadi fields. Average plant height was clearly influenced by the amount of runoff water, as the cereal crops in the wetter field sites 2 and 3 tended to be taller than the same varieties in the drier sites 1 and 4 (Table 6).

Our results also showed that barley grains tend to have lower $\delta^{13}C$ and lower $\delta^{15}N$ values than wheat grains in both the fertilizer pot experiments and with runoff farming in the terraced wadi fields.

Concerning stable isotope results in relation to runoff water, cereal grains from the wetter sites 2 and 3 have the lowest $\delta^{13}C$ values, ranging from $-24.34$ to $-25.50\%$. The related $\Delta^{13}C$ values range from 16.24 to 17.44 (Table 10). On the other hand, cereal grains from the drier sites 1 and 4, which received less runoff water, have the highest $\delta^{13}C$ values, ranging from $-20.83$ to $-23.94\%$. The corresponding $\Delta^{13}C$ values range from 12.59 to 15.82. Compared with the controlled tap water irrigation in the pot experiments, resulting in $\Delta^{13}C$ values of grains ranging from 15.62 to 17.47‰, it seems that the drier wadi fields received less water (runoff), as $\Delta^{13}C$ values are as low as 12.59‰.

Concerning $\delta^{15}N$, the fields were not manured by the Bedouin. But there is a clear correlation in most cases with soil moisture variations of the studied terraced wadi fields, which received variable amounts of runoff water. The drier field sites 1 and 4 show relatively high $\delta^{15}N$
values: 8.77‰ (wheat), 6.92‰ (barley), 7.37‰ (wheat), 3.60‰ (barley). On the other hand, the wetter sites 2 and 3 yielded the two lowest δ15N values in our overall results: 3.23‰ (wheat) and 2.16‰ (barley). But two other δ15N values from the wetter sites are quite high (7.27‰ wheat and 5.27‰ barley). Therefore, it seems that other factors are also involved with respect to individual plants, possibly the spatially random manuring effect by sheep and goats. The animals are allowed to graze the stubble after the harvest, subsequently leaving fertilized spots (urine/dung) that may influence crops during the following growing season.

CRediT authorship contribution statement

Danielle van Bommel: Methodology, Writing - original draft, Writing - review & editing. Hendrik J. Bruins: Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing. Naftali Lazarovitch: Methodology, Supervision, Writing - review & editing. Johannes van der Plicht: Methodology, Supervision, Writing - review & editing.

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References


Johannes van der Plicht: Conceptualization, Methodology, Supervision, Writing – original draft, Writing: review & editing.


