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RESEARCH

Agricultural resilience and land-use from an Indus settlement in north-western India: Inferences from stable Carbon and Nitrogen isotopes of archaeobotanical remains

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Abstract

Stable isotopic compositions of carbon and nitrogen ($\delta^{13}C$, $\delta^{15}N$) of archaeological grains/seeds recovered from different cultural layers of an Indus (Harappan) archaeological site 4MSR (29°12'87.2"N; 73°9'421"E; Binjor, western Rajasthan, India) provide insights into the Harappan agriculture between ~2900 to ~1800 BCE. The $\delta^{13}C$ values were used to retrieve hydrological status, while $\delta^{15}N$ values were used to gauge agricultural intensification. Isotopic data of grains/seeds were generated representing three Indus phases (i) Early phase (~2900−2600 BCE), (ii) Transitional phase (~2600−2500 BCE), and (iii) Mature phase (~2500−1800 BCE). We find $\delta^{13}C$ values of barley grains (winter crop) varied in overlapping ranges for all the three phases −21.34‰ ± 1.9; −22.55‰ ± 1.6 and −22.75‰ ± 1.7 respectively (n=10 for each phase) indicating insignificant changes in hydrology for winter crops. For summer crops like cotton, average $\delta^{13}C$ values for Transitional phase −23.44‰ ± 1.8 were not significantly different from those of Mature phase −22.55‰ ± 2.5. The $\delta^{15}N_{barley}$ values varied in wider range, however, intra-phase variability appears to have overlapping values but showing overall increase from Early (7.72‰ ± 1.8) to Mature phase (11.17‰±7.2) indicating a plausible agricultural intensification. We also measured $\delta^{13}C$ of host soil organic matter (SOM) and sediment $\delta^{15}N$ to assess regional environmental conditions. In contrast to the trends observed for archaeological grains/seeds, $\delta^{13}C_{SOM}$ values showed a statistically significant enriching trend from Early (−23.54‰ ± 1.4) to Mature phase (−20.40‰ ± 1.9) hinting a growing aridity in the region. We surmise that Harappan farmers of western Rajasthan region might be managing arable hydrological conditions in their fields through agricultural interventions to continue agriculture practices despite growing aridity in the vicinity. The high proportion of water-demanding crop cotton during the Mature phase despite of changing environmental conditions, also corroborate our interpretation, possibly grown for the trade purposes.

Keywords Agricultural resilience · Land-use · Indus civilization · Late Holocene · Hydrology · Carbon and Nitrogen isotopes

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Introduction

Evidences of first organized life-style and agrarian human subsistence are found since the beginning of the Indus Civilization that spread along the Indus and the Ghaggar-Hakra river systems (along the present day India-Pakistan international border) (Giosan et al. 2012; Levey and Burke 1959; Possehl 2002; Weber et al. 2010). While human subsistence during the Early phase was mainly dependent on agricultural and pastoral activities, the Mature phase witnessed a variety of artisan activities and trade of goods with other contemporary civilizations (Park and Shinde 2014). It has been argued that the Indus Civilization experienced significant shifts in the environmental conditions *i.e.* arrival of monsoonal dryness during the second half of the Mature phase which possibly led to migrations and decline of this civilization (Dixit et al. 2014; Enzel et al. 1999; Giosan et al. 2012; Kathayat et al. 2017; MacDonald 2011; Petrie et al. 2017; Pokharia et al. 2017; Possehl 2002; Sarkar et al. 2016; Sharma et al. 2020a; Singh et al. 1971; Staubwasser et al. 2003; Wright 2010). Did these environmental changes affect agricultural strategies and production, especially from the Early to Mature phase of the Indus era? While palaeoclimatologists are broadly in agreement about monsoonal dryness prevailing during the latter part of the Mature phase (Dixit et al. 2014; Giosan et al. 2012; 2018; Gupta et al. 2003; Kathayat et al. 2017; MacDonald 2011; Sarkar et al. 2016; Staubwasser et al. 2003 Wasson et al. 1984), archaeo-botanists continue to debate its impact(s) on agriculture (Petrie and Bates 2017; Petrie et al. 2017; Pokharia et al. 2011, 2014, 2017; Sharma et al. 2020a; Singh et al. 1971, 1974). These studies yield two schools of thoughts: (i) monsoonal climate played a major role in shaping up the Harappan life-style, especially its subsistence (Bates et al. 2017; Kaushal et al 2019; Petrie and Bates 2017; Petrie et al. 2016; Pokharia et al. 2011, 2014, 2017; Sharma et al. 2020a; Sarkar et al. 2016; Weber 2003) and (ii) Harappan farming ironically arrived during deteriorating monsoonal conditions and was adaptive in nature, since its inception. Geological records largely support the latter view (Berkelhammer et al. 2012; Dixit et al. 2014; Enzel et al. 1999; Giosan et al. 2012, 2018; Gupta et al. 2003; Kathayat et al. 2017; MacDonald 2011; Prasad and Enzel 2006; Staubwasser et al. 2003).

In this communication, we present stable C and N isotopic data of archaeological grains/seeds recovered from an archaeological site 4MSR of western Rajasthan (India) which tends to reinforce the latter hypothesis. In addition to these, we also measured C and N isotopes of soils derived from host habitational sediments. The study site is a rural settlement, it can be well expected that archaeological/ habitational soil-sediments recovered from different cultural layers would have come from nearby arable land. Combined usage of C and N isotopes of crops vis-à-vis host soil-sediments from the studied archaeological site was aimed to provide an integrated information about cropping pattern and agro-hydrological status in the arable Harappan agriculture fields (Agnihotri et al. 2021; Wang et al. 2008). Where macro-botanical grains are expected to provide information about past crop-hydrological status, C and N isotopic data (along with their contents *viz.* TOC% and TN%) of soils recovered from different cultural periods may provide information about contemporary ecological status *i.e.* vegetation type (C-3 versus C-4) and in turn dryness of soils (Agnihotri et al. 2021; Araus et al. 1997; Ma et al. 2012; Parker et al. 2011; Peukert et al. 2012; Pokharia et al. 2017; Rosen et al. 1999; Simpson et al. 1999; Styring et al. 2016; Wang et al. 2008). This rationale is predominantly based on the principle that C isotopic data is a good indicator of palaeo-hydrology and vegetation type (Ferrio et al. 2005; Ma et al. 2012; Parker et al. 2011; Wang et al. 2008) and N isotopic data of plants/crops and soils can be governed by both environmental factors as well as agricultural amendments employed in agricultural fields such as manuring, irrigation etc. (Araus et al. 1997; Aguilera et al. 2008, 2017; Bogaard et al. 2013; Ferrio et al. 2005; Lee et al. 2005; Riehl et al. 2014; Styring et al. 2016, 2017; Wang et al. 2008; Wallace et al. 2013, 2015).

The isotopic values ($\delta^{13}C$) can be influenced by different environmental and biological factors, such as light, altitude, temperature water-logging, salinity, atmospheric CO_2 concentration, nutrient availability, genotypically and environmentally determined physiological characteristics of the species. (Jones et al. 2021 and reference therein). Semi-arid conditions of the studied site 4MSR (Binjor) situated on the bank of dried Ghaggar river channel (~160 km away from the major urban centre of Indus Civilization *i.e.* Harappa town) could be an ideal locale to investigate agricultural manifestations (advancements in agricultural practices) versus hydrological status of agricultural fields in the past. For the 4MSR site, twelve (12) cultural layers were identified by archaeologists based on the material culture (such as pottery type, tools, seals etc.) and these cultural layers cover a total time span from ~2900 BCE to ~1800 BCE. Scientific chronologies of cultural layers were established by a combination of AMS and conventional radiocarbon dating of macro-botanical remains and soil organic matter recovered from nine strata (Sharma et al. 2020a and b).

It has to be noted that the majority of the archaeological researches carried out on Indus valley sites provide a host of information about their material-culture, advent of metal technologies, architectural prowess, trade, and overall socio-economic status of ancient settlers (Agarwal 1971; Asthana 1993; Bhan et al. 2002; Giosan et al. 2012; Kenoyer and Miller 1999; Lal et al. 2003; Marshall 1931; Possehl 2002; Sana Ullah 1931, 1940; Sharma et al. 2020b; Shinde 2016; Vats 1940). To the best of our knowledge, studies on Indus agronomy, crop-diversity, strategies on intensification are relatively sparse (García-Granero et al. 2016; Miller et al. 2006, 2015; Petrie and Bates 2017; Petrie et al. 2016; Weber et al. 2010). This study provides the first combined set of C and N isotopic data of Indus crops from a well dated archaeological site spanning the beginning of Early phase to the end of Mature phase. We also made an attempt to contextualize the derived palaeo-agricultural information with available knowledge gleaned from contemporary European and Chinese archaeological sites.

Chronology, archaeological background and macro-botanical details

The site 4MSR (29°12'87.2"N; 73°9'421"E), is situated in the dry alluvial bed of the Ghaggar river in western

Rajasthan (Fig. 1A). This area along the India-Pakistan border of western Rajasthan (District Anupgarh) is known to be a semi-arid region. Based on ^{14}C dating of charcoal, archaeological grains (barley, wheat and rice) and habitational soil-sediments, chronology of all the twelve cultural layers were ascertained (please see supplementary Table 1S). The total time-span covered by the obtained chronology has been subdivided into three time-windows following traditional Indus chronology (Kenoyer 1991a, b). According to this convention, three periods are: the Early phase ca. ~2900−2600 BCE; Transitional phase ~2600−2500 BCE and the Mature phase ~2500−1800 BCE. Fig. 1B, contour map of the site show an excavated trenches with stratigraphic details from natural bed sediment to modern humus *i.e.* decreasing depth in mean sea level unit. Section in the Fig. 1C and D show the location of soil-sediment sample collected from the Early, Transitional and Mature phase stratigraphic cultural layers. As stated earlier, there are twelve distinct identified cultural layers. The upper layers (one to four) stored remnants of the Mature phase, while the middle layers (five to seven) represented a Transitional phase followed by deeper cultural layers belonging to the Early phase of the Indus era.

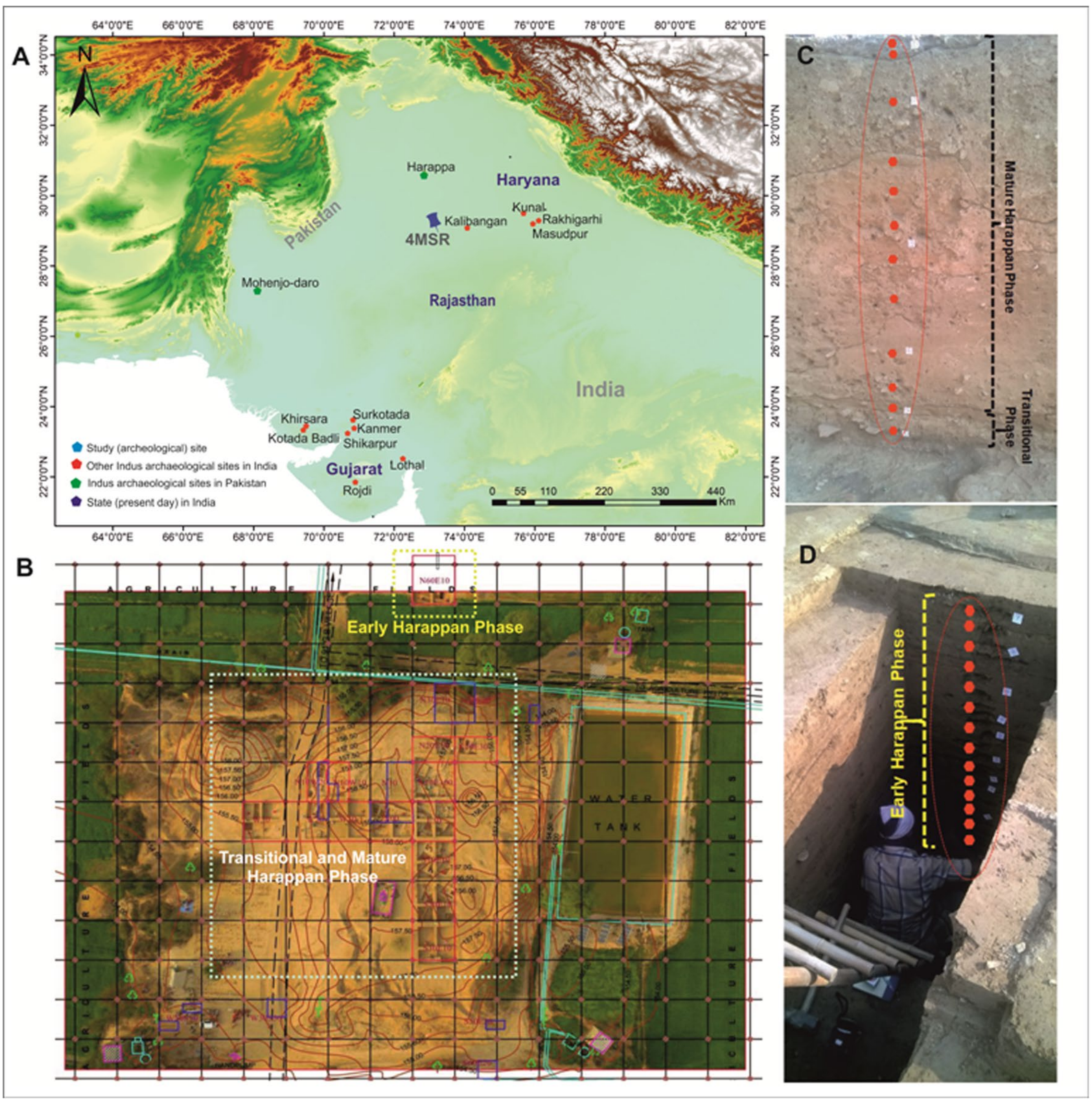

Fig. 1 **A** Map showing location of archaeological site 4MSR, Rajasthan along with other Indus sites (created by using mapping software *ArcGIS 10.3*). **B** Contour map of the site showing aerial view of the excavated trenches taken by drone. **C** Section shows the location of sample collection from the Mature Harappan and Transitional phase stratigraphic layers. **D** Trench representing the sample collection area from the Early Harappan phase deposit

Several studies have been conducted along the palaeochannel of the Ghaggar (erstwhile Saraswati) river, originating in the northwest Himalayas and is supposed to have flown southwest towards the Gujarat Kachchh region (Chatterjee et al. 2019; Ghose et al. 1979; Giosan et al. 2012; Gupta et al. 2004; Joshi et al. 1984; Kar et el., 2004; Lal 2002; Marshall 1931; Oldham 1886, 1893; Possehl 1999; Singh et al. 2017; Yashpal et al. 1980). This relict channel is thought to have catered to several phases of human settlements of the Indus culture in north-western India (Giosan et al. 2012; Lal et al. 2003; Marshall 1931; Mughal 1997; Possehl 2002, Sharma et al. 2020a; Vats 1940 and references therein). The site 4MSR (locally known as Binjor) evolved from a typical agricultural settlement to a major rural craft production centre that manufactured copper artefacts, beads from semi-precious stones and a wide variety of terracotta products and may have exported them to other urban Harappan sites nearby and far-flung areas. A large series of different shapes of hearths, furnaces and kilns with a cluster of multi-purpose workshops for industrial activities indicate a large rural metal-working settlement at the site 4MSR (Sharma et al. 2020b). A range of recovered artifacts of gold and copper, seashells and terracotta such as pendant frames, earrings, beads, spacers, chisels, bangles, needles, fish hooks, big storage pots, twin pots, broken perforated jars, terracotta beads and broken terracotta bangles, weights, seals, terracotta toys (humped bulls) confirmed the industrial nature of the site (Sharma et al. 2020b).

The macro-botanical assemblage recovered from the site is shown in supplementary Fig. 1S (data adopted from Sharma et al. 2020a). In total 199 macro-botanical samples were collected by floating 7122 L (990 L from Early phase, 1825 L from Transitional phase and 4307 L from Mature phase levels) of sediment volume, systematically from different cultural contexts (floors, hearths, pits) during the course of excavation. However, only 156 samples (Early phase=13, Transitional phase=32, and Mature phase=111) yielded the macro-remains (Sharma et al. 2020a). The assemblage was comprising of a variety of cereals and leguminous crops, *viz.*, *Hordeum vulgare*, *Triticum aestivum/durum*, *Oryza sativa*, *Setaria* sp., *Pisum arvense*, *Lens culinaris*, *Cicer arietinum*, *Lathyrus* sp. and *Vigna* sp., etc. Besides these, oleiferous and fibrous crops, *viz., Sesamum indicum*, *Linum usitatissimum* and *Gossypium* sp. were also been recorded (Sharma et al. 2020a). Fig. 2 (data adopted from Sharma et al. 2020a) presents pie charts depicting relative proportions of Indus summer (*Oryza sativa*, *Setaria* sp., *Vigna* sp., *Gossypium* Sp., and *Sesamum indicum*) and winter (*Hordeum vulgare*, *Triticum* sp., *Pisum arvense*, *Lens culinaris*, *Cicer arietinum*, *Lathyrus* sp. and *Linum usitatissimum*) crop species during the Early, Transitional and the Mature phases. It is noteworthy here that summer crops appear to have introduced mainly during the Transitional phase (Fig. 2B). Intensification and diversification of various crops appear to dominate Indus croplands belonging to the Mature phase (Fig. 2C). Presence of *Gossypium* sp. show an exponential increase from Early to Mature phase is also noteworthy from this rural industrial site (Fig. 2). The abundance of *Gossypium* seeds during the Mature phase suggests their prolonged cultivation as a fibrous crop owing to favourable climatic conditions. Being an indigenous crop, *Gossypium* has great importance for agriculture, industry and trade, especially for tropical and subtropical regions. This huge proportion of *Gossypium* comparing to other cereals and legumes indicate its extensive usage plausibly for trade purposes. The exploitation of *Gossypium* fabric has also been recorded from

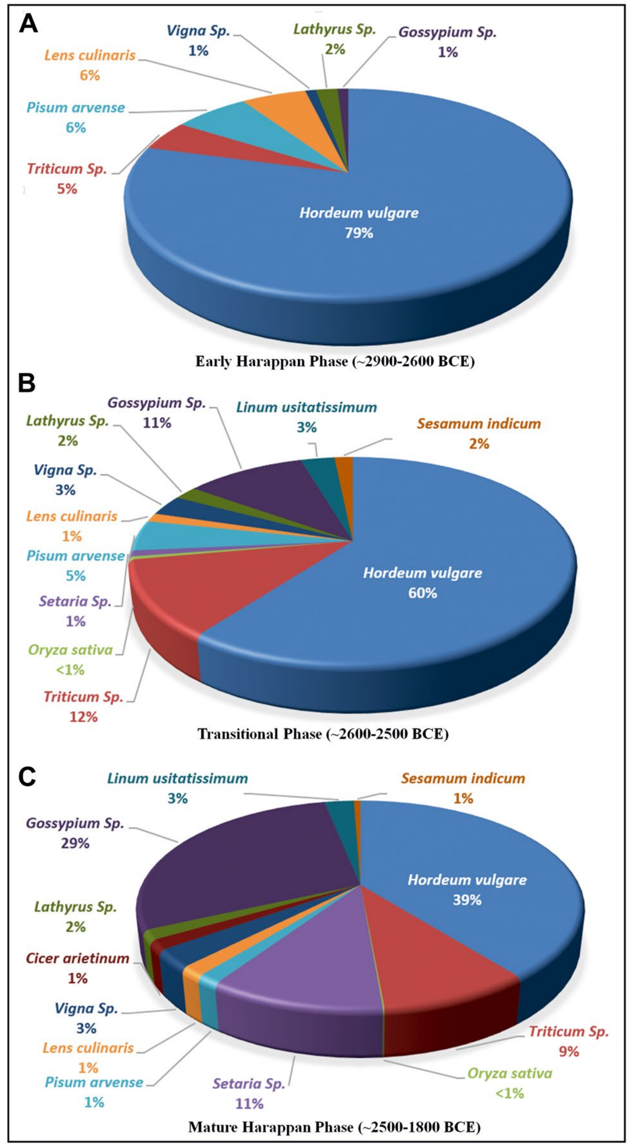

Fig. 2 Pie charts showing the relative proportion of crop species during (A) Early phase (absolute count n=109), (B) Transitional phase (absolute count n=438), and (C) Mature phase (absolute count n=1051) of Indus era recovered from the site 4MSR (modified from Sharma et al. 2020a)

several other Indus archaeological sites. Potsherd with the impression of a fabric corroborates the macro-botanical finds recovered from the site and also indicates intensive usage/trade, as this site was an industrial centre and might have involved in the trade activities. The 4MSR archaeological site has yielded various metal artifacts along with a variety of domestic hearths from the cultural layers belonging to the Mature phase of the Indus era (Sharma et al. 2020a and b).

Materials and Methods

Macro-botanical remains are large enough to be recognized with the naked eye or low-powered microscope (Ford 1979; Fritz 2005; Pearsall 2000). The macro-botanical samples (archaeological grains/seeds; supplementary Fig. 1S) were collected from all the excavated trenches. Major collection areas were floor, hearths and pits (belonging to the Mature phase; from topmost cultural layer number 1 to number 4), soils of the Transitional phase (layer number 5 to 7) and the Early phase (deeper cultural layers number 8 to 12). Botanical grains/seeds were separated from soil using water floatation technique in the field itself (Sharma et al. 2020a). Segregated samples were identified as per taxonomical classification up to the genus and species level and photo-documented (Sharma et al. 2020a). For carbon and nitrogen stable isotopic measurements, segregated archaeological grains of barley (winter crop; n=10), seeds of cotton (summer crop; n=10) and tiny vetch (leguminous weed; n=10) were considered. Well-preserved grains and seeds (preservation grade P3) of aforementioned three taxa were selected for isotopic analysis in order to ensure accurate identification and to minimize any possible isotopic offset from badly preserved grains produced in higher temperatures (Hubbard and Al Azm 1990). Binning of grains/seeds was done to represent different phases of the Indus era *i.e.* Early, Transitional and Mature phase. It is noteworthy that even though the study site falls under the semi-arid region of western Rajasthan (District Anupgarh), the modern-day landscape appears to be significantly influenced by the Indira canal in the vicinity (since 1980s) which changed arable fields into lush green farm lands (Fig. 1B) (Anonymous 2021).

We also collected soil-sediments from all the twelve stratigraphic cultural layers along with the natural bed sediment (beneath the oldest (bottommost) cultural layer of Early phase) and sediment belonging to modern humus from the vicinity of the archaeological site for measuring their C and N isotopic compositions. The site 4MSR is situated in the dry alluvial bed of the Ghaggar river (Ali 1941; Oldham 1893) which is now extinct. During its active phase, the channel was receiving waters and alluvium from the Himalaya (Kar 2011; 2014). The alluvium of this dry bed is of variable texture mainly representing from sandy loam to clayey sediments (Shyampura and Sehgal 1995). The surface soil in the area is fertile for agriculture (Anonymous 2021).

Carbon and Nitrogen isotopic analyses of archaeological grains/seeds and soil-sediments

We measured the $\delta^{13}C$ and $\delta^{15}N$ values along with C and N contents of archaeological grains/seeds (and soil-sediments) using an Elemental Analyzer (EA; Pyrocube®, Elementar® Germany) coupled with Isotope Ratio Mass spectrometry (EA-IRMS; Precision®, Elementar® UK) in continuous flow mode. A total of seventy (70) archaeological grains/seeds (of barley, cotton, tiny vetch) were collected from different cultural layers representing all the three phases (Early, Transitional, and Mature). The well-preserved grains and seeds (n=10) of each taxon (barley, cotton and tiny vetch) have been extracted randomly from the different samples of each phase (Early, Transitional and Mature) to cover the broad cultural stretch. The archaeological grain/seed samples were mildly washed to remove any adhering dirt/soil because these samples were collected by the water floatation technique which has already removed the soil from the grain/seed samples. The washed grains/seeds were then dried at 60 °C for 48 hours and then stored in vials. The dried grain samples were mildly powdered using an agate mortar and pestle. ~0.2-1.0 mg weights of these were taken in clean tin cups, which were subsequently pressed into oval shaped pellets. Hence, due to sandy loam nature of soil and ease with which it was cleaned from grain/seed samples, no chemical pre-treatment was carried out to further clean them (such as etching). We followed the analysis with mild cleaning and without pre-treatment to avoid any alteration in the original isotopic compositions as it is reported that there is no significant effect of using pre-treatments to remove contamination from entire or powdered grains (Aguilera et al. 2017). Although Vaiglova et al. (2014) observed the mean differences of 0.2‰ for the archaeological barley between the untreated and treated samples. However, the acid treatment itself cause the alteration in the $\delta^{13}C$ signals of cereal grains, *e.g.* the cereal grains treated with the lowest concentration of HCl (1 M) recorded a mean value of −23.17‰, while a strong acid treatment (6 M HCl) gave slightly more positive mean value −23.06‰ (Aguilera et al. 2017). Therefore, to avoid the alteration of the original signal we decided to not follow the chemical pre-treatment of the samples. It is also important to mention that the process of carbonization do not affect the $\delta^{13}C$ values in cereal grains significantly within the range of temperatures between ~~200–400°C) (Araus et al. 1997; Aguilera et al. 2008; Ferrio et al. 2007). There are studies (Charles et al. 2015; Fraser et al. 2013; Kaushal et al. 2019) that have demonstrated that lower charring temperatures between 200-240°C (for about a duration of six hours) under reducing conditions produce morphologically intact carbonized grains. For $\delta^{15}N$ signal also, Bogaard et al. (2007) reported insignificant changes for grains carbonized at 230°C for up to 24 hours. Therefore, we chose morphologically intact (well-preserved) archaeological carbonized grains/seeds only upto the preservation class three (Hubbard and Al Azm 1990) for isotopic analyses. It is important to underscore that earlier archaeo-isotope workers have not catagorically reported any significant differences between pre-treated and non-treated grains samples (Aguilera et al. 2017; Kaushal et al. 2019; Lightfoot and Stevens 2012; Masi et al. 2014).

Samples of host soil-sediments, however, were pre-treated *i.e.* subjected to decalcification to measure the $\delta^{13}C_{SOM}$ values (Agnihotri et al. 2021). For this, ~1-2 grams of dried/homogenized sediment aliquots (without sieving to avoid biasness) were treated with 5% Hydrochloric acid and kept for ~8-10 hours (overnight) at room temperature. Treated samples were then washed several times with deionised water to remove any excess of chloride ion. Washed sediment samples were then again dried in an oven at ~50-60°C followed by mildly re-powdering with a pestle in an agate mortar. Finally grounded powders were dried and dried powders were then transferred in clean plastic vials. A total of 51 samples were analysed on EA-IRMS. Data quality of measured C and N contents together with $\delta^{13}C$ and $\delta^{15}N$ values was checked throughout the analysis using a suite of *in-house* and international IAEA standards. Accuracy of measured $\delta^{13}C$ and $\delta^{15}N$ data was better than 0.2‰, and for elemental concentrations, it was better than 5% (based on duplicate analysis). Detailed methodology of the used EA-IRMS facility is published elsewhere (Agnihotri et al. 2020). The isotopic data are reported using the standard delta notations. Standard for determining C isotopic data is Vienna-PDB, while N isotopic data is normalized with $^{15}N/^{14}N$ ratio of atmospheric N_2 (Tables 1 and 2). Chemical and isotopic data are arranged phase wise, constrained by cultural identification of habitational layers (based on materials such as pottery, seal, metal objects etc.) and the determined radiocarbon chronology (Sharma et al. 2020a; Tables 1 and 2).

Estimation of carbon isotope discrimination factor ($\Delta^{13}C$)

We computed the $\Delta^{13}C$ values using measured $\delta^{13}C$ values of crop grains/seeds to evaluate crop-water status (Aguilera et al. 2008; 2012; Farquhar et al. 1989; Ferrio et al. 2005; Styring et al. 2016; Wang et al. 2008). $\Delta^{13}C$ values were computed following Farquhar et al. (1989) using the formula-

$$\Delta^{13}C = (\delta^{13}C_{air} - \delta^{13}C_{plants})/(1 + \delta^{13}C_{plants}/1000) \quad (1)$$

Past $\delta^{13}C_{air}$ values were inferred by interpolating a range of data from Antarctic ice-core records together with modern data from two Antarctic stations (Halley Bay and Palmer Station) of the CU-INSTAAR/NOAA-CMDL network for atmospheric CO2 (ftp://ftp.cmdl.noaa.gov/ccg/co2c13/flask/readme.html). In fact, slightly different $\delta^{13}C_{air}$ values for the Early and Mature Harappan phase (−6.3‰ and −6.4‰ respectively) were used. We used estimated $\Delta^{13}C_{crop\text{-}remains}$ values to ascertain crop-water status (Araus et al. 1997; Aguilera et al. 2008, 2017; Ferrio et al. 2005; Lee et al. 2005; Riehl et al. 2014; Styring et al. 2016, 2017; Wang et al. 2008; Wallace et al. 2013, 2015).

Indus landscapes were resource-rich (in terms of availability of fertile soil and seasonal rainfall in both summer and winters). Numerous archaeological evidences reveal Harappan settlers were using water management practices in dwelling areas as well as in farming (by channelling of river water to crop fields or using ground waters for irrigation purpose). For instance, Harappans apparently evolved a more developed irrigation technology than their predecessors that allowed to exploit the spacious and fertile Indus River basin (Kenoyer 1991b). The network of dams, canals and reservoirs at Indus site at Dholavira indicates elaborated water management system during the Indus time (Bisht 1998–1999). Hence, human efforts might have played a significant role to manage agriculture activities required to feed communities. Several recent studies attempted to glean clues about changes in past agronomy under the changing monsoonal climate (Pokharia et al. 2017; Sarkar et al. 2016; Sharma et al. 2020a). These studies remained devoid of any numerical data to compare hydrological status of Indus farmlands.

Statistical analyses

We conducted non-parametric One-way ANOVA test (Kruskal-Wallis test) which investigates population of data categorized among different phases by retaining or rejecting the null hypothesis. These statistical validation tests were performed for both C and N isotopic data generated for grains/seeds as well as sedimentary layers using SPSS software (version# 21).

Results

Measured $\delta^{13}C$ and $\delta^{15}N$ values along with the estimated $\Delta^{13}C$ values of archaeological grains/seeds *viz.* barley, cotton, and tiny vetch from all the three phases (Early, Transitional and Mature) are presented in the Table 1. Tiny vetch is an associated leguminous weed of winter crops like barley, wheat, gram and lentil (Zohaib et al. 2014). The crop-water

Table 1 Measured $\delta^{13}C$ and $\delta^{15}N$ values along with the estimated $\Delta^{13}C$ values of archaeological barley, cotton and common/tiny vetch (weed) grains/ seeds. Total number of grains/seeds $n = 10$ has been selected for each crop/ weed from all the three phases. (Abbreviations: Total Nitrogen (TN%), Total Carbon (TC%), Carbon/Nitrogen (C/N weight ratios)

Sample ID	TN (%) (Measured)	$\delta^{15}N$ (‰) (Measured)	TC (%) (Measured)	$\delta^{13}C$ (‰) (Measured)	$\Delta^{13}C$ (‰) (Estimated)	C/N (Calculated)
***Hordeum vulgare* (Barley)**						
Early Harappan Phase						
BE-1	1.9	7.9	47.5	-21.5	15.5	24.5
BE-2	1.7	8.4	43.8	-18.9	12.8	26.3
BE-3	1.8	8.1	46.9	-21.2	15.2	25.5
BE-4	1.2	8.4	41.4	-21.3	15.3	35.5
BE-5	2.0	6.4	49.1	-20.5	14.5	24.9
BE-6	3.1	9.2	43.9	-18.3	12.3	14.2
BE-7	1.5	11.0	42.8	-22.2	16.2	28.3
BE-8	1.9	7.0	46.4	-21.2	15.2	24.1
BE-9	0.9	4.8	38.4	-24.5	18.7	41.5
BE-10	2.1	5.8	40.4	-23.9	18.0	19.7
Transitional Phase						
BT-1	1.7	6.6	43.5	-23.9	18.0	25.0
BT-2	2.7	7.3	51.9	-21.6	15.6	19.2
BT-3	1.5	8.4	45.0	-24.4	18.6	29.4
BT-4	1.6	12.8	46.6	-22.6	16.7	30.0
BT-5	2.5	12.7	45.6	-20.0	14.0	18.0
BT-6	4.0	5.3	43.1	-19.7	13.7	10.7
BT-7	2.1	6.7	45.0	-23.1	17.2	21.5
BT-8	2.2	7.5	46.0	-22.6	16.7	20.5
BT-9	2.0	7.3	43.4	-24.1	18.3	21.3
BT-10	3.0	6.9	43.0	-23.4	17.5	14.5
Mature Harappan Phase						
BM-1	3.2	4.9	48.4	-20.0	13.9	15.3
BM-2	1.9	7.7	43.4	-21.6	15.5	22.3
BM-3	2.8	13.3	43.2	-21.9	15.8	15.5
BM-4	2.0	6.1	41.5	-24.3	18.3	20.7
BM-5	1.7	30.3	44.7	-24.1	18.2	26.3
BM-6	2.5	10.4	48.7	-23.2	17.2	19.8
BM-7	2.5	8.0	55.0	-23.7	17.7	22.3
BM-8	3.0	9.0	48.2	-25.5	19.6	15.9
BM-9	1.8	12.6	47.6	-22.3	16.2	26.5
BM-10	2.9	9.4	39.7	-21.0	14.9	13.8
***Vicia* sp. (common/tiny vetch, weed)**						
Transitional Phase						
VT-1	4.2	4.7	44.9	-21.6	15.6	10.7
VT-2	5.5	5.6	43.5	-20.0	14.0	7.9
VT-3	3.9	1.0	40.3	-22.5	16.5	10.3
VT-4	5.0	1.6	43.9	-24.5	18.7	8.8
VT-5	4.4	10.5	44.1	-23.7	17.8	9.9
VT-6	5.2	4.1	44.7	-22.5	16.6	8.6
VT-7	5.3	4.3	40.1	-22.4	16.4	7.5
VT-8	5.0	1.6	40.8	-23.7	17.9	8.2
VT-9	4.5	5.9	40.6	-24.7	18.9	9.0
VT-10	4.8	2.6	37.6	-23.4	17.5	7.8
Mature Harappan Phase						
VM-1	1.9	1.8	18.3	-23.8	17.8	9.7
VM-2	3.5	2.6	46.9	-24.1	18.1	13.2

Table 1 (continued)

Sample ID	TN (%) (Measured)	$\delta^{15}N$ (‰) (Measured)	TC (%) (Measured)	$\delta^{13}C$ (‰) (Measured)	$\Delta^{13}C$ (‰) (Estimated)	C/N (Calculated)
VM-3	4.2	0.8	42.7	-24.2	18.2	10.1
VM-4	4.8	0.8	41.8	-26.1	20.3	8.7
VM-5	4.7	1.1	41.4	-24.7	18.8	8.8
VM-6	6.0	7.1	42.0	-24.4	18.5	7.0
VM-7	4.0	1.3	44.5	-24.7	18.8	11.2
VM-8	3.4	3.1	36.3	-21.4	15.3	10.6
VM-9	4.0	3.6	40.4	-23.3	17.3	10.0
VM-10	3.9	4.5	31.8	-22.9	16.9	8.1
***Gossypium* sp. (Cotton)**						
Transitional Phase						
GT-1	4.3	1.2	45.8	-22.7	16.7	10.6
GT-2	4.6	12.3	36.4	-23.0	17.1	8.0
GT-3	4.6	20.5	32.8	-24.2	18.3	7.1
GT-4	5.2	5.1	39.4	-23.3	17.4	7.5
GT-5	5.4	22.1	43.7	-24.5	18.6	8.2
GT-6	2.1	4.2	47.0	-25.1	19.3	22.4
GT-7	3.7	14.1	31.5	-20.5	14.5	8.4
GT-8	4.2	1.3	42.7	-24.8	19.0	10.2
GT-9	4.7		43.8	-20.5	14.5	9.3
GT-10	2.0	11.9	52.3	-25.8	20.0	25.6
Mature Harappan Phase						
GM-1	3.6	12.9	45.6	-25.1	19.2	12.5
GM-2	4.6	16.4	38.2	-20.1	13.9	8.3
GM-3	5.2	9.4	34.8	-23.1	17.1	6.7
GM-4	5.4	7.1	37.0	-23.8	17.9	6.8
GM-5	4.5	15.7	35.3	-20.0	13.9	7.8
GM-6	4.5	9.3	35.5	-22.0	16.0	7.9
GM-7	5.0	13.7	36.9	-19.1	13.0	7.3
GM-8	4.2	5.4	34.4	-22.4	16.3	8.2
GM-9	4.3	10.7	35.8	-22.6	16.6	8.3
GM-10	1.1	9.5	45.5	-27.2	21.4	39.9

status of the winter and summer seasons was assessed using $\Delta^{13}C$ values of barley and cotton crops, respectively. Measured $\delta^{13}C_{SOM\ and\ TC}$, $\delta^{15}N_{TN}$, Total Organic Content/Total Nitrogen (TOC/TN) or simply C/N weight ratios, Total Inorganic Content/Total Organic Content (TIC/TOC) values of soil-sediments from different cultural phases have been presented in the Table 2.

Fig. 3 shows the box-whisker plots of the measured $\delta^{13}C$ values of archaeological grains of barley and seeds of cotton and weed (tiny vetch) during the Early, Transitional and Mature phases. Average $\delta^{13}C$ values of barley for the Early, Transitional and Mature phases were found to be −21.34‰ ± 1.9, −22.55‰ ± 1.6 and −22.75‰ ± 1.7, respectively (Fig. 3A; Table 1). Thus, they were found to have varied in overlapping ranges which can be interpreted in terms of similar hydrological conditions throughout, albeit a marginally drier status for the grains of the Early phase. Summer crops appeared mainly during the Transitional phase (Sharma et al. 2020a) and average $\delta^{13}C_{cotton}$ values during the Transitional phase (−23.44‰ ± 1.8) were found to be marginally depleted compared to those during the Mature phase −22.55‰ ± 2.5, indicating better hydrological status of the Transitional phase (with respect to those in Mature phase) (Fig. 3G). No significant differences were found for the $\delta^{13}C$ values for both barley and cotton during all three identified phases. Statistical validations of the aforesaid statements were ascertained using non-parametric one-way ANOVA tests which retained the null hypothesis.

The $\delta^{13}C$ values of the weed plant (not sown/ seeded crop) 'tiny vetch' were also used to gauge environmental conditions of Harappan agricultural fields. Average $\delta^{13}C_{tiny\ vetch}$ values for the Transitional and Mature phase were −22.91‰

Table 2 Measured $\delta^{13}C_{SOM\ and\ TC}$, TC%, $\delta^{15}N_{TN}$ and TN% values along with calculated TOC/TN, TIC/TOC ratios of soil-sediments from different cultural phases at 4MSR, Rajasthan, India. (Abbreviations: SOM= Soil Organic Matter, TC= Total Carbon, TOC= Total Organic Carbon, TN=Total Nitrogen, TIC=Total Inorganic Carbon)

Sample ID	TN (mg/g)	$\delta^{15}N$ (‰)	TC (mg/g) bulk	$\delta^{13}C$ (bulk) (‰)	$\delta^{13}C$ (SOM) (‰)	TOC (mg/g)	TIC (mg/g)	TOC/TN	TIC/TOC
Humus (Modern) and Agricultural (wheat) field Sediment									
S1	26.4	7.3	549.4	-12.4	-25.2	159.3	390.1	6.0	2.4
S2	55.8	8.7	741.0	-9.5	-24.3	376.4	364.6	6.7	1.0
S3	41.2	7.6	851.7	-12.5	-25.3	597.7	254.0	14.5	0.4
S4	135.9	7.5	960.7	-15.6	-25.1	266.0	694.7	2.0	2.6
S5	47.1	7.4	674.5	-16.1	-25.8	289.5	385.0	6.1	1.3
S6	14.9	9.4	527.4	-6.6	-22.1	270.0	257.3	18.2	1.0
AF	40.1	8.5	684.0	-11.7	-23.5	153.6	530.4	3.8	3.5
Mature Harappan and Transitional Phase Sediment									
MH1a	42.6	8.7	875.4	-9.2	-18.6	580.0	295.4	13.6	0.5
MH1b	34.7	8.3	802.8	-6.1	-19.6	310.0	492.8	8.9	1.6
MH2	14.0	11.5	526.4	-7.1	-19.8	260.0	266.4	18.5	1.0
MH3a	30.5	14.0	767.7	-9.8	-21.4	415.0	352.7	13.6	0.8
MH3ax	15.9	14.0	892.4	-12.1	-20.9	310.0	582.4	19.4	1.9
MH3ay	2.5	16.2	219.6	-4.9	-23.2	80.0	139.6	31.7	1.7
MH3az	3.9	15.7	240.6	-6.1	-23.3	100.0	140.6	25.4	1.4
MH3b	18.9	11.0	605.3	-9.8	-21.1	280.0	325.3	14.8	1.2
MH4a	32.6	9.9	680.5	-8.1	-18.0	420.0	260.5	12.9	0.6
MH4b	35.4	10.5	1028.8	-12.1	-18.2	820.0	208.8	23.2	0.3
TP5	42.6	9.7	1222.3	-13.3	-22.5	620.0	602.3	14.6	1.0
TP6	25.0	8.5	870.0	-8.0	-22.8	370.9	499.1	14.8	1.3
Early Harappan Phase Sediment									
EH1	17.3	10.5	1359.2	-11.0	-24.2	305.8	1053.3	17.7	3.4
EH2	13.9	9.8	1861.4	-10.9	-23.5	383.4	1477.9	27.6	3.9
EH3	22.0	10.9	1207.8	-10.4	-24.5	521.8	686.0	23.7	1.3
EH4	23.0	9.7	765.2	-7.3	-23.2	248.0	517.2	10.8	2.1
EH5	16.7	7.7	602.7	-5.1	-24.0	122.4	480.3	7.3	3.9
EH6	10.7	6.9	545.2	-4.7	-22.9	174.2	371.1	16.2	2.1
EH7	9.6	14.5	559.0	-4.8	-25.1	113.6	445.5	11.8	3.9
EH8	17.4	9.2	840.8	-9.9	-23.1	378.6	462.2	21.8	1.2
EH9	15.9	14.1	716.8	-5.9	-24.4	153.3	563.5	9.7	3.7
EH10	26.7	7.8	740.6	-7.7	-23.1	286.4	454.2	10.7	1.6
EH11	15.6	7.3	658.6	-5.7	-24.8	108.0	550.6	6.9	5.1
EH12	16.5	6.8	868.0	-7.1	-23.8	164.3	703.7	10.0	4.3
EH13	33.5	6.7	893.2	-9.9	-19.2	462.0	431.1	13.8	0.9
EH14	17.0	8.1	1028.2	-7.4	-23.1	286.9	741.3	16.9	2.6
EH15	11.7	11.6	782.5	-7.4	-23.1	135.1	647.4	11.6	4.8
EH16	9.2	8.2	599.9	-3.2	-23.6	136.7	463.2	14.9	3.4
EH17	8.5	14.3	1266.7	-3.1	-24.1	91.6	1175.2	10.7	12.8
EH18	13.1	5.1	528.3	-3.2	-23.9	165.2	363.1	12.6	2.2
EH19	13.4	6.7	543.9	-3.4	-24.2	103.7	440.1	7.7	4.2
EH20	13.9	7.9	572.4	-3.7	-23.7	114.1	458.3	8.2	4.0
EH21	12.9	12.9	559.1	-2.8	-22.6	103.8	455.3	8.0	4.4
EH22	12.9	7.4	550.8	-4.9	-21.7	152.0	398.8	11.8	2.6
EH23	17.7	10.5	485.0	-3.6	-21.6	116.7	368.3	6.6	3.2
EH24	15.5	9.7	464.0	-3.9	-22.1	136.1	327.8	8.8	2.4
EH25	14.9	11.0	435.1	-3.3	-23.3	103.2	331.8	6.9	3.2

Table 2 (continued)

Sample ID	TN (mg/g)	$\delta^{15}N$ (‰)	TC (mg/g) bulk	$\delta^{13}C$ (bulk) (‰)	$\delta^{13}C$ (SOM) (‰)	TOC (mg/g)	TIC (mg/g)	TOC/TN	TIC/TOC
EH26	7.1	7.5	505.3	-3.3	-23.3	90.3	415.1	12.7	4.6
EH27	8.9	6.5	543.1	-3.4	-27.2	84.9	458.1	9.6	5.4
EH28	5.1	7.6	488.5	-3.0	-25.1	54.5	434.0	10.8	8.0
EH29	12.1	6.9	520.6	-3.3	-24.1	131.1	389.5	10.9	3.0
Bed Sediment									
BS1	1.9	-3.4	529.1	-3.0	-27.7	147.6	381.4	79.5	2.6
BS2	5.6	7.4	566.3	-3.0	-26.2	93.8	472.5	16.8	5.0
BS3	6.1	12.2	659.0	-3.2	-24.0	126.9	532.1	20.8	4.2

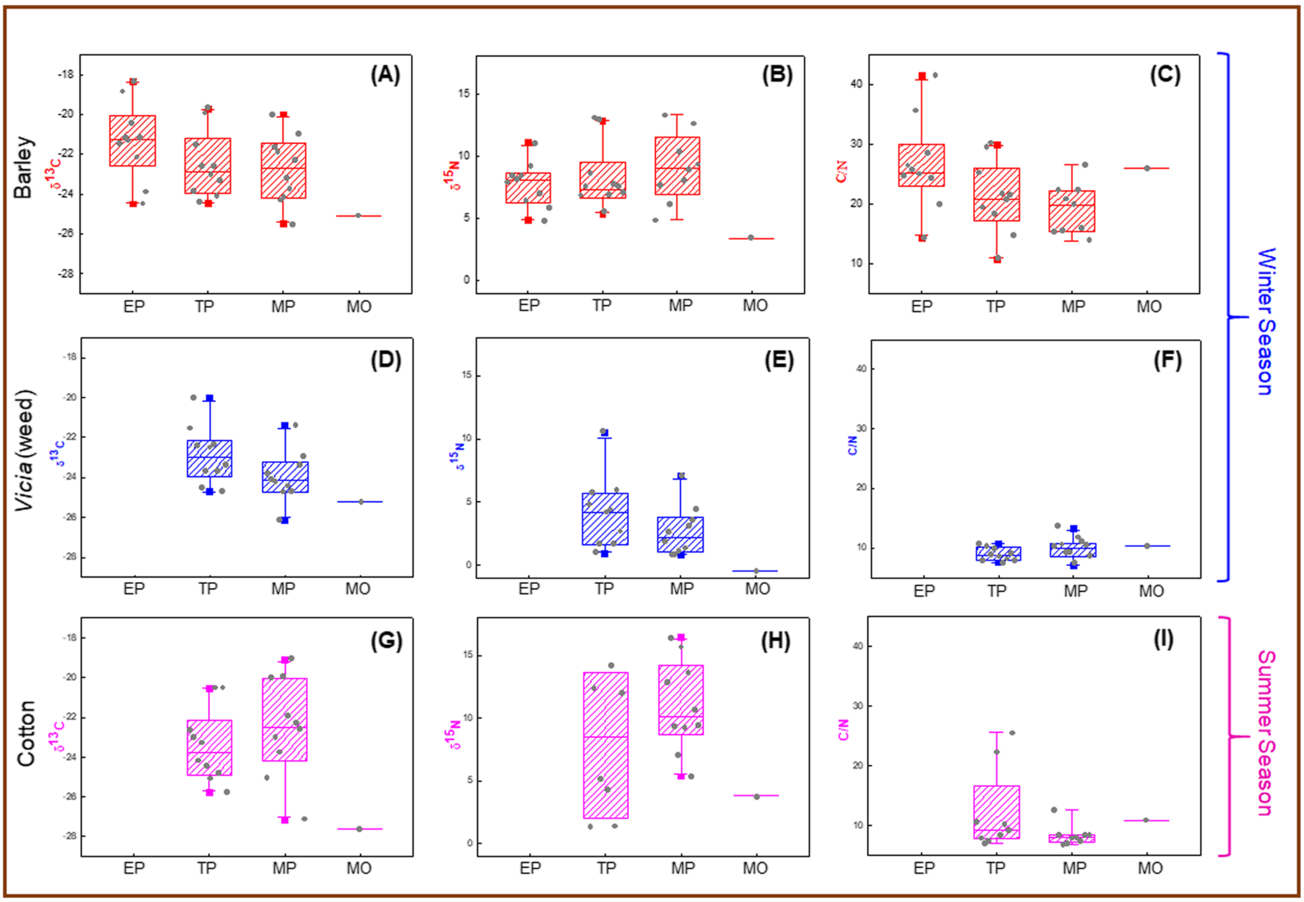

Fig. 3 Box-Whisker plots showing the $\delta^{13}C$ (A, D, G), $\delta^{15}N$ values (B, E, H), and C/N ratios (C, F, I) of barley, Vicia (common/tiny vetch) and cotton respectively, recovered from different cultural phases from the archaeological site 4MSR. Data points (shown in grey dots) display number of seeds/grains measured (*n*=10; for each crop and weed). The line inside the box represents median, upper half of the box represents upper quartile, while the lower half represents lower quartile. (Abbreviations: EP= Early Harappan Phase; TP= Transitional Phase; MP= Mature Harappan Phase; MO= Modern)

± 1.4 and −23.97‰ ± 1.3 respectively (Fig. 3D; Table 1). These values also indicated more or less similar hydrological status during the Transitional and Mature phases as yielded by the winter crop barley (Fig. 3 (A).

For comparing the hydrological status of Harappan crops grown at the site 4MSR with the hydrological status of crops (isotopic data) from other archaeological sites around the world, we used estimated $\Delta^{13}C$ values of barley, cotton and

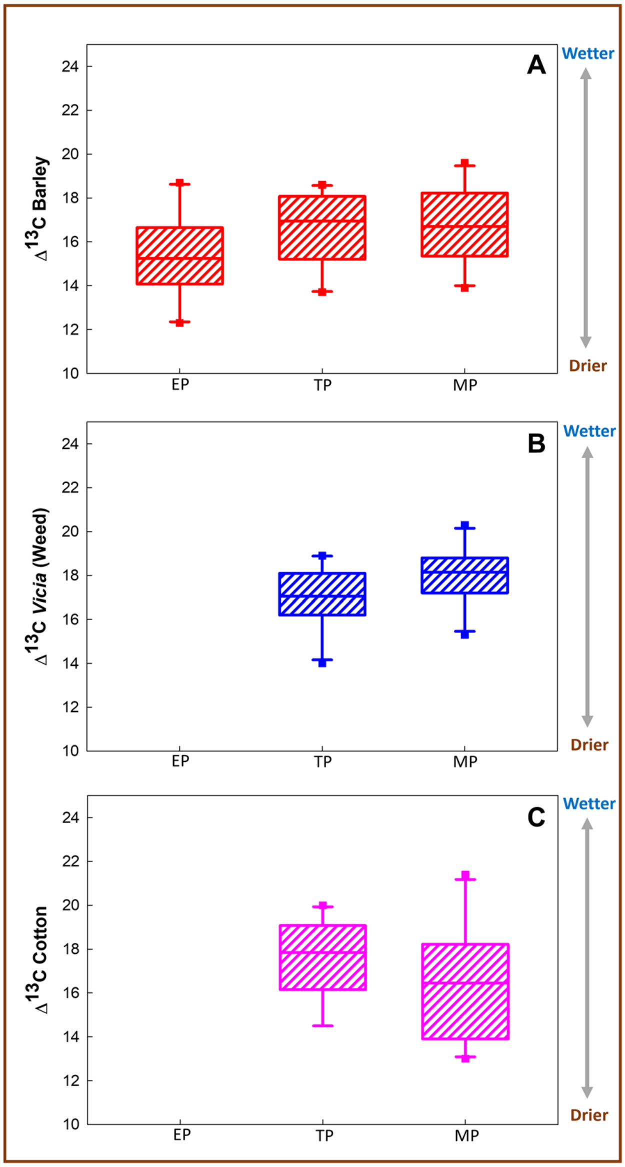

Fig. 4 Box-Whisker plots showing the Δ^{13}C (**A**, **B**, **C**) of barley, Vicia (common/tiny vetch) and cotton respectively (n=10; for each crop and weed), recovered from different cultural phases from the archaeological site 4MSR. The line inside the box represents median, upper half of the box represents upper quartile, while the lower half represents lower quartile. (Abbreviations: EP= Early Harappan Phase; TP= Transitional Phase; MP= Mature Harappan Phase)

tiny vetch during different phases (Fig. 4; Table 1). Estimated average Δ^{13}C values for barley from our study site were 15.37‰ ± 2.0, 16.63‰ ± 1.7, 16.74‰ ± 1.8 for the Early, Transitional and Mature phases respectively (Fig. 4A; Table 1). Intriguingly, values during the Early phase were found to be of drier hydrological status compared to those of the Transitional and Mature phases. For summer crop cotton, average Δ^{13}C values for the Transitional phase (17.55‰ ± 1.9) indicated a slightly wetter status compared to that of the Mature phase (16.53‰ ± 2.6) (Fig. 4C; Table 1). In contrast, average Δ^{13}C values of tiny vetch (weed) indicated a drier hydrological status of this winter crop for the Transitional phase compared to that of the Mature phase (17.00‰ ± 1.5 and 18.00‰ ± 1.3 respectively) (Fig. 4B; Table 1). It is important to mention here that these archaeobotanical samples were not pre-treated with any chemicals prior to analysis as there is no significant effect of using pre-treatments to remove contamination (Aguilera et al. 2017), however, there is study by Vaiglova et al. (2014) which reported the mean difference of 0.2‰ for the archaeological barley between treated and nontreated samples. Further, Masi et al. (2014) used estimated Δ^{13}C values to assess the growing conditions of fossil cereal grains without chemically pre-treating them. They also compared this data with the stable carbon isotope data available for other Near Eastern sites. Therefore, our data could be used to compare with other sites accordingly.

Fig. 5A shows box-whisker plots of measured δ^{13}C values of the soil organic matter along with sediment δ^{15}N values and C/N weight ratios from different cultural phases of the same occupation during the Indus era (Fig. 5B, C). C/N ratios of soils primarily indicate nature of soil, but they could also mimic environmental dryness *i.e.* higher the C/N ratio drier the soil is (Jiao et al. 2016). Average δ^{13}C values of soil organic matter during the Early, Transitional and Mature phases (−23.54‰ ± 1.4, −22.65‰ ± 0.3, −20.40‰ ± 1.9, respectively) depict a conspicuous enhancing trend from Early to Mature phase (Fig. 5A; Table 2). Statistical validation of aforesaid trend and distinctiveness of δ^{13}C values of soil organic matter during different phases (the Early, Transitional and Mature phases) was ascertained by the non-parametric One-way ANOVA test which rejected the null hypothesis ($p = 0.000$). This enhancing trend could be interpreted as prevailing aridity in the region and it is well supported by $\delta^{15}N_{soil\text{-}sediment}$ values which also show an increasing trend (validated by One-way ANOVA test; $p = 0.015$) from Early (9.10‰ ± 2.5) to Mature phase (11.98‰ ± 2.8) via Transitional phase (9.11‰ ± 0.9) (Fig. 5B; Table 2).

This increasing trend in $\delta^{15}N_{soil\text{-}sediment}$ could, however, may be due to complex mixture of environmental and agricultural intensifications (crop rotation and manuring activities) (Aguilera et al. 2008; Boggard et al. 2007, 2013; Bol et al. 2005; Choi et al. 2006; Fraser et al. 2011; Senbayram et al. 2008; Styring et al. 2016, 2019; Szpak et al. 2014). To investigate various possibilities, δ^{15}N values of archaeological grains were used in tandem with TN contents. Fig. 3B displays $\delta^{15}N_{barley}$ values during the Early, Transitional and Mature phases, (7.72‰ ± 1.8, 8.16‰ ± 2.5, 11.17‰ ± 7.2 respectively) fall within overlapping ranges (validated by one way ANOVA test; $p = 0.196$), but show an increase from Early to Mature phase. It could be, however, noticed that intra-phase variability in $\delta^{15}N_{barley}$ values (depicted by

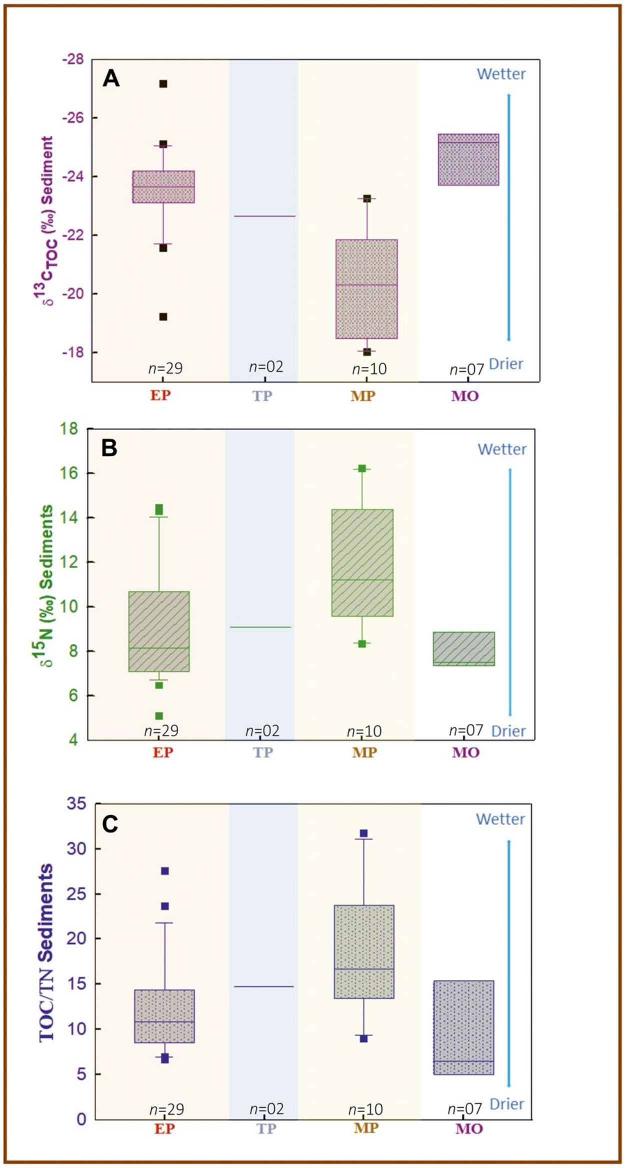

Fig. 5 Box-Whisker plots showing (A) $\delta^{13}C_{SOM}$, (B) $\delta^{15}N_{Sediment}$ values, and (C) $C/N_{Sediment}$ ratios of soil-sediments from different cultural phases. The line inside the box represents median, upper half of the box represents upper quartile, while the lower half represents lower quartile. The values lies outside the min and max range are outliers. (Abbreviations: EP= Early Harappan Phase; TP= Transitional Phase; MP= Mature Harappan Phase; MO= Modern)

standard deviations) overall increased from Early to Mature phase. Total Nitrogen contents of barley grains showed overlapping ranges from the Early (1.81% ± 0.6) to Transitional (2.34% ± 0.8) and then Mature phase (2.42% ± 0.5) (Table 1). The enhancing intra-phase variability of $\delta^{15}N_{barley}$ values from the Early to the Mature phase may be a combined effect of changes in cropping pattern and agricultural intensification adopted by Harappan farmers.

For the summer crop, $\delta^{15}N_{cotton}$ values during the Transitional phase show much larger variability (10.29‰ ± 7.8) compared to that of the Mature phase 11.00‰ ± 3.6, most likely due to crop-diversification adopted during the Transitional phase and its impact on arable soil (Fig. 3H; Table 1). However, $\delta^{15}N_{cotton}$ values did not show any statistically significant difference (validated by one way ANOVA test; $p = 0.799$) in the Early, Transitional and Mature phases ($p = 0.450$). Average TN contents of cotton crops also do not show significant variation (validated by one way ANOVA test; $p = 0.768$) from the Transitional phase to the Mature phase (4.09% ± 1.2 in Transitional phase and 4.25% ± 1.2 in Mature phase; Table 1). The weed plant (tiny vetch) also showed a larger degree of variability in $\delta^{15}N$ during the Transitional phase (4.18‰ ± 2.8) compared to that for the Mature phase (2.68‰ ± 2.0) (Fig. 3E; Table 1). Besides, tiny vetch showed the lower $\delta^{15}N$ values as expected for the leguminous plants (Fig. 3E; Table 1). C/N values for archaeological barley grains shown in Fig. 3C indicate better degree of preservation for grains during the Transitional and Mature phases compared to those from Early phase. Two higher (outlier) values for instance, clearly due to poorer preservation. Similarly, the C/N ratios of tiny vetch and cotton seeds also showed the good degree of preservation (Fig. 3F, I).

Discussion

Average $\delta^{13}C$ values of soil organic matter indicates growing aridity from the Early to Mature phase (Fig. 5A), which could also be contributed by the C_4 crop proportion as indicated by the archaeobotanical assemblage *i.e.* relatively high proportion of *Setaria* sp. (Fig. 2C) (Sharma et al. 2020a). If the enriched $\delta^{13}C$ values of sediments were due to higher cultivation of C_4 millets then also it corroborates growing dryness during the later part of Mature phase which might have forced the farmers to grow a drought resistant crop rather than C_3 barley as a crop-management practice at the time of prevailing dryness in the region. However, interestingly the carbon isotope data of archaeological seeds/grains grown during both winter and summer seasons (Figs. 3(A) and (G) do not show such aridity trend clearly indicating mitigation of water requirement by using water-management practices. Our earlier work at Khirsara (23°27'N, 69º03'E), a Harappan site in the semi-arid region of Kachchh, Gujarat also demonstrated a major shift in crop-assemblage (towards drought resistant millet-based crops) well supported by a significant enhancement in the $\delta^{13}C$ values of soil organic matter at ~2250 BCE (Pokharia et al. 2017). Cultural continuity was maintained despite this significant crop-shift likely enforced by prevailing monsoonal aridity. Several regional geological records do present evidences for significant monsoonal dryness (Dixit et al. 2014, 2018; Prasad et al. 2014; Staubwasser et al. 2003).

The enriching trend in $\delta^{13}C_{SOM}$ values (Fig. 5A) indicate environmental conditions possibly varied from wetter to drier conditions. This inference could be supported by macro-botanical assemblage that shows the arrival of drought resistant crops (*e.g.* millets) during the late Mature phase as mentioned above (Sharma et al. 2020a). However, it is also noteworthy here that the proportion of water-demanding crop especially cotton is increased during the Mature phase despite of growing aridity in the region suggests cultivation of crop for the trade purposes. It seems that the Harappan farmers have used their efficient crop management skills for the shifting of crops as per their social need and basic requirements. During Mature phase, the food crop barley got reduced with the increasing proportion of millets, however, the proportion of fibre crop cotton got increased possibly for the trade indicates economic exploitation of crop. Plausibly the existing trade practices at the site would have also utilized cotton as a fibre trade. Further, the cultivation of cotton in growing aridity along with the isotope values of archaeobotanical remains together hints the crop-water management at the settlement. The farmers would have managed water requirement of crops through river channelling or irrigation practices. Earlier, geological repositories of north-western India also have shown gripping aridity during the increasing craft (metallurgical) activities of Harappans based on the recovered material-culture (Dixit et al. 2014; Kathayat et al. 2017; Sarkar et al. 2016; Sharma et al. 2020b). Taken together, it appears that there was a gradual transformation in the agriculture prowess of Harappan farmers from the Early to Mature phase which appears to have outplayed prevailing aridity in the region. All these evidences suggest that the agriculture continued to the end of the Mature phase (~1800 BCE) together with upcoming industrial activities. $\delta^{13}C$ and $\delta^{15}N$ data of studied (well preserved) archaeological grains, however, do not show any significant changes. This observation led us to infer that it is likely that Harappan farmers in the western Rajasthan area was able to manage their agriculture by the application of other means such as crop shifting, irrigation and similar interventions. Cultivation of cotton (water-demanding crop) in relatively high proportion during Mature phase also supports the faming strategies which has been followed to cope up the trade requirement despite of growing aridity in the region. More intrusive analyses of the Indus agronomical treasures are needed. Drawn inferences, however, appear to be well corroborated by the analysis of botanical assemblage from the site which noticeably shows (i) crop-diversification during the intermediate Transitional phase and (ii) the advent of millet-based crops during the later part of the Mature phase, attributable to the increased monsoonal aridity in the region (Sharma et al. 2020a).

Routson et al. (2019) have noted a decreasing trend in net precipitation during early to mid-Holocene globally (for mid-latitudes). This inference is well corroborated by regional hydro-climatic records of the Indian monsoon (Fleitmann et al. 2003; Gupta et al. 2003). It has been demonstrated that the $\Delta^{13}C$ values of archaeological agricultural grains (such as barley) recovered from the different archaeological sites (along with the sites falling under semi-arid to arid zones) typically ranging between 15.0 to 22.0‰ were grown under ~100-250 mm of mean annual precipitation (Araus et al. 1997; Aguilera et al.2008; Ferrio et al. 2005; Gron et al. 2017, 2021; Kanstrup et al. 2014; Wallace et al. 2013, 2015; Vaiglova et al. 2020). Araus et al. (1997) have shown lower $\Delta^{13}C_{barley}$ values from archaeological sites in the Fertile Crescent and western Mediterranean (Spain) as indicator of poorer water status during arid epochs. Numerous other studies also have demonstrated that the lower $\Delta^{13}C$ values resulting from the poor to moderate water availability reflected by the grains grown in drier conditions (Ferrio et al. 2005; Riehl et al. 2014; Wallace et al. 2013, 2015). Studies have reported $\Delta^{13}C$ values of barley ranging between 16.2 to 18.0‰ during mid to late Holocene (~3000−1800 BCE) (Aguilera et al. 2008, 2012; Ferrio et al. 2005; Flohr et al. 2011; Mora-Gonzalez et al. 2016; Reihl et al. 2014; Wallace et al. 2013, 2015). Araus et al. (1997) suggested $\Delta^{13}C$ value ~18‰ for barley crop imply irrigation practices in the arable fields (Mora-González et al. 2016). However, $\Delta^{13}C$ values below 16-17‰ are generally regarded as as a moderately poor water availability. Average $\Delta^{13}C$ values for barley grains grown during the Early phase was found to be 15.37‰ ± 2.0, indicating marginally drier status of grains compared to those during Transitional phase (16.63‰ ± 1.7) and the Mature phase (16.74‰ ± 1.8) (Fig. 4A). The overlapping $\Delta^{13}C$ values of archaeobotanical grains/seeds thus indicating the practice of water-management for agricultural produce irrespective of changing environmental conditions in the region (Dixit et al. 2014; Enzel et al. 1999; Giosan et al. 2012; Prasad et al. 2014; Sarkar et al. 2016; Singh et al. 1974). $\Delta^{13}C$ values of cereals grown during the Mature phase were found to be higher (Fig. 4A), thus indicate that the farming strategies has been practiced in an arid Indus region probably anthropogenically managed (rain fed + irrigation) (Wallace et al. 2013) due to the increasing dryness in temporal domain (during end part of the Mature phase). The study of the oxygen isotope of two foraminifer species *Neogloboquadrina dutertrei* and *Globigerinoides sacculifer* from the Indus River delta in the Arabian Sea also provided the evidence for the seasonal changes in the Indus region (Giesche et al. 2019). This study recorded strong winter monsoon between 4.5 to 4.3 kyr and reduction in both winter and summer rainfall during 4.1 Kyr and also suggest the growth of Indus urban centres coincided with increased winter rainfall, however, the de-urbanism and change in subsistence strategies followed a reduction in both winter and summer season rainfall (Giesche et al. 2019).

Thus, the Δ^{13}C values of barley grown during the Mature phase in growing aridity along with the cultivation of water demanding crops such as cotton and linseed supports our hypothesis of farming strategies such as water management or river channelling practiced by the Indus farmers (for site chronology please see supplementary Table 1S). While Giosan et al., (2018) provided evidence for a stronger winter monsoon between ~4.5 and 3.0 Kyr. Kathayat et al. (2017) provided evidence for drier conditions between ca. 4.3 and 3.3 Kyr from a detailed reconstruction of the summer monsoon in the Harappan domain. Our macro-botanical data (Sharma et al. 2020a) clearly indicate that the Harappan farmers shifted their cropping strategy from winter crops to summer crops by growing millets, cotton and leguminous crops like *Vigna* sp.

Average $\Delta^{13}C_{cotton}$ values varied in the range 17.55‰ ± 1.9 for the Transitional phase and 16.53‰ ± 2.6 for the Mature phase (Fig. 4C; Table 1), indicating well-watered conditions (rain fed via summer precipitation + irrigation) during the Transitional phase. It may be due to change in course of summer monsoon that reached the western Rajasthan Indus farmlands (~2600-2500 BCE) and supported crop-diversification. Summer monsoon however, appears to have subsequently declined toward late Mature phase as evidenced by arrival of millet-based cropping pattern (Sharma et al. 2020a). Similar observations have also been made in our earlier studies (Pokharia et al. 2017). We surmise that the Harappan farmers exploited both the seasonal rainfall and other means of water management in arable lands, such as steering river waters into their agricultural fields. More isotopic data of archaeological grains from other peripheral archaeological sites are needed to garner much deeper insights into the Indus farming especially for the later part of the Mature phase (~1900−1800 BCE) of the Indus era.

δ^{15}N values of the crop-remains in conjunction with soil-sediment have been used to assess aridity in farmlands and agricultural intensifying efforts (*e.g.* manuring) (Agnihotri et al. 2021; Bogaard et al. 2007; Kanstrup et al. 2012; Styring et al. 2017). δ^{15}N values of host soil-sediment largely reflect land-use history; larger the magnitude greater the reworking of arable soils (Peukert et al. 2012). Enhanced δ^{15}N values of host soil-sediment could also be due to enhanced aridity (loss of water taking out lighter isotope bound nitrogen from soil). Manuring of farmlands with animal dung generally result in enhanced δ^{15}N values of host soil-sediments (Bol et al. 2005; Szpak et al. 2014). For instance, the effect of cattle dung manure in farmlands recorded δ^{15}N values ranging between +2‰ to +8‰, while the values for pig manure range between +15‰ to +20‰ (Bateman and Kelly 2007; Szpak et al. 2014).

To deduce the factual interpretation of δ^{15}N data, Nitrogen concentration data (TN %) greatly help in deciphering the aforementioned processes. Aridity conditions would favour higher δ^{15}N values with lower TN contents, while organic manuring would result in higher TN contents (due to richness of nitrates and ammonia in soils) along with higher δ^{15}N values (Fuertes-Mendizábal et al. 2018; Gron et al. 2021; Szpak 2014). TN contents in farmlands could also be enhanced by cropping leguminous plants (*e.g.* pulses) that fix nitrogen from the atmosphere. In this kind of agricultural intensification, agricultural grains/seeds would show enhanced TN contents but lower δ^{15}N values (as δ^{15}N of atmospheric N_2 is regarded as 0.0‰; van Klinken et al. 2000). Similar effect would be seen in case of application ammonia based fertilizers (urea) as these contain large pool of reactive Nitrogen that has been fixed from atmospheric source (using Haber process) (Bateman et al. 2005). This case, however, is applicable only in modern-day agricultural fields, as this practice was introduced in India after the 1970's.

Archaeological barley grains from the studied site (4MSR) show an enhancing trend in δ^{15}N values in terms of their intra-phase variability (as determined by standard deviation) from the Early to Mature phases. Macro-botanical data revealed a conspicuous crop-diversification was conducted during the short Transitional phase via adopting leguminous crops (pulses) (Sharma et al. 2020a). This short duration of Transitional phase also witnessed marginally enhanced TN contents ($p = 0.084$) (Table 1). This observation could be interpreted in terms of successful crop-shifting strategy adopted by Harappan farmers to enhance soil nutritional health and their agricultural produce during the Transitional phase which continued towards the end of Mature phase. As a matter of fact, a significant diversification of crops (towards pulses) was inferred with two-fold enhancement (in abundance) from the Early to Transitional phase, and further two-fold enhancement from Transitional to Mature phase (using macro-botanical data from this site earlier; Sharma et al. 2020a).

Earlier in controlled agronomic conditions, Bogaard et al. (2013) quantified ancient manuring practice from the measured δ^{15}N values of modern bulk cereal samples (barley and wheat) cultivated in Europe and noted higher δ^{15}N values (ranging from 6-9‰) correspond to high manuring rates (≥35+ tons/hectare) while lower values (≤3.0‰) corresponds to long-term unmanured cultivation. Fraser et al., (2011) also recoded δ^{15}N values of modern bulk cereal samples (wheat and barley) grown in Germany under different manuring rates and quantified δ^{15}N values (1) 0.0 to 3.0‰ as low manuring, (2) ~3.0 to 6.0‰ as medium manuring and (3) above 6.0‰ as high manuring. Nitsch et al. (2017) published δ^{15}N values of barley ranging between 5.4 to 6.8‰ for Early Bronze Age and 4.0‰±1.2 for Late Bronze Age from Archontiko. In the context of the above mentioned data, our isotope dataset would possibly support a manifestation of crop-management through diversification, for instance, by cultivating more leguminous crops.

Conclusions

Following conclusions could be drawn from the study-

- $\delta^{13}C$ values of soil organic matter clearly indicate a progressive regional aridity *i.e.* a transition from wetter to drier conditions. The growing aridity was found to have well corroborated by the crop-assemblage data that recorded dominance of millet-based crops during the later part of Mature phase (Sharma et al. 2020a).
- The $\delta^{13}C$ values of both winter and summer crops (barley and cotton) do not indicate any significant difference in the hydrological conditions among different Indus phases (Early, Transitional and Mature phase) indicating adoptive water management practices of Indus farming.
- Observed scenario indicate that the Harappan farmers were most likely managing the hydrological status by other means such as channelling river waters into their agricultural fields.
- $\delta^{15}N$ soil-sediments (along with Total Nitrogen contents) indicate progressive agricultural intensification from Early to Mature phase, which yielded better crop-quality and soil-fertility under prevailing aridity.
- Lower $\delta^{15}N$ values (with enhanced Total Nitrogen contents) of weed (tiny vetch) demonstrate plausible impact of crop-diversification and efficacy of crop-management by sowing pulses during the Mature phase.
- It appears that Harappan farmers were capable of changing their farming strategies during the Mature phase.

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Declarations

Competing interests The authors declare no competing interests.

References

Agnihotri R, Gahlaud SKS, Patel N et al (2020) Radiocarbon measurements using new automated graphite preparation laboratory coupled with stable isotope mass-spectrometry at Birbal Sahni Institute of Palaeosciences, Lucknow (India). J Environ Radio 213:106156

Agnihotri R, Patel N, Srivastava P et al (2021) A new chronology based on OSL and radiocarbon dating for the archaeological settlements of Vadnagar (western India) along with magnetic and isotopic imprints of cultural sediments. J Archaeolog Sci: Rep 38:103045

Agrawal DP (1971) The Copper Bronze Age in India. Munshiram Manoharlal Publishers, New Delhi

Aguilera M, Araus JL, Voltas J et al (2008) Stable carbon and nitrogen isotopes and quality traits of fossil cereal grains provide clues on sustainability at the beginnings of Mediterranean agriculture. Rapid Commun Mass Spectrometry 22:1653–1663

Aguilera M, Ferrio JP, Pérez G et al (2012) Holocene changes in precipitation seasonality in the western Mediterranean Basin: a multi-species approach using $\delta^{13}C$ of archaeobotanical remains. J Quaternary Sci 27:192–202

Aguilera M, Zech-Matterne V, Lepetz S et al (2017) Crop fertility conditions in north-eastern gaul during the la tène and roman periods: a combined stable isotope analysis of archaeobotanical and archaeozoological remains. Environ Archaeo 23(4):323–337

Ali SM (1941) The problem of desiccation of the Ghaggar plain. Indian Geograph J 16:166–178

Anonymous (2021) Krishi Vigyan Kendra (an agricultural extension ICAR-ATARI), Sriganganagar district, India. https://sriganganagar.kvk2.in/district-profile.html

Araus JL, Febrero A, Buxó R et al. (1997) Changes in carbon isotope discrimination in grain cereals from different regions of the western Mediterranean basin during the past seven millennia. Palaeoenvironmental evidence of a differential change in aridity during the late Holocene. Global Change Biology 3:107–118

Asthana S (1993) Harappan trade in metals and minerals: a regional approach. In: Possehl G (ed) *Harappan Civilization*. American Institute of Indian Studies, Delhi. 271–285

Bateman AS, Kelly SD, Jickells TD (2005) Nitrogen isotope relationships between crops and fertilizer: implications for using nitrogen isotope analysis as an indicator of agricultural regime. J Agricult Food Chem 53:5760–5765

Bateman AS, Kelly SD (2007) Fertilizer nitrogen isotope signatures. Isotopes Environ Health Studies 43:237–247

Bates J, Singh RN, Petrie CA (2017) Exploring Indus crop processing: combining phytolith and macrobotanical analyses to consider the organisation of agriculture in northwest India c. 3200–1500 BC. Vegetation History Archaeobot 26:25–41

Berkelhammer M, Sinha A, Stott L et al (2012) An abrupt shift in the Indian monsoon 4000 years ago. Geophysical Monograph 198:75–87

Bhan KK, Vidale M, Kenoyer JM (2002) Some important aspects of the Harappan technological tradition. In: Settar S, Korisettar R (eds) Indian Archaeology in Retrospect, vol 2. Protohistory: Archaeology of the Harappan Civilization. Indian Council of Historical Research, New Delhi, pp 223–272

Bisht RS (1998–99) Dholavira and Banawali: two different paradigms of the Harappan Urbis forma. *Purattatva* 29:14–32

Bogaard A, Heaton THE, Poulton P et al (2007) The impact of manuring on nitrogen isotope ratios in cereals: archaeological implications for reconstruction of diet and crop management practices. J Archaeol Sci 34:335–343

Bogaard A, Fraser RA, Heaton THE et al. (2013) Crop Manuring and Intensive Land Management by Europe's First Farmers. Proceedings of the National Academy of Sciences U.S.A. 110(31):12589–12594

Bol R, Eriksen J, Smith P et al (2005) The natural abundance of ^{13}C, ^{15}N, ^{34}S and ^{14}C in archived (1923–2000) plant and soil samples from the Askov long-term experiments on animal manure and mineral fertilizer. Rapid Commun Mass Spectrom 19:3216–3226

Charles M, Forster E, Wallace M et al. (2015) Nor ever lightning char thy grain: establishing archaeologically relevant charring conditions and their effect on glume wheat grain morphology. STAR: Science & Technology of Archaeological Research 1:1–6

Chatterjee A, Ray JS, Shukla AD et al (2019) On the existence of a perennial river in the Harappan heartland. Sci Rep 9:17221. https://doi.org/10.1038/s41598-019-53489-4

Choi WJ, Arshad A, Chang SX et al (2006) Grain N-15 of crops applied with organic and chemical fertilizers in a four-year rotation. Plant Soil 284:165–174

Dixit Y, David AH, Giesc A et al (2018) Intensified summer monsoon and the urbanization of Indus Civilization in northwest India. Sci Rep 8:4225

Dixit Y, Hodell DA, Sinha R et al (2014) Abrupt weakening of the Indian summer monsoon at 8.2 kyr B.P. Earth Planetary Sci Lett 391:16–23

Enzel Y, Ely LL, Mishra S et al (1999) High-resolution Holocene environmental changes in the Thar Desert, northwestern India. Science 284:125–128

Farquhar GD, Ehleringer JR, Hubick KT (1989) Carbon isotope discrimination and photosynthesis. Annual Rev Plant Physiology Plant Molecular Bio 40:503–537

Ferrio JP, Araus JL, Buxó R et al. (2005) Water management practices and climate in ancient agriculture: inference from the stable isotope composition of archaeobotanical remains. Vegetation History and Archaeobotany 14:510–517

Ferrio JP, Voltas J, Alonso N et al (2007) Reconstruction of climate and crop conditions in the past based on the carbon isotope signature of archaeobotanical remains. Terres Eco 1:319–332

Fleitmann D, Burns SJ, Mudelsee M et al (2003) Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. Science 300:1737–1739

Flohr P, Jenkins E, Müldner G (2011) Carbon stable isotope analysis of cereal remains as a way to reconstruct water availability: Preliminary results. Water History 3:121–144

Ford RI (1979) Paleoethnobotany in American archaeology. In: Schiffer MB (ed) Advances in Archaeological Method and Theory, vol 2. Academic Press, New York, pp 285–336

Fraser RA, Bogaard A, Heaton T et al (2011) Manuring and stable nitrogen isotope ratios in cereals and pulses: Towards a new archaeobotanical approach to the inference of land use and dietary practices. J Archaeolog Sci 38(10):2790–2804

Fraser R, Bogaard A, Charles M et al (2013) Assessing natural variation and the effects of charring, burial and pre-treatment on the stable carbon and nitrogen isotope values of archaeobotanical cereals and pulses. J Archaeological Science 40:4754–4766

Fritz G (2005) Paleoethnobotanical Methods and Applications. In: Maschner HDG, Chippindale C (eds) Handbook of archaeological methods. Altamira Press, Walnut Creek (CA), pp 771–832

Fuertes-Mendizábal T, Estavillo JM, Duñabeitia MK et al (2018) ^{15}N natural abundance evidences a better use of N sources by late nitrogen application in bread wheat. Front Plant Sci 9:853. https://doi.org/10.3389/fpls.2018.00853

Ghose B, Kar A, Husain Z (1979) The lost courses of the Saraswati River in the Great Indian Desert: new evidence from Landsat imagery. Geograph J 145(3):446–451

Giesche A, Staubwasser M, Petrie C et al (2019) Indian winter and summer monsoon strength over the 4.2 ka BP event in foraminifer isotope records from the Indus River delta in the Arabian Sea. Climate Past 15:73–90

Giosan L, Clift PD, Macklin MG et al (2012) Fluvial landscapes of the Harappan civilization. Proc National Acad Sci USA 109:E1688–E1694

Giosan L, Orsi WD, Coolen M et al (2018) Neoglacial climate anomalies and the Harappan metamorphosis. Climate Past 14:1669–1686

García-Granero JJ, Lancelotti C, Madella M et al (2016) Millets and Herders: the origins of plant cultivation in semiarid North Gujarat (India). Current Anthropol 57:149–173

Gron KJ, Grocke DR, Larsson M et al (2017) Nitrogen isotope evidence for manuring of early Neolithic Funnel Beaker Culture cereals from Stensborg, Sweden. J Archaeolog Sci Rep 14:575–579

Gron KJ, Larsson M, Grocke DR et al (2021) Archaeological cereals as an isotope record of long-term soil health and anthropogenic amendment in southern Scandinavia. Quaternary Sci Rev 253:106762. https://doi.org/10.1016/j.quascirev.2020.106762

Gupta AK, Anderson DM, Overpeck JT (2003) Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. Nature 42:354–357

Gupta AK, Sharma JR, Sreenivasan G et al (2004) New findings on the course of river Sarasvati. J Indian Soc Remote Sensing 32:1–24

Hubbard RNLB and al Azm A (1990) Quantifying preservation and distortion in carbonized seeds; and investigating the history of Frike production. J Archaeolog Sci 17:103–106

Jiao F, Shi XR, Han F et al (2016) Increasing aridity, temperature and soil pH induce soil C-N-P imbalance in grasslands. Scientific Rep 6:19601

Jones PJ, O'Connell TC, Jones MK et al (2021) Crop water status from plant stable carbon isotope values: A test case for monsoonal climates. Holocene 31(6):993–1004

Joshi JP, Bala M, Ram J (1984) The Indus Civilisation: a reconsideration on the basis of distribution maps. In: Lal BB, Gupta SP (eds) Frontiers of the Indus Civilization. Books and Books, New Delhi, pp 511–530

Kanstrup M, Holst MK, Jensen PM et al (2014) Searching for long-term trends in prehistoric manuring practice. ^{15}N analyses of charred cereal grains from the 4th to the 1st millennium BC. J Archaeolog Sci 51:115–125

Kanstrup M, Thomsen IK, Mikkelsen PH et al (2012) Impact of charring on cereal grain characteristics: linking prehistoric manuring practice to δ15N signatures in archaeobotanical material. J Archaeological Sci 39(7):2533–2540

Kar A (2011) Geoinformatics in spatial and temporal analysis of wind erosion in Thar Desert. In: Anbazhagan S, Subramanian SK, Yang X (eds) Geoinformatics in Applied Geomorphology. CRC Press, Boca Raton, USA, pp 39–62

Kar A (2014) Agricultural land use in arid Western Rajasthan: Resource exploitation and emerging issues. Agropedology 24(02):179–196

Kar A, Singhvi AK, Juyal N et al. (2004) Late Quaternary Aeolian Sedimentation History of the Thar Desert. In: Sharma, Singh and De (eds) *Geomorphology and Environment*. ACB Publication, Kolkata, India. 105–122

Kathayat G, Cheng H, Sinha A et al (2017) (2017) The Indian monsoon variability and civilization changes in the Indian subcontinent. Science Advances 3(12):e1701296. https://doi.org/10.1126/sciadv.1701296

Kaushal R, Ghosh P, Pokharia AK (2019) Stable isotopic composition of rice grain organic matter marking an abrupt shift of

hydroclimatic condition during the cultural transformation of Harappan civilization. Quaternary Int 512:144–154
Kenoyer JM (1991) Urban process in the Indus tradition: a preliminary model from Harappa. In: Meadow RH (ed) Harappa Excavations 1986–1990. Prehistory Press, Madison, pp 29–60
Kenoyer JM (1991) The Indus Valley tradition of Pakistan and Western India. J World Prehistory 5(4):331–385
Kenoyer JM, Miller HM-L (1999) Metal technologies of the Indus Valley tradition in Pakistan and Western India. In: Pigott VC (ed) The emergence and development of metallurgy. University Museum, Philadelphia, pp 107–151
Lal BB, Thapar BK, Joshi JP et al. (2003) Excavations at Kalibangan: The Early Harappans (1960–1969). Memoirs of the ASI, No. 98, New Delhi: Archaeological Survey of India
Lal BB (2002) The Sarasvati Flows on: The Continuity of Indian Culture. Aryan Books International, New Delhi, India
Lee X, Feng Z, Guo L et al (2005) Carbon isotope of bulk organic matter: A proxy for precipitation in the arid and semiarid central East Asia. Global Biogeochem Cycles 19:1–8
Levey M, Burke JE (1959) A study of ancient Mesopotamian bronze. Chymia 5(37):50
Lightfoot E, Stevens RE (2012) Stable isotope investigations of charred barley (*Hordeum vulgare*) and wheat (*Triticum spelta*) grains from Danebury Hillfort: implications for palaeodietary reconstructions. J Archaeological Sci 39:656–662
Ma J-Y, Sun W, Liu X-N et al (2012) Variation in the stable carbon and nitrogen isotope composition of plants and soil along a precipitation gradient in Northern China. PLoS ONE 7(12):e51894. https://doi.org/10.1371/journal.pone.0051894
MacDonald G (2011) Potential influence of the Pacific Ocean on the Indian summer monsoon and Harappan decline. Quaternary Int 229:140–148
Marshall J (1931) Mohenjo-daro and the Indus civilization. Arthur Probsthain, London
Masi A, Sadori L, Restelli FB et al (2014) Stable carbon isotope analysis as a crop management indicator at Arslantepe (Malatya, Turkey) during the Late Chalcolithic and Early Bronze Age. Vegetation History Archaeobot 23:751–760
Miller HM-L (2006) Water supply, labor requirements, and land ownership in Indus floodplain agricultural systems. In: Marcus J and Stannish C (eds) *Agricultural Strategies*. Cotsen Institute of Archaeology UCLA, Los Angeles, 92–128
Miller HM-L (2015) Surplus in the Indus Civilisation: agricultural choices, social relations, political effects. In: Morehart CT, de Lucia K (eds) Surplus: The Politics of Production and the Strategies of Everyday Life. University Press of Colorado, Colorado, pp 97–120
Mora-González A, Delgado-Huertas A, Granados-Torres A et al. The isotopic footprint of irrigation in the western Mediterranean basin during the Bronze Age: the settlement of Terlinques, southeast Iberian Peninsula. Vegetation History and Archaeobotany 25:459–468
Mughal MR (1997) *Ancient Cholistan: archaeology and architecture*. Ferozsons Press
Nitsch E, Andreou S, Creuzieux A et al (2017) A bottom-up view of food surplus: using stable carbon and nitrogen isotope analysis to investigate agricultural strategies and diet at Bronze Age Archontiko and Thessaloniki Toumba, northern Greece. World Archaeo 49(1):105–137
Oldham CF (1893) The Saraswati and the lost river of the Indian desert. J Royal Asiatic Soc Great Britain Ireland 25(01):49–76
Oldham RD (1886) On probably changes in the geography of the Punjab and its rivers: an historico-geographical study. J Asiatic Soc Bengal 55:322–343
Park J-S, Shinde V (2014) Characterization and comparison of the copper-base metallurgy of the Harappan sites at Farmana in Haryana and Kuntasi in Gujarat, India. J Archaeolog Sci 50:126–138
Parker AD, Lee-Thorp J, Mitchell PJ (2011) Late Holocene Neoglacial conditions from the Lesotho highlands, southern Africa: phytolith and stable carbon isotope evidence from the archaeological site of Likoaeng. Proc Geologists' Assoc 122:201–211
Pearsall DM (2000) Palaeoethnobotany: A handbook of procedures, 2nd edn. Academic Press, San Diego (CA)
Petrie CA, Bates J (2017) Multi-cropping', intercropping and adaptation to variable environments in Indus South Asia. J World Prehistory 30:81–130
Petrie CA, Singh RN, Bates J et al (2017) Adaptation to variable environments, resilience to climate change: investigating Land, Water and Settlement in northwest India. Curr Anthropology 58(1):1–30
Petrie CA, Bates J, Higham T et al (2016) Feeding ancient cities in South Asia: dating the adoption of rice, millet and tropical pulses in the Indus civilisation. Antiquity 90(354):1489–1504
Peukert S, Bol R, Roberts W et al (2012) Understanding Spatial Variability of Soil Properties: A Key Step in Establishing Field- to Farm-Scale Agro-Ecosystem Experiments: Understanding Spatial Variability of Soil Properties. Rapid Commun Mass Spec 26:2413–2421
Pokharia AK, Agnihotri R, Sharma S et al (2017) Altered cropping pattern and cultural continuation with declined prosperity following abrupt and extreme arid event at ~4,200 yrs BP: Evidence from an Indus archaeological site Khirsara, Gujarat, western India. PLoS ONE 12(10):1–17
Pokharia AK, Kharakwal JS, Srivastava A (2014) Archaeobotanical evidence of millets in the Indian subcontinent with some observations on their role in the Indus civilization. Journal of Archaeological Science 42(1):442–455
Pokharia AK, Kharakwal JS, Rawat RS et al (2011) Archaeobotany and Archaeology at Kanmer, a Harappan Site in Kachchh, Gujarat: Evidence for Adaptation in Response to Climatic Variability. Curr Sci 100:1833–1846
Possehl GL (2002) The Indus civilization: A contemporary perspective. AltaMira Press, Walnut Creek
Possehl GL (1999) Indus Age: The beginnings. University of Pennsylvania Press, Philadelphia (PA)
Prasad S, Enzel Y (2006) Holocene paleoclimates of India. Quaternary Res 66(3):442–453
Prasad V, Farooqui A, Sharma A et al (2014) Mid-Late Holocene monsoonal variations from mainland Gujarat, India: A multi-proxy study for evaluating climate culture relationship. Palaeogeography, Palaeoclimatology, Palaeoecology 397:38–51
Riehl S, Pustovoytov KE, Weippert H et al (2014) Drought stress variability in ancient Near Eastern agricultural systems evidenced by δ13C in barley grain. Proc National Acad Sci U.S.A. 111:12348–12353
Rosen DZ, Lewis CA, Illgner PM (1999) Palaeoclimatic and archaeological implications of organic- rich sediments at tifftidell ski resort, near Rhodes, Eastern Cape Province, South Africa. Trans Royal Soc South Africa 54(2):311–321
Routson CC, McKay NP, Kaufman DS et al (2019) Mid-latitude net precipitation decreased with Arctic warming during the Holocene. Nature 568:83–87
Sana Ullah M (1931) Copper and bronze utensils and other objects. In: Marshall J (ed) Mohenjo-daro and the Indus Civilization, vol 2. Arthur Probsthain, London, pp 481–488
Sana Ullah M (1940) The sources, composition, and technique of copper and its alloys. In: Vats MS (ed) Excavations at Harappa. Government of India Press, New Delhi, pp 378–382

Sarkar A, Mukherjee AD, Bera MK et al (2016) Oxygen isotope in archaeological bioapatites from India: Implications to climate change and decline of Bronze Age Harappan civilization. Scientific Rep 6(26555):1–9

Senbayram M, Dixon L, Goulding KWT et al (2008) Long-term influence of manure and mineral nitrogen applications on plant and soil 15N and 13C values from the Broadbalk Wheat Experiment. Rapid Commun Mass Spec 22:1735–40

Shyampura RL, Sehgal J (1995) Soils of Rajasthan for optimum land use plan. NBSS Publication 51. NBSSLUP, Nagpur. 76

Sharma S, Agnihotri R, Pokharia AK et al (2020) Environmental magnetic, Geochemical and Sulfur isotopic imprints of an Indus archaeological site 4MSR from western India (Rajasthan): Implications to the Indus industrial (metallurgical) activities. Quaternary Int 550:74–84

Sharma S, Manjul SK, Manjul A et al (2020) Dating adoption and intensification of food-crops: insights from 4MSR (Binjor), an Indus (Harappan) site in northwestern India. Radiocarbon 62(5):1349–1369

Shinde V (2016) Current perspectives on Harappan civilization. In: Schug GR and Walimbe SR (eds) A comparison to south Asia in the past. John Wiley & Sons

Simpson IA, Bol R, Bull ID et al (1999) Interpreting early land management through compound specific stable isotope analyses of archaeological soils. Rapid Commun Mass Spec 13:1315–1319

Singh A, Thomsen KJ, Sinha R et al (2017) Counter-intuitive influence of Himalayan river morphodynamics on Indus Civilisation urban settlements. Nature Commun 8:1617. https://doi.org/10.1038/s41467-017-01643-9,2017

Singh G (1971) The Indus Valley culture seen in the context of postglacial climatic and ecological studies in north-west India. Archaeol Phys Anthrop Oceania 6:177–189

Singh G, Joshi RD, Chopra SK et al (1974) Late Quaternary history of vegetation and climate in the Rajasthan Desert, India. Philosop Trans Royal Soc London 267:467–501

Staubwasser M, Sirocko F, Grootes P et al (2003) Climate change at the 4.2 ka BP termination of the Indus Valley Civilization and Holocene south Asian monsoon variability. Geophys Res Lett 30:1425–1429

Styring AK, Charles M, Fantone F et al (2017) Isotope evidence for agricultural extensification reveals how the world's first cities were fed. Nature Plants 3:17076

Styring AK, Ater M, Hmimsa Y et al (2016) Disentangling the effect of farming practice from aridity on crop stable isotope values: a present-day model from Morocco and its application to early farming sites in the eastern Mediterranean. Anthropocene Rev 3:2–22

Styring AK, Höhn A, Linseele et al. (2019) Direct evidence for agricultural intensification during the first two millennia AD in northeast Burkina Faso. J Archaeolog Sci 108:104976

Szpak P (2014) Complexities of Nitrogen Isotope Biogeochemistry in Plant-Soil Systems: Implications for the Study of Ancient Agricultural and Animal Management Practices. Front Plant Sci 5:1–19

Vaiglova P, Snoeck C, Nitsch E, Bogaard A, Lee-Thorp J (2014) Impact of contamination and pre-treatment on stable carbon and nitrogen isotopic composition of charred plant remains. Rapid Commun Mass Spectrom 28(23):2497–2510

Vaiglova P, Gardeisen A, Buckley M et al (2020) Further insight into Neolithic agricultural management at Kouphovouno, southern Greece: expanding the isotopic approach. Archaeolog Anthropolog Sci 12:43. https://doi.org/10.1007/s12520-019-00960-y

VanKlinken GJ, Richards MP and Hedges REM (2000) An overview of causes for stable isotope variations in past European human populations: environmental ecophysiological and cultural effects. Ambrose SH and Katzenberg MA (eds) In: *Biogeochemical Approaches to Palaeodietary Analysis*. Kluwer Academic, New York, pp 39–63

Vats MS (1940) *Excavations at Harappa*, vols. Government of India Press, Delhi, I- II

Wallace MP, Jones G, Charles M et al (2015) Stable carbon isotope evidence for Neolithic and Bronze Age crop water management in the eastern Mediterranean and southwest Asia. PLoS ONE 10:e0127085

Wallace MP, Jones G, Charles M et al (2013) Stable carbon isotope analysis as a direct means of inferring crop water status and water management practices. World Archaeology 45(3):388–409

Wang G, Feng X, Han J et al (2008) Paleovegetation reconstruction using δ13C of soil organic matter. Biogeosci 5:1325–1337

Wasson RJ, Smith GI, Agarwal DP (1984) Vegetation and seasonal climate changes since the last full Glacial in the Thar Desert, NW India. Palaeogeography, Palaeoclimatology, Palaeoecology 46:345–372

Weber SA (2003) Archaeobotany at Harappa: Indications for change. In: Weber SA, Belcher WR (eds) Indus ethnobiology: New perspectives from the field. Lexington Books, Maryland, pp 175–198

Weber SA, Tim B and Lehman H (2010) Ecological continuity: An explanation for agricultural diversity in the Indus Civilization and beyond. Man and Environment XXXV(1):62–75

Wright RP (2010) The Ancient Indus: Urbanism. Economy and Society, Cambridge, Cambridge University Press

Yashpal BS, Sood RK, Agrawal DP (1980) Remote sensing of the 'lost' Saraswati' river. *Proceedings*. Indian Acad Sci (Earth and Planet Sci) 89:317–331

Zohaib A, Ehsanullah, Tabassum T et al. (2014) Influence of water soluble phenolics of *Vicia sativa* L. on germination and seedling growth of pulse crops. *Scientia Agriculturae* 8(3):148–151