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RESEARCH

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Crops in Motion: Strontium Isotope Analysis of Cereal Provenance in a Foraging-Oriented Neolithic Economy

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Abstract
Strontium isotope analysis offers a powerful tool for investigating mobility and provenance in prehistoric contexts, yet its application to archaeobotanical finds remains limited. This study applies $^{87}Sr/^{86}Sr$ analysis to charred cereal grains from Molino Casarotto, an Italian Middle Neolithic wetland site characterised by a foraging-oriented subsistence strategy and unusually limited cereal use compared to contemporary Neolithic farming sites. A locally defined bioavailable $^{87}Sr/^{86}Sr$ baseline was established through systematic sampling of modern plants across distinct lithological units surrounding the site. The isotope ratios of the archaeological cereals reveal a non-local and heterogeneous supply pattern, with values consistent with both regional fluvial units and more radiogenic extra-regional sources. These results provide direct evidence for a spatial decoupling between crop production and consumption and demonstrate the methodological viability of strontium isotopes for tracing cereal provenance. By extending isotopic provenancing to plant remains, this study contributes a new analytical framework for investigating crop circulation and provisioning systems in prehistoric societies. More broadly, it highlights the potential of archaeobotanical isotopic data to address fundamental questions concerning surplus, exchange, and the organisation of economic networks in non-state contexts.

Keywords Archaeobotany · Charred cereal grains · $^{87}Sr/^{86}Sr$ · Wetland site · Exchange networks · Middle Neolithic

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Introduction

The Neolithic in northern Italy was characterised by diverse and flexible subsistence strategies, reflecting the interplay of environmental variability, resource availability, and cultural practices. Archaeobotanical and faunal evidence reveals a broad spectrum of 'mixed economies' in which agriculture, herding, hunting, fishing, and the gathering of wild fruits, nuts, and molluscs coexisted in varying proportions. Although long-term trends point to increasing crop cultivation and domestic animal husbandry, some groups maintained a strong reliance on wild resources, underscoring the persistence of foraging-orientated practices alongside emerging agro-pastoral systems (Breglia et al., 2025; Castelletti & Rottoli, 1997; Rottoli & Castiglioni, 2009; Rottoli & Pessina, 2007; Tecchiati et al., 2020; Zanetti et al., 2020).

Molino Casarotto, a lakeside Middle Neolithic (MN, ca. 4700–4000 BCE) site, represents a striking example of this pattern (Bagolini et al., 1973; Jarman, 1976). Its archaeobotanical assemblage is overwhelmingly dominated by wild resources, as well as its faunal record, reflecting a strategy centred on gathering, hunting, and fishing, with domestic species playing only a marginal role (Boyle, 2014; Breglia et al., 2025; Tecce, 2020). This stands in marked contrast to regional trajectories, where agriculture and herding progressively intensified, highlighting the local distinctiveness and flexibility of the site's economy. At the same time, Molino Casarotto fits within the broader MN expansion into a range of environmental settings, likely supported by diversified resource exploitation (Tiné, 2015).

A small number of cereal grains was recovered at Molino Casarotto. Yet, the absence of chaff remains and cereal-related phytoliths strongly suggests that cereal processing did not occur on-site (Breglia et al., 2025). This pattern is unlikely to result from preservation bias given both the common recovery of uncharred plant remains and the systematic archaeobotanical sampling strategy across the excavated area (Breglia et al., 2025). In combination with the broader bioarchaeological evidence, this raises the possibility that cereals were not cultivated locally but introduced from outside the site.

Determining the provenance of these crops is essential for assessing the role of staple foods within broader systems of exchange and economic interaction in the Neolithic. Strontium isotope ($^{87}Sr/^{86}Sr$) analysis offers a promising avenue, as strontium signatures reflect the geology of the soils where plants grew or animals grazed. Although widely used to investigate human and animal mobility (Bentley 2006; Borić & Price, 2013; Evans et al., 2019; Holt et al., 2021; Lengfelder et al., 2019; Linscott et al., 2023; Lugli et al., 2019, 2022; Madgwick et al., 2019a, 2019ba, 2019b, 2019a, 2019ba, 2019b; Manfrin et al., 2026; Montgomery, 2010; Nafplioti, 2021; Richards et al., 2021; Sabatini et al., 2022; Whelton et al., 2018), this method has been applied far less frequently to plant remains (Bogaard et al., 2014; Larsson et al., 2020; Steen Henriksen et al., 2024). This is partially the result of low concentrations of strontium in seeds and concerns over diagenesis. However, advances in the sensitivity of mass spectrometric analysis and increasing evidence that diagenetic strontium can be at least partially leached from grains (e.g. Larsson et al., 2020) means that the potential of this method can now be enhanced. When applied to crops, strontium isotopes have the potential to trace the movement of plant resources from cultivation areas through trade and exchange networks, challenging traditional models that portray Neolithic communities as self-sufficient and exchange as restricted to raw materials or prestige goods. Archaeological evidence for such processes remains scarce and largely material-focused, leaving cultivation management and food resource mobility poorly understood.

This study represents the first robust application of $^{87}Sr/^{86}Sr$ analysis to archaeobotanical cereal remains in Italy and assesses whether the cereals recovered at Molino Casarotto were locally grown or introduced. Beyond the pioneering work at Çatalhöyük (Bogaard et al., 2014), no similar studies have been conducted in the Mediterranean, highlighting the novelty of our contribution to understanding prehistoric crop mobility in this area.

Archaeological Evidence for Subsistence and Exchange at Molino Casarotto

The Molino Casarotto site is situated in the so-called Fimon Valleys within the Berici Hills complex (Veneto, north-eastern Italy). Initially discovered in 1943 during peat extraction, it was systematically excavated between 1969 and 1972 by Lawrence H. Barfield and Alberto Broglio, who identified the site as belonging to the second phase of the Square-Mouthed Pottery (SMP) culture. The site represents one of the earliest peri-lacustrine settlements in northern Italy, with three recorded inhabitation areas featuring large combustion structures, shell middens, and wooden platforms interpreted as prepared living surfaces (Bagolini et al., 1973; Lawrence H. Barfield & Broglio, 1986; Broglio & Fogolari, 1970). Recent fieldwork conducted in 2022 as part of the ERC-CoG GEODAP project reopened and extended the northern sector of Area II, revealing additional combustion features and a curved alignment of posts interpreted as a structural boundary demarcating the inhabited area from the surrounding wetland. Bayesian modelling of radiocarbon dates obtained from wooden posts, animal bones, charred seeds, and peat layers indicates that the settlement was occupied between 4680 and 4440 cal BCE (Nicosia et al., 2025, 2026).

The subsistence economy at Molino Casarotto is documented by a rich bioarchaeological record that is both extensive and methodologically robust. Systematic sampling of all major depositional contexts yielded 4337 plant macro-remains representing 76 taxa, dominated by wild wetland and woodland resources. Aquatic plants, particularly water chestnut (*Trapa natans*), along with nuts and fleshy fruits, account for the majority of identified remains (2068 out of 2306), whereas domesticated crops are sporadic. Cereal grains and pulses are extremely rare and unaccompanied by chaff or other processing by-products. Analyses of plant micro-remains, including 17 sediment samples from 11 stratigraphic units (SU), corroborate these findings: no phytoliths diagnostic of cereal husks were detected, while reed beds and other hygrophilous vegetation dominate. Overall, the botanical records testify a largely predominant use of wild resources (Breglia et al., 2025; Jarman, 1971).

Faunal evidence shows a similar pattern. Terrestrial assemblages are largely composed of wild taxa, notably red deer, roe deer, and wild boar, whereas domestic species are scarce and quantitatively marginal. Freshwater resources are abundant: fish bones and mollusc shells document intensive exploitation of the adjacent lacustrine environment (Boyle, 2014; Breglia et al., 2025; Jarman, 1976). Taken together, these datasets illustrate a highly specialised subsistence strategy focused on (i) the exploitation of wetland and aquatic resources, both plant and animal; (ii) hunting of large ungulates; and (iii) minimal incorporation of crops and domesticates. This economic profile contrasts sharply with contemporary agro-pastoral sites, highlighting a locally adapted strategy that leverages the productivity of the Fimon Valleys wetland.

Complementary evidence from lithic studies provides independent insight into supra-local connections. The assemblage from the 2022 excavations includes 45 artefacts—16 retouched tools, 22 blades and bladelets, 6 flakes, and one lamellar core—indicative of a predominantly laminar production system. Petrographic and macroscopic analyses identify almost all artefacts as high-quality Maiolica flint (grey-pink to reddish varieties) sourced from the central-western Lessini Mountains. Large blades preserve cortical surfaces, suggesting procurement from primary outcrops or karstic soil deposits, while the absence of early-stage débitage indicates that blanks were imported as finished or semi-finished products (Nicosia et al., 2025). This pattern is consistent with specialised extraction and production centres in the Lessini area and with widespread circulation of these flints across northern Italy during the Neolithic (Barfield, 1990, 1993, 2000; Bernabò Brea et al., 2006; Cavulli et al., 2002; Longo et al., 2004; von Nicolai & Töchterle, 2020).

A polished greenstone axe from SU 7 provides further evidence of long-distance exchange. Mineralogical composition and texture suggest a provenance in the Western Alps, possibly linked to workshops in the Rivanazzano area (Oltrepò Pavese). Such greenstone axes are widespread in northern Italy and well attested at other sites in the Berici Hills around Lake Fimon, highlighting connections that extend well beyond the regional scale documented for flint procurement (Biagi & D'Amico, 2013).

Together, archaeobotanical, archaeozoological, and lithic evidence portray a community whose subsistence strategies were firmly rooted in local wetland and wild resources, while simultaneously participating in regional and extra-regional exchange networks for lithic and stone materials. This apparent asymmetry between highly localised food production and the circulation of toolstone provides the archaeological framework for addressing a central theme of this study: the provenance of the cereal grains recovered at Molino Casarotto, investigated through strontium isotope analysis.

Geological and Archaeological Framework for Baseline Design

The study area encompasses the Berici Hills, where Molino Casarotto is located, and adjacent landscapes in western Veneto, which concentrate most of the MN settlement evidence (Fig. 1). In eastern Veneto, human occupation is documented

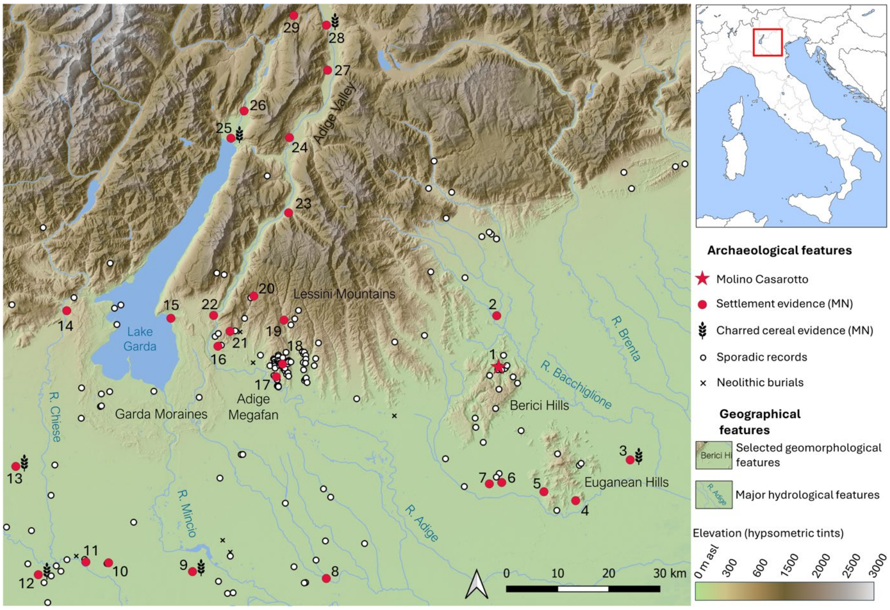

Fig. 1 Distribution map of known Middle Neolithic sites in the study area: 1, Molino Casarotto; 2, Vicenza—Dal Molin; 3, Maserà di Padova; 4, Monselice; 5, Le Basse di Valcalaona; 6, Noventa Vicentina—Capo Villa; 7, Ca' Bissara; 8, Ostiglia—La Vallona; 9, Levata di Curtatone; 10, Casatico di Marcaria; 11, Mosio—Fondo Montecucco; 12, Vho di Piadena; 13, Isorella; 14, Gavardo—Roccolino; 15, Rocca di Garda; 16, Sant'Ambrogio di Valpolicella; 17, Quinzano Veronese; 18, Monte Spigolo; 19, Lugo di Grezzana; 20, Scalucce di Molina; 21, Vaio di Lena; 22, Rocca di Rivoli; 23, Ala—Le Corone; 24, Isera—La Torretta; 25, Riva del Garda—Via Brione; 26, Arco—Moletta; 27, Romagnano Loc III; 28, Trento—La Vela; 29, Covelo di Terlago. Site data are based on published sources (Capuis et al., 1992; RAPTOR, 2026; Tiné, 2015). The map additionally highlights major geomorphological and hydrological features of the region and was produced using QGIS

only from the final MN and more clearly during the Late Neolithic, whereas for the period considered here only sporadic or chronologically uncertain records are available. No MN sites are known from the inner mountain areas, except for the Adige Valley acting as a natural corridor, nor from the lower plain and lagoon–coastal zone, where possible evidence may be buried beneath thick alluvial deposits (Capuis et al., 1992; RAPTOR, 2026; Tiné, 2015).

For these reasons, the analysis focuses on areas with securely documented MN occupation. As $^{87}Sr/^{86}Sr$ depends on composition, age, and diagenetic history of rocks, variability in the geological substrate in this region—including both bedrock and deposits—exerts a primary control on the bioavailable strontium isotope composition of soils and plants, providing the geochemical basis for provenance studies. At the same time, the $^{87}Sr/^{86}Sr$ baseline is here conceived as an archaeological construct rather than a comprehensive geological representation. Its aim is to capture the range of bioavailable $^{87}Sr/^{86}Sr$ values that would have been accessible to Neolithic communities operating within the environmental and socio-economic landscape surrounding Molino Casarotto.

Although a national bioavailable strontium isoscape for Italy is available (Lugli et al., 2022), its primary objective is to provide a predictive framework at the national scale. In contrast, the present study required a hypothesis-driven baseline specifically designed to test alternative archaeological scenarios of cereal provenance. In the study area, several geological units considered archaeologically relevant are represented in the existing isoscape by relatively sparse sampling and interpolated values, while the underlying dataset combines different sample types collected under diverse sampling strategies. A dedicated baseline based on a standardised modern plant sampling protocol was therefore developed to characterise the geological units considered most relevant to the archaeological questions addressed here. However, the resulting baseline should not be considered exhaustive and wider primary sampling may refine the range of locally bioavailable $^{87}Sr/^{86}Sr$ values and improve the characterisation of within-unit variability.

The baseline was intentionally designed at a regional scale, as this represents a reasonable and analytically tractable spatial framework for assessing the provenance of staple food resources. Sampling was therefore guided by archaeological relevance, prioritising geological units located within the site's immediate hinterland and in areas potentially connected to documented patterns of Neolithic mobility and exchange.

Local sampling centred on the Berici Hills to characterise the strontium signature of the site's immediate surroundings (Fig. 2). Additional samples targeted nearby fertile landscapes and areas with known Neolithic activity: the Bacchiglione and Adige floodplains as the closest agricultural plains; the Euganean Hills for their Neolithic occupation, documented agricultural practices, and local flint sources; the Adige megafan and Lake Garda moraines as strategic junctions linking the upper Adige Valley, the Lessini Mountains, and the Venetian and central Po plains. Finally, the Lessini Mountains were included due to their direct archaeological connection with Molino Casarotto through the procurement of high-quality flint, with sites specialised in extraction and lithic production. Together, these units define a geologically and geomorphologically heterogeneous landscape with the potential to generate distinct bioavailable strontium isotope domains (Carta geologica d'Italia, 2009).

Materials and Methods

Modern Baseline Sampling

Modern arboreal vegetation was systematically sampled across the region to establish a regional $^{87}Sr/^{86}Sr$ baseline framework for the interpretation of archaeological plant remains (SI Tab S1). This approach was taken due to the increased precision of primary sampling, as opposed to machine learning approaches when trained on insufficient local data (Holt et al., 2025). Sampling targeted vegetation growing on contrasting geological substrates, according to the 11 geological units previously defined, under the assumption that plant $^{87}Sr/^{86}Sr$ ratios reflect the strontium isotopic composition of the surrounding environment (Holt et al., 2021; James et al., 2025; Snoeck et al., 2020). For each geological unit, one or two plots were selected at least

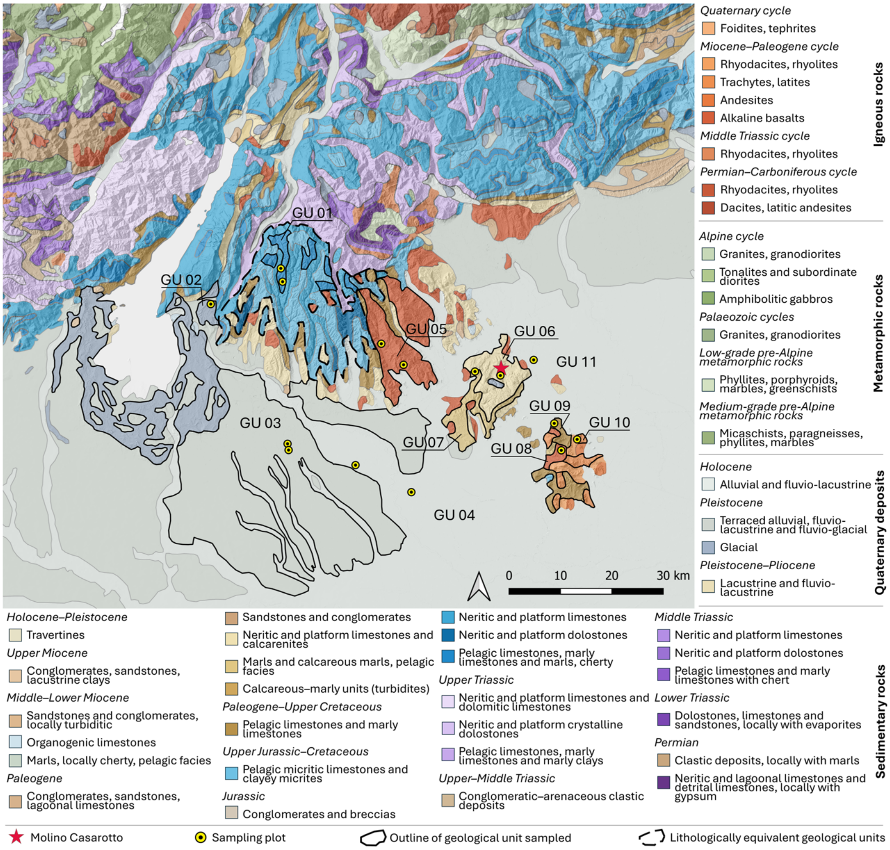

Fig. 2 Geological map of the study area showing the sampled geological units (GU) for the construction of the bioavailable Sr baseline and the location of the sampling plots. Geological units targeted for sampling are highlighted, and plot positions are indicated. The map was produced using QGIS

50 m from cultivated fields, roads, rivers, and artificial channels to minimise contamination from fertilisers, pesticides, traffic-derived aerosols, and non-local water sources (Fig. 2). Generally, sampling took place at distances far greater than 50 m from potential sources of contamination, and potential risks were carefully considered in all instances. At each sampling plot, leaf material from different tree species was homogenised prior to analysis in order to obtain a composite $^{87}Sr/^{86}Sr$ signal representative of the locality and to reduce the influence of taxon-specific or individual outliers (French et al., 2024; Macheridis et al., 2024). Where multiple sampling plots were available within the same lithological unit, plant material was further homogenised to obtain a composite unit-level signature. These values represent the integrated signal of the sampled material rather than individual plot-level measurements. Leaf material was collected from native and, where unavoidable, allochthonous tree and shrub species growing in managed and unmanaged settings. Rather than replicating crop root depths, these were targeted to provide the best analogue

for archaeological soils by avoiding shallow ephemeral root systems that are more likely to take up modern contaminant strontium and deep root systems that could access deep water system strontium sources. Leaves were hand-picked from a single individual per species at heights between 50 and 300 cm and under variable light exposure, air-dried indoors, and transferred to the Cardiff University BioArchaeology laboratory for further processing. They were gently dry-wiped to remove any adhering contaminants, freeze-dried, and crushed to tea leaf consistency. Equal weights of crushed plant material from each of the individual plants from each geological unit were combined to create representative samples. The resulting homogenised plants samples weighed 113.9–205.4 mg.

Homogenised plant samples were transferred to the CELTIC laboratory for chemical digestion. Samples were transferred to clean beakers, and 4 mL of concentrated HNO_3 was added to each sample. A lid was placed on each beaker and partially tightened, allowing for gas to escape, and the samples were left to digest under a fume hood for approximately a week. Next, 4 mL of 30–32% H_2O_2 was added to each sample. Again, a partially tightened lid was placed on each sample, and the samples were left to digest under a fume hood for another week. Finally, the lids were removed, and the samples were placed on a hot plate to dry down overnight.

When the samples were fully dried, 1 mL of 8 M HNO_3 was added to each sample, and the samples were covered with fully tightened lids and allowed to flux on a hot plate for 1 day until fully redissolved. The redissolved digested samples were then transferred to clean microcentrifuge tubes using unique clean pipette tips and centrifuged for 2–3 min. Only the liquid portion of the sample was transferred to the columns for strontium extraction and isotope analysis, following the protocol for column chemistry used for the archaeobotanical samples, archaeobotanical leachates, and sediment leachates (see below). This regional $^{87}Sr/^{86}Sr$ baseline framework provides the reference against which archaeological cereal remains have been compared to assess their provenance.

Sediment Leachates from the Burial Environments

Sediment samples from SU 5, 7, and 20, corresponding to the sedimentary matrix around the cereal grains, were leached to provide a baseline for interpreting the seed leachates. Sediment samples were placed in clean glass dishes and allowed to dry overnight in a 65 °C oven. Thoroughly dry samples were then powdered with an agate mortar and pestle, and 1.0 g of each powdered sample was transferred to the CELTIC clean laboratory for further processing. In CELTIC, the powdered sediment samples were placed in clean Teflon beakers, and 8 mL of 2 M HCl was added to each sample. After 72 h, 1.0 mL of sediment leachate was pipetted into clean microcentrifuge tubes and centrifuged for 15 min. Approximately 950 μL of leachate was then pipetted into clean beakers and left uncovered on a 120 °C hotplate to dry down overnight. The dry sediment leachates were then redissolved in 1 mL 8 N HNO3 and allowed to flux overnight on a 120 °C hotplate before being loaded into columns for strontium extraction chemistry (see below).

Archaeobotanical Samples and $^{87}Sr/^{86}Sr$ Isotope Analysis

The cereal assemblage comprises nine charred caryopses, eight of which were identified to species level, including emmer (*Triticum dicoccum*), einkorn (*T. monococcum*), naked wheat (*T. aestivum/durum*), and barley (*Hordeum vulgare*). One additional charred caryopsis was excluded from further analyses due to poor preservation, which prevented confident identification to genus or species level and did not allow secure attribution to a cultivated cereal. Sample selection was based on taxonomic identification and secure stratigraphic provenance. All cereal remains derive from SU 5, 7, and 20, each associated with domestic hearth contexts, and no chaff remains were recovered from the site. In the absence of chaff, three caryopses (one from each stratigraphic unit) were selected for radiocarbon dating to exclude potential later intrusions (see Results). The remaining five charred caryopses (one emmer from SU 5; one emmer and one naked wheat from SU 7; one emmer and one naked wheat from SU 20) were selected for strontium isotope analysis (Fig. 3).

Prior to analysis, caryopses were visually inspected, gently cleaned of adhering sediment, and handled with clean tools. Individual seeds were crushed in an agate mortar and pestle, weighed (SI Tab S2), and transferred to clean Teflon beakers. Following similar methods to Millet et al. (2008) performed on rock samples, crushed seeds were leached in 3 mL of 2 M HCl for 2 h at room temperature. In the last 15 min, samples were centrifuged so that the sample and supernatant were separated. The leachate was then pipetted off the sample. Both a lower HCl concentration and a shorter procedural time were used for leaching compared with previous studies (e.g. Ryan et al., 2021;

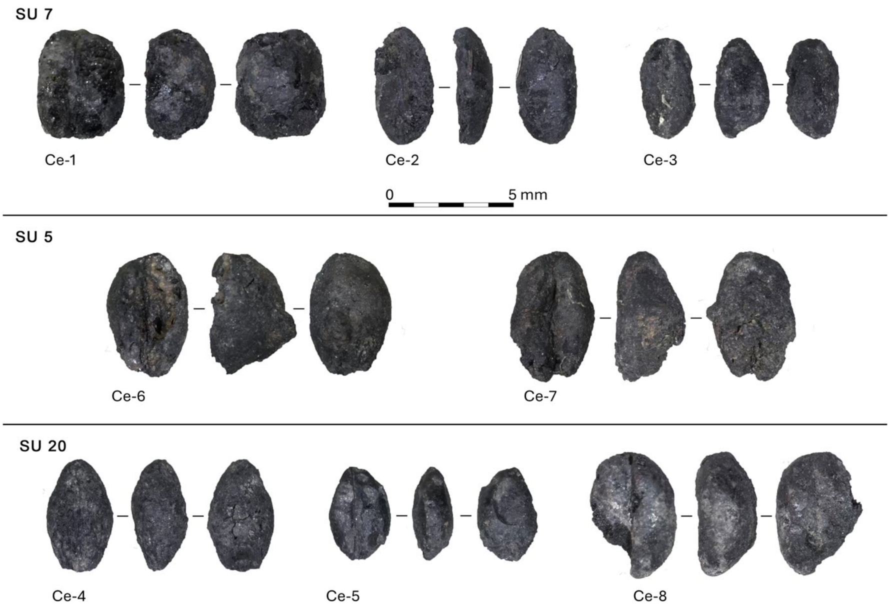

Fig. 3 Cereal remains (Ce-1–Ce-8) recovered from Molino Casarotto, organised by stratigraphic unit (SU). Each image panel corresponds to a different unit, showing all cereals identified in that layer

Styring et al., 2019). This new method was used so that measurable concentrations of Sr remained in the individual caryopses due to their predicted low Sr concentration. This less aggressive method is commonly used for leaching rock samples, where Sr is structurally bound in mineral structures and therefore harder to leach compared to organic samples. This represents a compromise between aggressive removal of diagenetic Sr and retaining the integrity of the sample. The matching of the leachate and soil results and the variability of the cereal results suggest that this is an effective approach, with the acknowledgment that some remnant diagenetic Sr may well remain. The samples were rinsed with MQ H_2O three times, pipetting each rinse off and adding it to the leachate samples, then digested with 1 mL of 8 M HNO_3 and 1 mL of 30% H_2O_2 at 100 °C for 48 h. Samples were then dried down and taken up in 1 mL of 7 M HNO_3 for column chemistry.

Leachates were retained for isotope analysis for comparison with cereal results. Then, for modern plant samples, archaeobotanical samples, archaeobotanical leachates, and sediment leachates, strontium was separated from the sample matrix by column chemistry. Firstly, Sr.Spec™ resin was extensively cleaned in 6 M HCl and MQ H_2O prior to being used in column chemistry. One millilitre columns were cleaned by soaking in 10% HNO_3 for several days and rinsing with MQ H_2O. One millilitre columns were loaded with 100 μL of Sr.Spec™ resin. Columns and resin were then further cleaned with alternating 1 mL volumes of 6 M HCl and MQ H_2O (three times each). Two volumes of 500 μL 7 M HNO_3 were added to condition the resin prior to sample loading in 7 M HNO_3, using a 1 mL volume for first pass and 500 μL volume for second pass. Calcium was eluted with successive amounts of 7 M HNO_3 (50 μL, 100 μL, 350 μL, 800 μL) before Sr collection into clean beakers with 3×500 μL of 0.05 N HNO_3. Samples were then evaporated at 95 °C, before being taken up in 500 μL 7 M HNO_3 for the second pass, during which the above procedure was repeated.

After the second pass through chemistry, samples were dried and taken up in 1.2 mL of 2% HNO_3 ready for analysis. $^{87}Sr/^{86}Sr$ ratios were measured using a Thermo Scientific Neoma MS/MS Multicollector ICP-MS in the CELTIC laboratory at Cardiff University. Analysis of NIST SRM 987 during analysis of cereals gave a $^{87}Sr/^{86}Sr$ value of 0.710273 ± 0.000016 (2SD, n = 4). In addition, an in-house coral standard (EC-5) was measured giving a $^{87}Sr/^{86}Sr$ value of 0.709163 ± 0.000029 (2SD, n = 5). All data are corrected to a NIST SRM 987 value of 0.710248. Due to the lower concentration (~2 ng) of Sr, sample Ce-8 (Sr-5) was measured using a Thermo Scientific Triton plus, which allows more accurate measurement of low-concentration samples (see SI Supplemental Method). For TIMS analysis, Sr was loaded on single outgassed Re zone refined filament alongside 1 μL Ta2O5 activator. The Ce-8 sample ran for 187 cycles. Full procedural blanks were 13 pg of Sr for samples and 19 pg of Sr for leachates.

Results

Baseline

The modern bioavailable strontium baseline, defined by plant samples from 11 geological units, spans a very wide $^{87}Sr/^{86}Sr$ range from 0.7054 to 0.7105 (Table 1).

Table 1 $^{87}Sr/^{86}Sr$ ratios of modern plant samples used to construct the bioavailable Sr baseline; columns indicate the geological unit (GU) ID, location, measured ratio, and 2SE

ID	Location	$^{87}Sr/^{86}Sr$	2SE
GU 01	Lessini Mountains, calcareous bedrock	0.708338	9.28E – 06
GU 02	Calcareous moraines of the Lake Garda glacier	0.708085	7.76E – 06
GU 03	Pleistocene Megafan of the River Adige	0.709148	6.94E – 06
GU 04	Floodplain of the River Adige	0.710581	6.68E – 06
GU 05	Lessini Mountains, basalt bedrock	0.705475	7.52E – 06
GU 06	Berici Hills, calcareous bedrock	0.708506	12E – 06
GU 07	Berici Hills, marls and calcareous marl bedrock	0.708597	11E – 06
GU 08	Euganean Hills, alkaline basaltic bedrock	0.706634	10E – 06
GU 09	Euganean Hills, marly limestone bedrock	0.708133	10E – 06
GU 10	Euganean Hills, trachyte bedrock	0.707272	12E – 06
GU 11	Floodplain of the River Bacchiglione	0.708742	15E – 06

Table 2 Strontium isotope results for sediment leachates from Molino Casarotto

ID	ID analysis	SU	$^{87}Sr/^{86}Sr$ Mean	2SE
ARC22MC-MF90	GDP-S1	20	0.708354	9E – 06
ARC22MC-MF1	GDP-S2	5	0.708378	1E – 05
ARC22MC-MF 118	GDP-S3	7	0.708273	1E – 05

Carbonate-dominated lithologies and fluvial deposits show intermediate values, whereas volcanic units display lower ratios. Analytical uncertainties are low ($\pm 2SE \leq 15E-06$), and the mean values of the different geological units are clearly separated, with no overlap within analytical uncertainty.

Sediment Leachates

The $^{87}Sr/^{86}Sr$ ratios of the sediment leachates were closely clustered, ranging from 0.708273 to 0.708378 (mean 0.708335, SD 4.5E – 05) with low analytical uncertainties (Table 2). As a group, the $^{87}Sr/^{86}Sr$ ratios of the sediment leachates are similar to but slightly lower than the bioavailable $^{87}Sr/^{86}Sr$ ratios of GU 06 and GU 07, the plant samples from the Berici Hills where the site is located.

Archaeological Sample

Three charred caryopses, one from each stratigraphic unit (SU 5, 7, and 20), were radiocarbon-dated at the University of Groningen to confirm secure stratigraphic provenance and to exclude potential later intrusions. The calibrated ^{14}C ages indicate that all dated cereals fall within the same chronological range, consistent with the archaeological context, and they place the samples in the MN (Table 3), supporting the contemporaneity of the samples selected for strontium isotope analysis.

The $^{87}Sr/^{86}Sr$ ratios of the archaeological cereal samples ranged from 0.7092 (Sr-1) to 0.7163 (Sr-2), with low analytical uncertainties (±2SE ≤ 17E − 06) (Table 3). This is a very wide range and showed marked inter-sample diversity, especially considering the limited dataset. All results were compared against the modern bioavailable baseline. Sr-2 displayed the highest ratio (0.7163), exceeding the range of all baseline units, as does Sr-3 (0.7117), though to a lesser extent, whereas Sr-1 and Sr-4 (0.7099), and Sr-5 (0.7100) fell within the range of River Adige units (Fig. 4).

Leachate analyses of the same samples yielded consistent $^{87}Sr/^{86}Sr$ ratios (0.70841–0.70849 $n = 5$, see SI Tab. S3) that matched the leachates from the burial environments (0.70827–0.70835 $n = 3$, Table 2) across all samples. This provides strong evidence for the removal of diagenetic strontium. It is not, however, possible to be certain that all diagenetic strontium has been removed, and therefore, it is likely that at least some remnant strontium remained in the seeds. However, variation in the primary seed results demonstrates that any remnant strontium from the burial environment did not have a dominant effect and that results are useful for exploring the origins of the crops.

Discussion

Baselines and Comparisons

The results of the baseline analyses, both of bioavailable and archaeological sediment strontium, provide an opportunity for useful comparisons. First, the consistent offset between the $^{87}Sr/^{86}Sr$ ratios of the sediment leachates and the local bioavailable $^{87}Sr/^{86}Sr$ ratios indicated by GU 06 and GU 07 reinforces previous studies that have identified similar offsets (Maurer et al., 2012; Willmes et al., 2018). Although the offset is small at ≈ 0.0002, results in the fourth decimal place are generally considered interpretable in archaeological studies, highlighting the importance of comparing like with like in assessments of provenance.

Additionally, the new $^{87}Sr/^{86}Sr$ ratios produced by this study, based on a local empirical baseline, enable a critical comparison with isoscapes modelled both on

Table 3 Strontium isotope results and radiocarbon dates for cereal grains from Molino Casarotto, with stratigraphic unit (SU) and taxon

ID	ID analysis	ID dating lab	Taxon	SU	Date (BP ± 1 s)	$^{87}Sr/^{86}Sr$ Mean	2SE
Ce-1	Sr-1	-	*T. aestivum/durum*	7	-	0.709228	13E − 06
Ce-2	14C-1	GrM-38271	*Hordeum vulgare*	7	5580 ± 80		
Ce-3	Sr-2	-	*T. dicoccum*	7	-	0.716344	17E − 06
Ce-4	Sr-3	-	*T. monococcum*	20	-	0.711789	12E − 06
Ce-5	14C-2	GrM-37476	*T. monococcum*	20	5915 ± 35		
Ce-6	14C-3	GrM-36418	*T. dicoccum*	5	5774 ± 25		
Ce-7	Sr-4	-	*T. dicoccum*	5	-	0.709976	9E − 06
Ce-8	Sr-5	-	*T. aestivum/durum*	20	-	0.710028	5E − 05

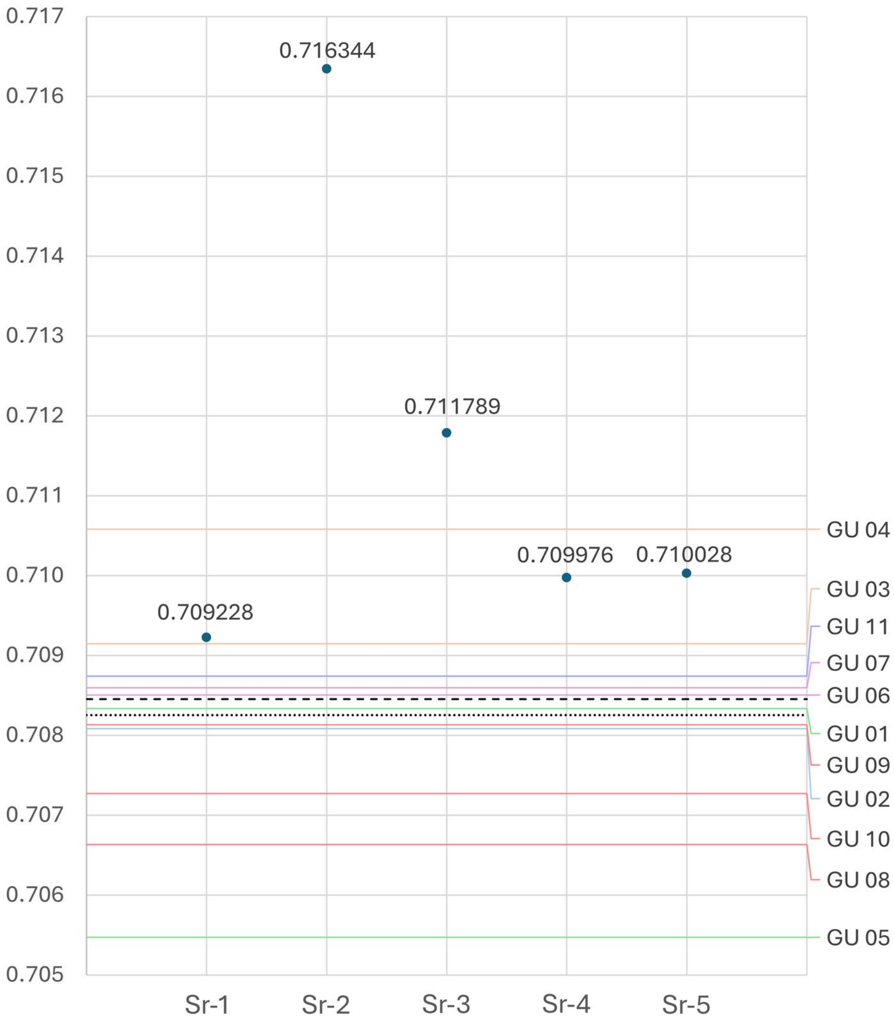

Fig. 4 Strontium isotope ratios ($^{87}Sr/^{86}Sr$) of archaeological cereal samples from Molino Casarotto, plotted against the modern bioavailable $^{87}Sr/^{86}Sr$ baseline and leachate data from soils (black dotted line) and cereal grains (black dashed line). The baseline includes the following geomorphological units: River Adige floodplain (GU 04, yellow), River Adige megafan (GU 03, orange), River Bacchiglione floodplain (GU 11, purple), Berici Hills (GU 06, GU 07, magenta), Lessini Mountains (GU 01, GU 05, green), Euganean Hills (GU 08, GU 09, GU 10, red), and Lake Garda moraines (GU 02, cyan)

bioavailable strontium archives and on a broader range of strontium archives (Lugli et al., 2022). The new $^{87}Sr/^{86}Sr$ ratios are compared with the ratios predicted for the same locations by Lugli *et al.*'s 'Bioavailable' and 'All' Universal Kriging isoscapes (Table 4). Where empirical ratios were derived from composite samples, the corresponding predicted values were averaged across the sampled locations.

For 6 of the 11 empirical ratios, the ratio predicted by the 'All' isoscape was closer than the ratio predicted by the 'Bioavailable' isoscape. In 4 instances, the

'Bioavailable' prediction was closer, and in 1 instance, the predictions were equally close. The slightly better performance of the isoscape incorporating non-bioavailable archives may indicate that different bioavailable archives are not necessarily interchangeable as predictors; the empirical values in this study come from leaves and sediment leachates, whereas the bioavailable dataset used to construct the isoscape incorporates additional archives such as snail shells, rodent teeth, food products, and mineral waters.

At the same time, the present empirical baseline should not be interpreted as a complete characterisation of local isotopic variability within individual geological units. Rather, it provides representative signatures for archaeologically defined source areas, allowing the evaluation of specific provenance scenarios. Additional primary sampling and replicate analyses of individual plants will be required to further quantify fine-scale variability and progressively refine regional bioavailable Sr datasets.

This comparison suggests that the predictive performance of an isoscape depends not only on the classification of the input archives as bioavailable or non-bioavailable, but also on the nature, spatial distribution, and representativeness of the underlying dataset. The observed discrepancies for several geological units further emphasise the value of locally acquired empirical baselines when provenance studies aim to discriminate among specific geological units selected on archaeological grounds rather than to describe broad regional isotopic trends. Overall, national-scale isoscapes and archaeologically targeted empirical baselines should therefore be considered complementary tools, operating at different spatial and interpretative scales in provenance studies.

Testing Alternative Models of Cereal Provenance

To interpret the provenance of cereals recovered at Molino Casarotto, four alternative scenarios were initially formulated, each implying distinct spatial and economic configuration.

Scenario A: Local agro-pastoral supply (Fig. 5A). Cereals originate from cultivation areas immediately surrounding the site, particularly the Berici Hills (GU 06–07) or the Bacchiglione floodplain (GU 11). Under this scenario, $^{87}Sr/^{86}Sr$ ratios should fall strictly within the local range.

Scenario B: Direct integration into flint procurement networks (Fig. 5B). Cereals would be acquired alongside Lessinian flint from core production areas (GU 01) or adjacent basalt units (GU 05), with isotope ratios matching these prealpine geological units.

Scenario C: Independent regional cereal networks (Fig. 5C). Cereals could circulate through regional agricultural areas, such as the Adige megafan (GU 03) and floodplain (GU 04), the Euganean Hills (GU 08–10), or the Bacchiglione floodplain (GU 11), without being directly linked to lithic exchange. Isotopically, this scenario could produce a more diverse range of $^{87}Sr/^{86}Sr$ ratios, reflecting

Table 4 $^{87}Sr/^{86}Sr$ ratios of modern plant samples and sediment leachates compared with approximate ranges of predicted $^{87}Sr/^{86}Sr$ in two modelled isoscapes (Lugli et al., 2022)

ID	Location	Empirical $^{87}Sr/^{86}Sr$	Lugli et al. (2022) 'Bioavailable' Universal Kriging	Lugli et al. (2022) 'All' Universal Kriging
GU 01	Lessini Mountains, calcareous bedrock	0.708338	≈ 0.7087	≈ 0.7083
GU 02	Calcareous moraines of the Lake Garda glacier	0.708085	≈ 0.7089	≈ 0.7087
GU 03	Pleistocene Megafan of the River Adige	0.709148	≈ 0.7088	≈ 0.7089
GU 04	Floodplain of the River Adige	0.710581	≈ 0.7084	≈ 0.7083
GU 05	Lessini Mountains, basalt bedrock	0.705475	≈ 0.7076	≈ 0.7068
GU 06	Berici Hills, calcareous bedrock	0.708506	≈ 0.7083	≈ 0.7083
GU 07	Berici Hills, marls and calcareous marls bedrock	0.708597	≈ 0.7083	≈ 0.7081
GU 08	Euganean Hills, alkaline basaltic bedrock	0.706634	≈ 0.7082	≈ 0.7057
GU 09	Euganean Hills, marly limestone bedrock	0.708133	≈ 0.7082	≈ 0.7067
GU 10	Euganean Hills, trachyte bedrock	0.707272	≈ 0.7083	≈ 0.7077
GU 11	Floodplain of the River Bacchiglione	0.708742	≈ 0.7085	≈ 0.7079
GDP-S1	Molino Casarotto	0.708354	≈ 0.7082	≈ 0.7083
GDP-S2	Molino Casarotto	0.708378		
GDP-S3	Molino Casarotto	0.708273		

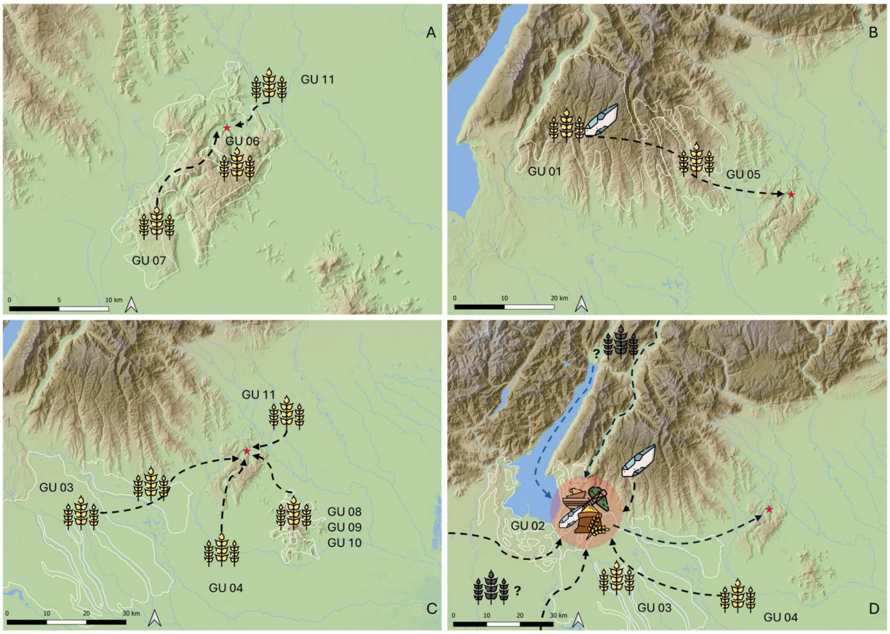

Fig. 5 Alternative provenance scenarios for cereals from Molino Casarotto: **A** local supply; **B** cereals acquired alongside Lessinian flint; **C** regional cereal circulation; **D** redistribution hub model involving multiple goods. Cereals potentially originating from unknown extra-regional sources are highlighted in black and marked with a question mark. The figure was produced using QGIS

the multiple independent sources of cereals across the region, depending on the nature of the networks.

Scenario D: Redistribution through regional exchange hubs (Fig. 5D). Cereals are transported via nodal hubs rather than direct agricultural networks. Candidate hubs include the Garda moraines (GU 02) and the Adige megafan (GU 03), connecting the Alpine–prealpine domain, Venetian hills, and central Po Plain. $^{87}Sr/^{86}Sr$ ratios would be expected to reflect mixed regional, and potentially extra-regional, signatures.

Comparison with the isotope data makes Scenario A and Scenario B unlikely, as none of the cereals falls within the currently defined local range or match the Lessinian units. Three samples (Sr-1, Sr-4, and Sr-5) are compatible with regional agricultural or nodal areas (Adige megafan and floodplain), making both Scenario C and Scenario D plausible for these specimens. However, the remaining two samples (Sr-2 and Sr-3) have higher ratios than are consistent with regional bioavailability, with Sr-3 showing moderately higher and Sr-2 markedly more radiogenic $^{87}Sr/^{86}Sr$ ratios, consistent with substrates substantially older or compositionally different than those present in the regional baseline. Taken together, the dataset is best accommodated by Scenario D (hub-based redistribution), as this model explains both regional and extra-regional provenance patterns. Scenario C alone appears insufficient to explain the observed variability, suggesting that additional or previously unconsidered circulation routes may have been involved. Although based on a small sample comprising the five grains available for analysis, the marked isotopic spread observed is difficult to reconcile with a single provenance area as currently understood, suggesting contributions from multiple source regions. While the Western Alps (source of the greenstone axe; see Nicosia et al., 2025) are a plausible extra-regional origin, other radiogenic regions—such as Valsugana valley or central Alps—cannot be excluded (Lugli et al., 2022). Overall, the isotopic evidence indicates that cereals at Molino Casarotto were not strictly local, supporting their integration into regional and extra-regional exchange systems. At the same time, circulation did not necessarily follow lithic exchange pathways, supporting a complex and multi-scalar organisation of Neolithic provisioning strategies, with different networks and supply catchments supporting different resources.

Implications for Subsistence Strategies and Interaction Networks

The strontium isotope evidence from Molino Casarotto provides new insights into mobility, economic specialisation, and inter-community interaction during the Middle Neolithic. The non-local provenance of several cereal grains demonstrates that even a community strongly specialised in wetland exploitation, hunting, and fishing was integrated into broader regional and extra-regional exchange networks. This decoupling of production and consumption indicates that subsistence strategies could be locally optimised for the exploitation of immediately available wild resources, while storable staple crops were obtained through socially mediated networks rather than through local cultivation.

Provenance studies have long contributed to reconstructing Neolithic exchange systems in northern Italy, revealing structured patterns of circulation organised around nodal areas of production and redistribution rather than simple linear transfers (Ammerman & Biagi, 2003; Barfield, 1981, 2000; Bernabò Brea et al., 2006; Pétrequin & Jeunesse, 1995; von Nicolai & Töchterle, 2020). Lithic raw materials, particularly Alpine greenstone and high-quality flint, document multi-scalar networks linking source areas, specialised workshops, and consumer communities across the Po Plain. Greenstone tools derived from high-pressure meta-ophiolites of the Western Alps were extracted in high-altitude contexts and secondary deposits, then redistributed from production centres such as Alba and Rivanazzano toward eastern regions (Bernabò Brea et al., 2006; D'Amico & Starnini, 2012; D'Amico et al., 2006; Pétrequin et al., 2006). A comparable but geographically inverse system structured the circulation of South-Alpine flint, especially the Lessinian flint, where extraction and workshop activities were concentrated near primary outcrops and distribution extended across much of northern Italy (Barfield, 1990, 1993, 2000; Cremaschi, 1981; Goldenberg, 2006; Negrino et al., 2006; Negrino & Starnini, 2006; Pedrotti & Salzani, 2010). Obsidian followed similarly structured south–north nodal pathways (Ammerman, 1979), reaching intermediary centres south of the Po Plain, such as Gaione, Pescale, and Fornace Cappuccini, before further redistribution (Ammerman & Polglase, 1998; Pessina & Radi, 2006; Polglase, 1988; Thorpe et al., 1979).

Due to their durability and the ability to characterise their geological and petrographic features, lithic materials have dominated archaeological reconstructions of exchange networks. Anthropological research has long recognised agricultural surplus as a fundamental precondition for processes of labour specialisation and intensified inter-community interaction, which in turn are implicated in the emergence of more complex forms of social organisation (Childe, 1936, 1950, 1958; Polanyi, 1944, 1957). In non-monetary and non-state societies, the mobilisation of surplus is generally understood as embedded within networks of reciprocity and redistribution, reinforcing social relationships rather than operating through market mechanisms (Humphreys, 1969; Polanyi, 1944). Agricultural surplus therefore did not necessarily automatically generate exchange, but it could reshape material and social conditions, facilitating intensified interaction and constituting a structural precondition for labour specialisation and the development of exchange networks (Tisdell & Svizzero, 2017).

Cereals are particularly significant in this respect because their storability and transportability increase their potential in accumulating and mobilising surplus, allowing specific actors to mediate and shape exchange networks (Mayshar et al., 2022). At the same time, surplus production may have altered needs and aspirations, stimulating the production of new goods and the expansion of exchange relationships (Sahlins, 1972; Xenos, 2021). Within this framework, the circulation of cereals in Neolithic northern Italy may have contributed to sustaining regional interaction networks and to supporting specialised production areas for high demand materials such as South-Alpine flint, greenstone axes, and ornaments, thereby promoting a degree of cultural convergence, as reflected in the widespread distribution of the SMP cultural horizon.

The present study, the first to undertake $^{87}Sr/^{86}Sr$ on archaeobotanical material in Italy, shows that economic specialisation and interdependence were not restricted to the circulation of lithic raw materials or prestige items, but could also involve essential subsistence resources. The identification at Molino Casarotto of cereals originating from distinct geological regions indicates a selective integration into multiscalar interaction networks and suggests that provisioning strategies were flexible and context-dependent rather than strictly localised. Communities lacking durable surplus crops or strategic raw materials may have participated in these networks through the circulation of perishable products linked to hunting and fishing activities (*e.g.* hides, preserved fish, and game meat), whose limited archaeological visibility is largely attributable to taphonomic bias. Antler could be another valuable resource that this community could utilise in these trade networks.

More broadly, this evidence complicates simplified models of Neolithisation based on the progressive replacement of foraging by farming. The coexistence of a highly specialised foraging economy with the incorporation of non-local agricultural products indicates that mixed economies could involve not only multiple subsistence strategies but also a spatial decoupling between production and consumption. Archaeobotanical models have traditionally linked the presence of cereal crop-processing remains to producer sites, while the absence of chaff has often been taken to challenge such interpretations; however, the application of strontium isotope analysis directly to grains provides a means to resolve this ambiguity, particularly at sites lacking macroscopic and microscopic chaff evidence. It is only through this novel programme of strontium isotope analysis on the sparse cereal assemblage that such valuable insights could be gained. This case therefore contributes to current models of Neolithic economic organisation, albeit on a small sample, by highlighting the interplay between local specialisation, mobility, and socially embedded exchange, while also emphasising the importance of evaluating individual communities within their specific environmental and cultural settings rather than through universal or linear developmental frameworks, and by opening new avenues for investigating local subsistence strategies.

Conclusions

This study provides further evidence for the vast untapped potential of strontium isotope analysis on plant remains to test for local/non-local cultivation and for investigating crop provenance in prehistoric contexts. By applying it to a small but well-constrained sample from Molino Casarotto—where multiple lines of evidence suggested cereals were non-local—we suggest that even limited datasets can yield clear insights into regional and extra-regional circulation of staple foods.

Methodologically, this supports the use of $^{87}Sr/^{86}Sr$ analysis to trace plant mobility, complementing traditional archaeobotanical and material-culture approaches. Theoretically, it opens new perspectives on how prehistoric communities organised subsistence, exchange, and social networks: non-local staples could be integrated into highly specialised local economies, revealing complex, multi-scalar provisioning strategies.

Although the present study demonstrates the promise of the approach, further work on modern reference collections is needed to better quantify variability at the scale of individual plants, cultivation plots, and geological units. Such datasets will provide an increasingly robust empirical framework for interpretating archaeobotanical $^{87}Sr/^{86}Sr$ data. As these bioavailable Sr baselines become progressively refined, strontium isotope analysis of plant remains is likely to play an increasingly important role in reconstructing prehistoric and protohistoric economic organisation, resource circulation, interaction networks, demographic dynamics, and the emergence of non-state complex societies.

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Declarations

Competing Interests The authors declare no competing interests.

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