



Flax use, weeds and manuring in Viking Age Åland: archaeobotanical and stable isotope analysis

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Abstract

Charred masses of nearly 100,000 *Linum usitatissimum* (flax) seeds were found in house remains from Tjudnäs on the Åland Islands, Finland, and radiocarbon dated to AD 880–1020. The flax seeds were large and discovered in lumps, which indicates that they had been pressed for their oil. The flax was accompanied by seeds of *Cuscuta epilinum*, *Lolium remotum*, *Galium spurium* and *Camelina alyssum/sativa*, which are specific weeds of flax fields that mimic it in the flax fields and during crop processing. Several of these species have now become extinct or rare after the introduction of more effective methods of weed control and less flax growing. This find demonstrates the antiquity of this obligate flax weed flora, which appears to have been introduced to Åland together with flax seeds intended for cultivation. Thousands of cereal grains discovered in Viking Age/early medieval (AD 750–1300) Kohagen show that a broad range of crops was grown, with high proportions of *Triticum aestivum* (naked wheat). Stable isotope analyses of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) ratios were done on the flax from Tjudnäs and other crops from Kohagen, all from samples dated AD 880–1020. The analyses showed high values of $\delta^{15}\text{N}$, which can be explained by considerable soil enrichment with manure, possibly also with maritime resources such as seaweed and fish. The $\delta^{13}\text{C}$ values varied between crops, with those for flax being lower than for cereals and *Pisum sativum* (peas), which could reflect different environmental conditions or differences in plant physiology. The factors affecting $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ in flax are, however, poorly understood due to the lack of experimental studies.

Keywords Flax · Archaeobotany · Stable isotope analysis · Viking Age · Flax weeds · Manuring

Introduction

Lumps of charred *Linum usitatissimum* (flax) seeds with associated flax field weeds and thousands of charred cereal grains were found at the sites of Tjudnäs and Kohagen. Both sites are dated to around AD 1000 and are situated in the Åland Islands archipelago in the northern Baltic Sea, where the topography and suitability for growing crops have changed immensely over time due to isostatic land uplift (Fig. 1). The earliest growing of crops on the islands was

done by the maritime hunter-gatherers of the Pitted Ware Culture (Gropkeramisk kultur), ca. 3000 BC (Table 1), when the archipelago was formed of small islands and skerries (islets) (Vanhanen et al. 2019). During the Bronze Age, land areas grew gradually larger from the uplift and plant growing continued. Little is known about the farming of the Early Iron Age, but later on, during the Late Iron Age, an increase in population and farming activities is shown by the archaeological and pollen data (for example, Callmer 1994; Núñez 1995; Ilves 2018a; Alenius 2014; Larsson et al. 2023).

For our period of study, the Late Iron Age (AD 550–1050), the area of the islands was 500–650 km², which is only half of their current size (Núñez 1995). On the higher parts there are exposed areas of bare granite bedrock with settlements and graves. Fine sediments found lower down were suitable for growing crops. Cultivation of light soils, shown by the finds of ancient plough marks created with a simple ard (Núñez 1995), was complemented with slash-and-burn cultivation, as indicated in the pollen data (Alenius et al. 2024). Heavy clay soils appear to have been used as pastures or

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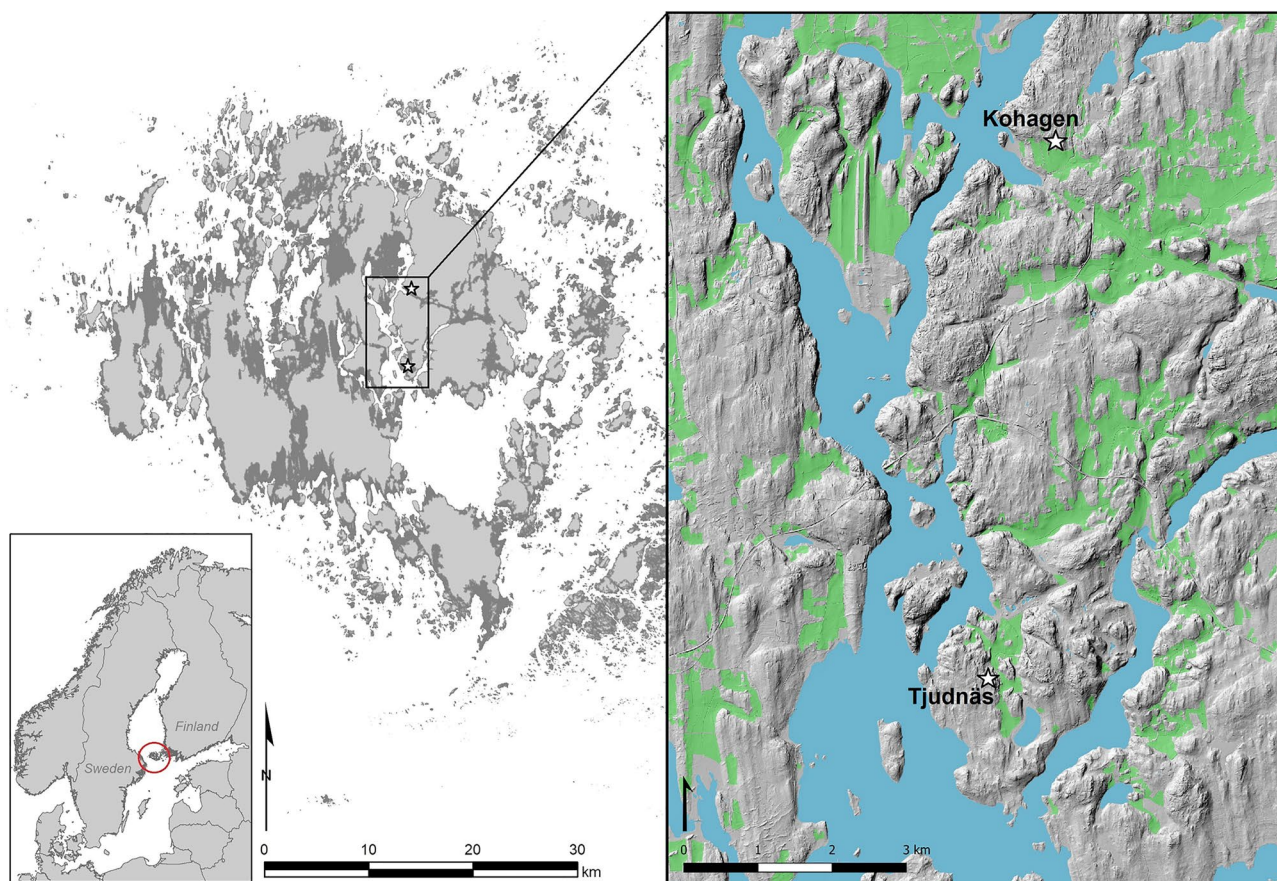


Fig. 1 Left, location of the Åland Islands and the main islands; available land during the Late Iron Age shown in lighter grey; image from ESRI (Environmental Systems Research Institute). Lower left, map of Scandinavia with location of the sites. Right, location of the settlement sites of Tjudnäs and Kvarnbo Kohagen. Present-day arable

areas, which mainly consist of clay soils and tills shown in green. The shoreline shown here is roughly consistent with that of the end of the Late Iron Age, circa AD 1050. Map data from Maanmittauslaitos (The national land survey of Finland), maps drawn by Kristin Ilves

Table 1 Archaeological periods and their dates for the Åland Islands

Phase	Period/culture	Cal age
Neolithic	Kamkeramiska kulturen (Comb Ware)	5500–3300 BC
	Gropkeramisk kultur (Pitted Ware)	3300–2800 BC
	Pitted Ware/Corded Ware	2800–2300 BC
	Kiukainen Ware	2300–1500 BC
Bronze Age	Early Bronze Age	1500–1100 BC
	Late Bronze Age	1100–500 BC
Early Iron Age	Pre-Roman Iron Age	500 BC–AD 1
	Roman Iron Age	AD 1–400
	Migration Period	AD 400–550
Late Iron Age	Merovingian Period	AD 550–750
	Viking Age	AD 750–1050
Medieval period	Early Medieval Period	AD 1050–1300
	Late Medieval Period	AD 1300–1520

meadows for making hay for fodder. The area of the lighter soils suitable for crops was, however, limited, and might not have been able to support a settlement only by farming (Jaatinen et al. 1989). This is reflected in archaeological findings indicating a mixed economy of animal husbandry, crop growing, fowling, fishing, hunting and trading (Storå et al. 2012; Ahola et al. 2014). According to earlier studies, *Hordeum vulgare* (barley) was the main crop, along with *Avena* (oats), *Triticum aestivum* (naked wheat), *Secale cereale* (rye), *Cannabis sativa* (hemp) and *Linum usitatissimum* (flax) (Núñez and Lempiäinen 1992; Andersson 2014, 2017; Lempiäinen-Avci 2021). Our finds from Tjudnäs and Kohagen add to this knowledge, showing the importance of naked wheat and flax at these sites.

Flax was one of the earliest plants to be domesticated, in the Near East as one of the founder crops together with wheat and barley. Its journey northwards was prolonged and it occurred sporadically in northern continental Europe during the Neolithic and Early Bronze Age and became more

common during the Late Bronze Age (Kirleis et al. 2012; Effenberger 2018). In Sweden and Åland the earliest flax is dated to the Late Bronze Age/Pre-Roman Iron Age transition, whereas in mainland Finland and Latvia the first finds are from the Roman Iron Age (Lempiäinen 2011; Viklund 2011; Karg 2012; Grikkpēdis and Matuzeviciute 2020; Vanhanen 2020). Today, flax is mainly grown for the production of fibres and oil. Waterlogged flax stalks are interpreted as direct evidence of retting flax to produce fibres (Alsleben 1995; Viklund 2011), whereas masses of many charred seeds, such as the Tjudnäs find, are considered to indicate food preparation or oil extraction (Larsson 2013). The types of flax used for oil have larger seeds than those used for their fibre, which is also noticeable in archaeobotanical material (Herbig and Maier 2011; Larsson 2013).

Historical records dating from the 16th century onwards show that flax was grown as a summer annual in Finland, both in slash-and-burn plots and in permanent fields (Soininen 1974, p. 178). It benefits from fairly large amounts of manure, preferably sheep dung (Grotenfelt 1899). Although flax is quite commonly found in archaeobotanical assemblages, it remains unclear how it was grown in prehistory. Analyses of stable isotopes of archaeobotanical material can be used to study these practices, as well as the growing conditions. The most common types of such analyses are those of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$). The isotopic ratio of $\delta^{13}\text{C}$ has been used for studying water availability to plants in the past (Ferrio et al. 2005), mainly in southern Europe, where rainfall tends to be a limiting factor for plant growth (Fiorentino et al. 2015). In northern Europe, it has been suggested that $\delta^{13}\text{C}$ values are mainly affected by the levels of organic matter in the soil (Gron et al. 2021). $\delta^{15}\text{N}$ values have been used for studying nutrient status in archaeological remains of crops (Fiorentino et al. 2015), which is increased by factors such as manuring, burning of vegetation and growing in soils that have naturally high $\delta^{15}\text{N}$ (Fraser et al. 2011; Szpak 2014; Hamerow et al. 2020). Regarding flax, experimental studies to understand the effects of manuring, charring or other factors on its levels of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ have not been done, and therefore the causes of variations in the isotopic signals are not well known. Analyses of $\delta^{13}\text{C}$ from archaeological flax remains have only rarely been done (Araus et al. 1999; Lightfoot et al. 2024). Here, we present analyses of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ from archaeobotanical remains of flax from Tjudnäs, as well as of cereals and peas from Kohagen, both in Åland.

Flax has a characteristic weed flora whose evolution was dictated by the growing conditions in the flax fields and the intensive weeding of them (Hjelmqvist 1950). Weeds from open ruderal habitats evolved by selection with the aid of human intervention into weeds of cultivated fields by mimicking the crops and their seeds (Barrett 1983). Accordingly, flax weeds resemble flax in their growth habit and their seed

sizes are also similar to those of flax (Hjelmqvist 1950). The distinctive weed flora of flax fields disappeared nearly completely from the Nordic countries when cotton replaced linen in the 19th century and so less flax was grown, as well as the introduction of more effective ways of controlling crop weeds (Soininen 1974, p. 180). Particular weeds are known to have infested flax fields, but their prehistory is poorly known (Lange 1978). These finds of weeds associated with lumps of linseed from Tjudnäs help to elucidate the prehistory of this weed flora.

This paper aims to shed light on the growing and use of flax in the Viking period, using archaeobotany and stable isotope analysis. The study material consists of lumps of thousands of flax seeds and associated weeds from the Late Iron Age site of Tjudnäs, and a mass find of cereal remains from the nearby site of Kvarnbo Kohagen, both on the Åland Islands, Finland (Fig. 1). The flax seeds were measured to study whether they were used to produce oil or fibres. Flax weeds are discussed with regard to how they mimic flax. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of cereals, peas and flax are examined to determine whether the ways of manuring, plant physiology, or environmental conditions affected these crops.

Tjudnäs, site description

The Late Iron Age and early medieval settlement site of Tjudnäs (site ID Su 12.4) is situated in the parish of Sund, near the tip of a peninsula bordered by two branching straits; during the Late Iron Age, these waterways were part of a navigable network across the Åland Islands (Fig. 1). Tjudnäs is today situated 20 m above sea level in an area with bare bedrock, till and clay. Two characteristic Late Iron Age houses with stone foundations (T1 and T2) and 100 m apart from each other were excavated there in the early 1950s (Dreijer 1955a). House T2 was in use for a rather short period during the Late Iron Age, but there was both earlier and later occupation of house T1 (Ilves 2018b, p. 72). Next to the area with the houses, there were three mounds of fire-cracked stones; although not archaeologically excavated, these are thought to date from the Late Iron Age too.

Several charred seed masses with large amounts of flax seeds were found during the excavation of house T1 in 1953, which were all found just outside the western wall of the building, within a 10–20 cm in thick layer of soot (Dreijer 1954). Unfortunately, the excavators followed the common practice of that time and only investigated the insides of the buildings, so this layer outside was not studied further and its extent and nature remains unknown. Furthermore, as with this house structure in general, the areas outside the building, at least close to the house walls, also displayed evidence of long-term occupation and use. In the same excavation unit as the charred flax lumps, there were finds of both Late Iron

Age and late medieval pottery, as well as many fragments of loom weights, a couple of iron nails and a piece of a clay pipe. A charred flax seed was radiocarbon dated to the Viking Age (Table 2).

Kohagen

The Late Iron Age and early medieval settlement site of Kvarnbo Kohagen (Site ID Sa 14.7), in the parish of Saltvik, was close to the shoreline as it was in this period and next to the main waterway that crossed the whole of Åland from north to south during the Late Iron Age and into the early medieval period (Fig. 1). This site is also defined by the remains of houses with stone foundations, which are 15–20 m a.s.l. in an area of bare bedrock, till and clay. Five of these houses were excavated in the 1950s and the beginning of the 1960s, and several overlapping settlement phases were recorded. The archaeological find material was varied and abundant, indicating intense activity at this settlement site as well as the wealth and high status of its residents (Ilves 2018b, p. 70).

The macrofossil material discussed in this study was from house K1, excavated in 1955 (Dreijer 1955b), from house K5, investigated in 1958 (Dreijer 1958) and from an area stretching out from the western wall of K5, excavated in 1960 (Dreijer 1961). House K1 was a well-preserved rectangular building, 9 m long and 5.5 m wide, divided into two rooms by a central transverse wall. Large quantities of charred cereals were found in the larger northern half of the house, especially to the south of the central hearth in the middle of the room. Most of the finds from K1 were from the northern half of the building. House K5, which had a slightly convex outline, was the largest of the investigated buildings at the site, measuring 18 m by 7.5 m. It was also divided into at least two parts by a transverse wall, with living quarters in the southern part. Plant remains from K5 were found both in the smaller northern room and close to the western and southern walls in the large and find-rich southern room. The

area to the west and outside K5 consisted of a cultural layer up to 40 cm thick which was rich in finds, including two concentrations of charred cereal grains about 3–4 m from the house wall. Artefact typology and radiocarbon dates show that the site was occupied from the beginning of the Viking Age up to the 12th–13th century (Table 2).

Materials and methods

The plant material from Tjudnäs is charred, and consists of 24 linseed lumps and a small soil sample of 90 ml. The approximate numbers of flax seeds in the lumps were counted by using the mean seed weight obtained during stable isotope analysis (0.00169 g), and then dividing the weight of the lumps by this value. The macrofossils from Kohagen were collected by hand; soil was sieved during the excavations, but the sieve meshes were probably not small enough for the retrieval of small plant remains. The identification of plant remains was carried out by Santeri Vanhanen at the University of Helsinki, using the reference collection at Luonnontieteellinen keskusmuseo (The Finnish Museum of Natural History) and at Arkeologerna, Statens historiska museer (The Archaeologists, National Historical Museums) in Lund, Sweden, using the reference collection there. Atlases of modern seeds were consulted during the identification work (Beijerink 1947; Cappers et al. 2006; Bojnašský and Fargašová 2007).

The radiocarbon dating was done at the Tandem laboratory at the University of Uppsala. The dates were calibrated with OxCal v. 4.4. (Bronk Ramsey 2021) using atmospheric data from Reimer et al. (2020).

Stable carbon and nitrogen isotope composition was measured for 51 individual cereal grains or seeds. The cereal grains and peas were from Kohagen, find number ÅM 328:56 and the flax seeds from Tjudnäs, ÅM 240:157, and both dated to 880–1020 cal AD (Table 2). Stable carbon and nitrogen isotope compositions were determined using a

Table 2 Details of the AMS radiocarbon dates from Kohagen (Saltvik) and Tjudnäs (Sund)

Site	Find number	House	Investigation unit	Material	Lab.code	¹⁴ C age (BP)	δ ¹³ C‰ V-PDB	Cal AD 2σ	Reference
Kohagen	ÅM 279:158	1	D5	<i>Triticum aestivum</i> s.l.	Ua-62411	932 ± 30	−24,1	1030–1210	This paper
Kohagen	ÅM 328:7	2	B1	Tuberous roots of <i>Filipendula vulgaris</i>	Ua-62412	796 ± 31	−26,5	1180–1280	This paper
Kohagen	ÅM 328:43	5	A5	Cerealia indet.	Ua-33352	1,115 ± 35	−25	770–1020	Ilves (2018b)
Kohagen	ÅM 328:258	5	D9	Cerealia indet.	Ua-33354	885 ± 35	−24,4	1040–1230	Ilves (2018b)
Kohagen	ÅM 328:157	5	C3	Cerealia indet.	Ua-33353	830 ± 35	−25,9	1160–1280	Ilves (2018b)
Kohagen	ÅM 328:56	1	A6	Hulled <i>Hordeum distichon</i> /vulgare	Ua-72633	1,097 ± 28	−22,3	880–1020	This paper
Tjudnäs	ÅM 240:157	1	D7	<i>Linum usitatissimum</i>	Ua-62413	1,094 ± 31	−27,8	880–1020	This paper

Thermo Delta V continuous flow isotope ratio mass spectrometer coupled to a NC2500 element analyser at the Cornell University Stable Isotope Laboratory (COIL), Ithaca, NY, USA. The isotope compositions were calibrated relative to the VPDB (Vienna Pee Dee Belemnite) and AIR (Ambient Inhalable Reservoir) scales using the in-house standards ‘KCRN’ (corn) and ‘CBT’ (trout). Measurement uncertainty was monitored using the internal plant standard (‘RICE’). Standard deviation for the run was 0.07‰ for $\delta^{15}\text{N}$ and 0.05‰ for $\delta^{13}\text{C}$. Accuracy was determined using the chemical methionine standard. Based on the results of these samples, delta values obtained between the amplitudes of 200 mV and 15,000 mV for $\delta^{15}\text{N}$ have an error associated with linearity of 0.51‰ and between 200 mV and 10,000 mV for $\delta^{13}\text{C}$ the error is 0.53‰ (for detailed results see ESM 1).

The plant remains were charred, and therefore the $\delta^{15}\text{N}$ values were corrected (-0.32‰) to compare them with uncharred material (Stroud et al. 2023). Carbon isotope discrimination ($\Delta^{13}\text{C}$) was normalised using a smoothed curve of $\delta^{13}\text{C}$ in atmospheric CO_2 (Ferrio et al. 2005, 2023), where past levels of $\delta^{13}\text{C}$ were obtained from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network database (White et al. 2015).

Results

Identification of seeds

The botanical finds at Tjudnäs consist of charred flax seed (linseed) masses and seeds of wild plants. The lumps were of different sizes, the largest one measuring $7.6 \times 7.2 \times 2.5$ cm, weighing between 0.19 and 33.6 g, and the approximate total number of flax seeds is estimated to be almost 100,000 (Fig. 2, ESM 2). The flax seeds measured $3.5\text{--}4.8 \times 1.7\text{--}2.6$ mm, average 4.3×2.1 mm (ESM 3).

A soil sample collected from the same context as the linseed lumps was sandy, containing some charcoal, slag, 1,862 flax seeds and some seeds of wild plants. Several weed seeds were attached to the charred flax seeds, which indicates that they were indeed part of the assemblage (Fig. 3). The weed species consisted almost entirely of specific weeds of flax (Table 3).

One of these flax weeds was identified as *Cuscuta epilinum* (flax dodder), based on the reticulate and foveate cell pattern of the seeds and their size, $1.2\text{--}1.4 \times 0.9\text{--}1.3$ mm, average 1.3×1.1 mm, although several *Cuscuta* species have rather similar seeds (Fig. 4). The size is in accordance with the reported range of modern seeds, $1.2\text{--}1.4 \times 1\text{--}1.2$ mm, whereas the closely related species *C. europaea* has somewhat smaller seeds, with a range of $1.1\text{--}1.3 \times 0.9\text{--}1.1$ mm (Bojnaňský and Fargašová 2007).



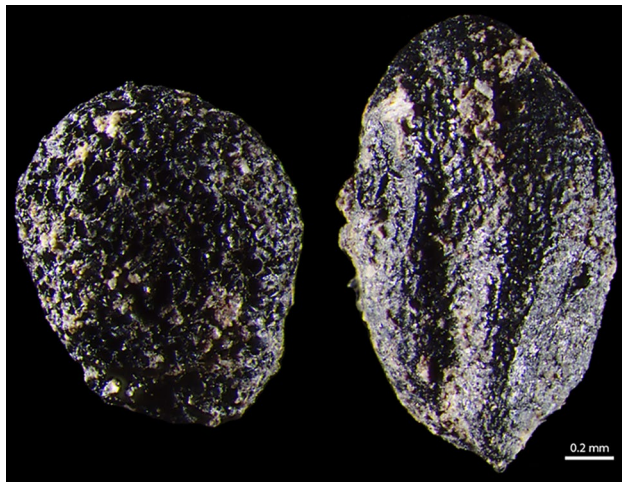
Fig. 2 A lump of charred *Linum usitatissimum* (flax) seeds from Tjudnäs (ÅM 240:157), measuring $6.5 \times 6.5 \times 2$ cm. Photo by Santeri Vanhanen



Fig. 3 Two charred seeds of *Linum usitatissimum* (flax) with an attached seed of *Cuscuta epilinum* (flax dodder). Photo by Santeri Vanhanen

Table 3 Seed list from a soil sample dated AD 880–1020 from Su 12.4 Tjudnäs gård, ÅM 240:157

Tjudnäs gård	ÅM 240:157
Cultivated plants	
<i>Linum usitatissimum</i> (flax)	1,862
Arable weeds	
<i>Cuscuta epilinum</i> (flax dodder)	146
<i>Lolium remotum</i> (flaxfield rye-grass)	91
<i>Galium spurium</i> (false cleavers)	44
<i>Stellaria media</i> (chickweed)	3
<i>Camelina sativa/alyssum</i>	2
<i>Persicaria lapathifolia/maculosa</i> (pale persicaria/red shank)	1

**Fig. 4** Left, charred seed of *Cuscuta epilinum*; right, charred seed of *Camelina sativa/alyssum*. Photo by Santeri Vanhanen

Lolium remotum (flax rye-grass) seeds are similar to *L. temulentum* (darnel), but in lateral view the darnel is more symmetrical, whereas flax rye-grass is flat on the dorsal side (Fig. 5; Beijerinck 1947). The seeds from Tjudnäs measured $2.6\text{--}3.9 \times 1.1\text{--}1.6$, average 3.3×1.4 mm, similar to the $3.4\text{--}4.0 \times 1.5\text{--}1.9$ mm of modern *L. remotum*, whereas *L. temulentum* has larger caryopses measuring $3.8\text{--}4.2 \times 1.6\text{--}1.8$ mm (Bojnaňský and Fargašová 2007).

Galium spurium (false cleavers) was identified by the seed morphology and the reticulate pattern on the seed surface. *G. spurium* consists of two subspecies, ssp. *vaillantii* and ssp. *spurium*. Both can grow in flax fields, but ssp. *spurium* is restricted to flax fields, while ssp. *vaillantii* is a common field weed and ruderal and distinguished by its hairy seeds (Mossberg and Stenberg 2018). The hairs grow on the pericarp of the seed, which is not often

**Fig. 5** Charred seeds of *Lolium remotum* (flax rye-grass); left, dorsal view; centre, ventral; right, lateral. Photo by Santeri Vanhanen

preserved in charred archaeobotanical material (Lange 1979). However, some of the seeds from Tjudnäs still had a preserved pericarp with no visible hairs but oblong features, which could suggest ssp. *spurium* (Fig. 6).

The seeds of *Camelina alyssum/sativa* measured 1.8×1.1 and 2.1×1.1 mm. Additionally, seeds of *Stellaria media* (chickweed) and *Persicaria lapathifolia/maculosa* (pale persicaria/redshank) represent plants that grow both as weeds or ruderals.

The flax seed measurements, breadth and width, were compared with those of the weeds (Fig. 7, ESM 3). They show that *Lolium remotum* seeds are somewhat narrower and shorter than those of flax, whereas *Camelina sativa/alyssum* and *Cuscuta epilinum* are clearly smaller.

More than 9,000 plant remains were analysed from Kohagen. These consisted mainly of cultivated plants, *Triticum aestivum* s.l. (naked wheat), *Hordeum distichon/vulgare* (hulled barley), *Avena sativa* (cultivated oat), *Pisum sativum* (pea) and *Secale cereale* (rye) (Table 4). A single floret base of *A. sativa* indicates that this is the cultivated species rather than wild oats. In addition to crops, there were some field weeds, shoreline plants and gathered wild plants. The remains from house K1 were dominated by *Triticum aestivum*, whereas the assemblage of house K5 has 43% *Hordeum vulgare* (hulled barley), 27% *T. aestivum* and 28% *Avena sativa*. *Secale cereale* occurred only in minor proportions in both houses. The sizes of the cereal grains were not measured, but it was noted that the rye grains were smaller than the other cereals.

Fig. 6 Charred seeds of *Galium spurium* (false cleavers); left and centre with the characteristic depression and reticulate pattern on the surface; right, with preserved seed coat. Photo by Santeri Vanhanen

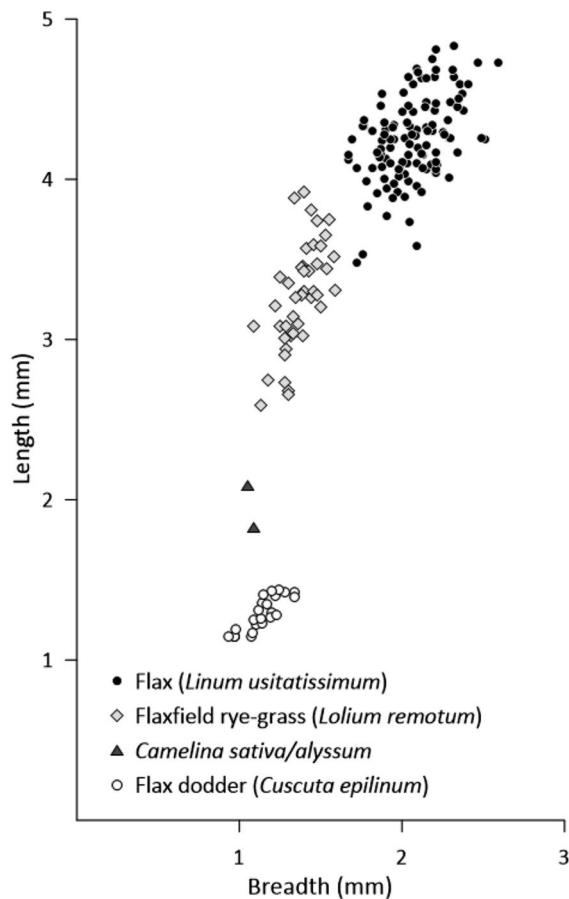


Fig. 7 Length and breadth measurements of *Linum usitatissimum*, *Lolium remotum*, *Camelina sativa/alyssum* and *Cuscuta epilinum* seeds from Tjudnäs. All measurements are given in ESM 3

Isotope measurements

The mean $\delta^{13}\text{C}$ values of the cereals and peas were similar. Oats had the lowest value of -25.1‰ , while peas, barley and naked wheat had similar mean values of around -24‰ , and rye had the highest of -23.2‰ (Fig. 8; Table 5). Flax deviated from these values, having a lower

mean $\delta^{13}\text{C}$ of -27.7‰ . When these values are converted to carbon isotope discrimination ($\Delta^{13}\text{C}$), oats had the highest value of 19.1‰ , whereas peas, barley and naked wheat had values around 18‰ and rye had a low value of 17.2‰ . The value of flax was higher at 21.9‰ .

The values of $\delta^{15}\text{N}$ were similar for the cereals and flax: naked wheat had the highest mean of 11.9‰ , followed by barley 11.3‰ , oats 10.5‰ and flax 10.5‰ , with rye the lowest at 8.8‰ . Peas had an even lower mean $\delta^{15}\text{N}$ of 2.2‰ .

Discussion, crop plants

The plant remains from Tjudnäs consisted of flax seeds and flax field weeds, but we do not know if other plants were grown at the site because soil samples were not collected. Flax is commonly found at archaeological sites around the Baltic region dating from the Bronze Age/Pre-Roman Iron Age transition onwards, but generally in much smaller numbers than cereal grains. Lumps similar to those from Tjudnäs were found at Uppåkra 2:25 in southern Sweden and were dated to the Roman Iron Age (Larsson 2013). Three of these lumps consisted of more than 200,000 flax seeds and one of around 150,000 seeds of *Camelina sativa*. Such finds may indicate that some households specialised in the growing and/or processing of oil plants.

The main cereals from Kohagen dated to the Viking Age and early medieval period were naked wheat, hulled barley and cultivated oat. All of these have been found at several Late Iron Age sites around the Baltic (Grabowski 2011; Vanhanen 2019; Grikkpēdis and Matuzeviciute 2020). *Triticum aestivum* was one the main cereals found at Kohagen. It has been suggested that the growing of naked wheat in the Late Iron Age was connected to an increase in urban settlement or high status lifestyles (Grabowski 2011, p 492; Bergman et al. 2017). Naked wheat is relatively common in finds from the Late Iron Age and Viking period in the Swedish region of Uppland, close to Åland (Ranheden 2007; Bergman et al. 2017). It also occurred in large quantities at some sites in Finland (Matiskainen 1984), although it remained generally uncommon (Vanhanen 2019). The amount of naked wheat at Kohagen was, however, much higher than from the Swedish

Table 4 Seed list from Saltvik 14.7 Kvarnbo Kohagen. Radiocarbon dates are given in Table 1

[illegible]

Material for stable isotope analysis was collected from AM 328:56 and dated AD 880–1020

*cal_{AD} (2 σ): D5 1030–1210, A5 770–1020, A6 880–1020, C3 1160–1280, D9 1040–1230

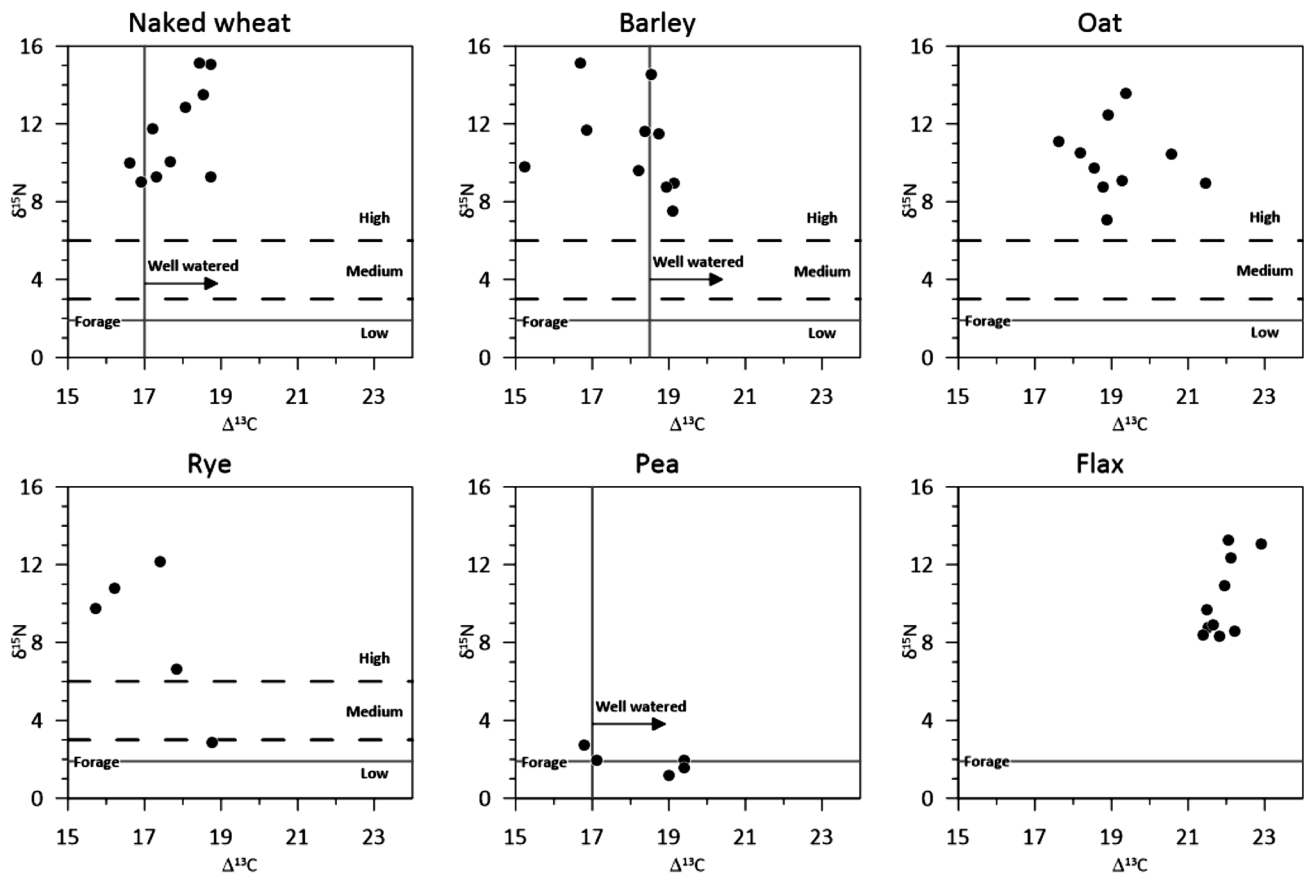


Fig. 8 Measurements of $\delta^{15}\text{N}$ and $\Delta^{13}\text{C}$ values in *Triticum aestivum* (naked wheat), *Hordeum vulgare* (barley), *Avena* sp. (oats), *Secale cereale* (rye) and *Pisum sativum* (peas) from Kohagen, and *Linum usitatissimum* (flax) from Tjudnäs, all dated cal AD 880–1020 (2 sigma). $\delta^{15}\text{N}$ values were corrected for charring (Stroud et al. 2023) and the value of local forage was estimated by subtracting 4‰

from the medieval and post-medieval sheep and cattle bone average (Bogaard et al. 2013) found at the island of Kökar, ca. 60 km south-east of our sites (Bläuer et al. 2016). Values for different manuring intensities were obtained from modern experimental data (Fraser et al. 2011), as well as for various amounts of watering (Wallace et al. 2013). Values are given in ESM 1

Table 5 Summary of stable isotope measurements. $\delta^{15}\text{N}$ values of charred plant remains were corrected (-0.32‰) to compare with the uncharred material (Stroud et al. 2023)

Species	Site	N	$\delta^{13}\text{C}$ ‰ range (mean)	$\Delta^{13}\text{C}$ ‰ range (mean)	$\delta^{15}\text{N}$ ‰ range (mean)	corrected $\delta^{15}\text{N}$ ‰ range (mean)	%N mean	%C mean
<i>Triticum aestivum</i> s.l.	Kohagen	10	−24.7 to −22.7 (−23.8)	16.6–18.8 (17.8)	9.3–15.5 (11.9)	9.0–15.1 (11.6)	2.8	51.1
<i>Hordeum distichon/vulgare</i>	Kohagen	10	−25.1 to −21.3 (−24.0)	15.2–19.2 (18.0)	7.8–15.5 (11.2)	7.5–15.1 (10.9)	2.9	52.3
<i>Avena</i> sp.	Kohagen	10	−27.3 to −23.6 (−25.1)	17.6–21.5 (19.2)	7.4–13.9 (10.5)	7.1–13.6 (10.2)	2.2	54.2
<i>Secale cereale</i>	Kohagen	10	−24.7 to −21.8 (−23.2)	15.7–18.8 (17.2)	3.2–12.5 (8.8)	2.9–12.2 (8.4)	2.3	53.6
<i>Pisum sativum</i>	Kohagen	5	−25.4 to −22.9 (−24.3)	16.8–19.4 (18.3)	1.5–3.1 (2.2)	1.2–2.8 (1.9)	2.7	52.6
<i>Linum usitatissimum</i>	Tjudnäs	10	−28.7 to −27.2 (−27.7)	21.4–22.9 (21.9)	8.6–13.6 (10.5)	8.3–13.2 (10.2)	2.9	67.2

mainland or Finland, which could reflect the prosperity of the site. *Secale cereale* appeared in such small proportions at Kohagen that it was probably a cornfield weed at this site. The relatively large range of cultivated plants shows the generally broad spectra of livelihoods in Iron Age Åland, which might have been a way of spreading risks, a strategy that has been suggested for the Late Iron Age in Åland in general (Larsson et al. 2023).

Causes of variation in $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$

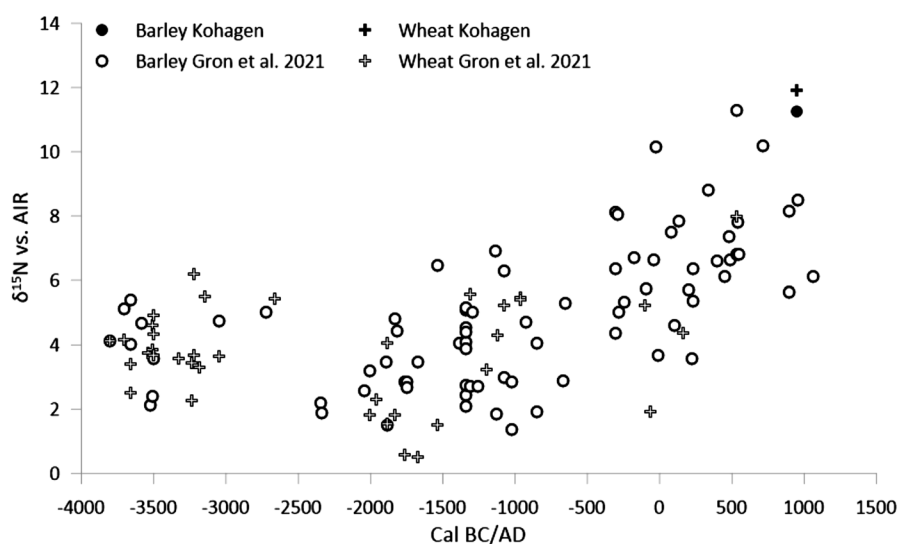
Corrected mean $\delta^{15}\text{N}$ values for cereals, peas and flax from Kohagen and Tjudnäs fall in the range of 8.4–11.6‰ (Table 5). Comparing these to the $\delta^{15}\text{N}$ values from the soils and natural vegetation of Åland is hampered by the lack of such studies on the islands. An estimate for the values of vegetation grazed by livestock (forage baseline) for the region can, however, be obtained by subtracting 4‰ from the $\delta^{15}\text{N}$ values of archaeological herbivore bone collagen in order to account for enrichment of $\delta^{15}\text{N}$ in the food web (trophic shift) when livestock eats plants from the surroundings (Bogaard et al. 2013; Hedges and Reynard 2007). This equates to an estimated forage value of 1.9‰ for sheep and goats in Kökar in the Åland archipelago (Bläuer et al. 2016; Table 2). The values of cereals and flax clearly exceed this and must have been increased by other factors (Fig. 8).

Studies in experimental settings and traditional farming regimes have shown that manuring increases the levels of $\delta^{15}\text{N}$ in cereals (Fraser et al. 2011, p 2,802). According to these experimental data, the cereals in our study probably received large amounts of manure (Fig. 8). The fields could have been manured with animal dung, which was indeed spread on the arable fields on Åland during later periods (Radloff 1795). As these sites are close to the sea, seaweed

might also have been used as a fertiliser, which has been shown to increase $\delta^{15}\text{N}$ values of barley and *Vicia faba* (field bean) (Blanz et al. 2019; Gröcke et al. 2021). However, seaweed was not used in Åland during the 18th century because sufficient animal dung was available (Radloff 1795, p 187) and no archaeobotanical finds of seaweed remains have so far been reported from Åland, as are found elsewhere in northern Europe (Mooney 2021). Manuring with fish remains has been shown to raise $\delta^{15}\text{N}$ values of *V. faba* (Gröcke et al. 2021). A significant proportion of bones found at Kohagen were of seals and fish (Storå et al. 2012) and therefore using such remains could have raised the $\delta^{15}\text{N}$ values. Burning of vegetation can also increase $\delta^{15}\text{N}$ values (Szpak 2014), and slash-and-burn cultivation was practised in historical and prehistoric times on Åland (Radloff 1795; Alenius et al. 2024). *Secale cereale* was the main crop grown using slash-and-burn (Radloff 1795, p 184), and therefore other crops would probably not show this increase. The corrected $\delta^{15}\text{N}$ values of the cereals clearly exceeds the estimated value of local forage, which implies manuring with animal dung and possibly even with fish remains and seaweed, or slash-and-burn in the case of rye. Seen in a broader perspective, the uncorrected $\delta^{15}\text{N}$ values of barley and wheat are very high in comparison with earlier data from Scandinavia (Fig. 9). One cause for this could be that an economy based mainly on livestock could concentrate all the available manure on small arable plots, resulting in a higher accumulation of manure there.

There are only a few earlier studies of $\delta^{15}\text{N}$ from archaeological flax finds. Neolithic, Iron Age and medieval material from the Netherlands showed that flax had raised $\delta^{15}\text{N}$ values of around 10‰ (Brinkkemper, pers. communication). Attempts to measure $\delta^{15}\text{N}$ of Bronze Age flax from the Must farm site in eastern England were unsuccessful, probably due to the small size of the seeds compared to cereal grains

Fig. 9 Scatter diagram showing $\delta^{15}\text{N}$ mean values plotted against dates, of *Hordeum vulgare* (barley) and *Triticum* spp. (wheat) from Kohagen, also of barley (both naked and hulled varieties) and wheat from other sites in southern Scandinavia (Gron et al. 2021; Table S2). Note that various wheat species (*T. aestivum*, *T. dicoccum* and *T. turgidum* ssp. *durum*) were identified. Values were not corrected for charring



(Lightfoot et al. 2024). The currently available data indicate that flax has similar or higher $\delta^{15}\text{N}$ values than cereal grains, which would suggest that they were both manured in a similar manner. However, this conclusion must be considered preliminary, because currently there are no experimental studies on how the $\delta^{15}\text{N}$ values of flax are affected by manuring, charring or other factors.

The $\delta^{15}\text{N}$ values of *Pisum sativum* are clearly lower than those of the cereals and flax, which is due to the ability of legumes to fix nitrogen from the atmosphere. The values are, however, slightly raised, having a corrected mean of 1.9‰. Highly manured *Vicia faba* in a traditional farming setting had $\delta^{15}\text{N}$ values of 2.2‰ (Fraser et al. 2011; Table 5c). At the Neolithic Kouphovouno site in Greece, a mean of 1.3‰ for peas was taken to indicate intensive manuring (Vaiglova et al. 2014), and similarly peas at Kohagen can be considered to have been intensively manured.

The plant remains at Tjudnäs and Kohagen had $\delta^{13}\text{C}$ values ranging from −28.7 to −21.3‰, average −24.9‰, which are consistent with reported south Scandinavian data, ranging from −28.5 to −21.3‰, average −24.7‰ (Gron et al. 2021). Variation in $\delta^{13}\text{C}$ is dictated by several factors, such as water intake, canopy effect, soil conditions and taxon (for example, van der Merwe and Medina 1991; Kohn 2010; Hamerow et al. 2020; Gron et al. 2021). According to pollen results, the landscape of Åland was relatively open during the Late Iron Age (Alenius et al. 2024), which would imply that the tree canopy effect was similar for both Kohagen and Tjudnäs. Earlier studies have shown that rye and naked wheat have the highest $\delta^{13}\text{C}$, barley lower and oats the lowest of the cereals (Wallace et al. 2013; Styring et al. 2017; Hamerow et al. 2020, p. 16). This corresponds with the mean values obtained from Kohagen (Table 5). Flax had clearly lower $\delta^{13}\text{C}$ than any of the cereals. The flax in the current study came from Tjudnäs and the cereals from Kohagen. Therefore, the different origins could explain why the flax has lower $\delta^{13}\text{C}$ than the cereals and peas. However, modern linseed from different sites in China, reported by Liang et al. (2022; Table 1), had low mean $\delta^{13}\text{C}$ values ranging between −29.9 and −28.1‰. Unpublished data from the Neolithic, Iron Age and medieval periods in the Netherlands show similar results in which flax had lower average $\delta^{13}\text{C}$ values than cereals, around −27‰ (Brinkkemper, pers. communication). Similarly lower $\delta^{13}\text{C}$ flax mean values (−24.6‰) compared to wheat (−23.4‰) are reported for Neolithic Tell Halula in Syria (Araus et al. 1999). At the Bronze Age settlement at Must, flax and barley had lower mean $\delta^{13}\text{C}$ values (both −24.2‰) than *Triticum dicoccum* (emmer) (−22.8‰) (Lightfoot et al. 2024; Table 31.03). The currently available data thus suggests that flax seeds often have lower $\delta^{13}\text{C}$ values than cereal grains. One reason for this could be the oil content in flax seeds, which lowers the $\delta^{13}\text{C}$ (Araus et al. 1999, p. 209). In general, our data agree with

earlier observations that $\delta^{13}\text{C}$ varies between taxa. Studies of modern *Linum* seeds are needed to understand the causes of variation in $\delta^{13}\text{C}$ in flax.

Carbon isotope discrimination ($\Delta^{13}\text{C}$) can be used to infer the watering status of different crops (Ferrio et al. 2005). Compared with present day crops (Wallace et al. 2013; Fig. 5), the wheat and peas in this study appear to have been well watered, whereas the barley was moderately watered (Fig. 8). The mean $\Delta^{13}\text{C}$ of barley (18.0‰) and wheat (17.8‰) are similar to earlier results from Scandinavia (Table 5), where barley had a mean 18.6‰ and wheat 17.9‰ (Gron et al. 2021; multimedia component 1). Seen in a historical perspective, barley has lower $\Delta^{13}\text{C}$ compared to other data from AD 1000, whereas there are no earlier measurements of wheat from this period (ESM 4). A high $\Delta^{13}\text{C}$ value for flax could show that this crop received plenty of water, but as pointed out above, the stable isotope signatures of this crop are poorly understood.

Weeds of flax

The weeds *Cuscuta epilinum*, *Lolium remotum*, *Galium spurium* and *Camelina alyssum/sativa* which were found at Tjudnäs are all characteristic of traditional flax fields. Several weeds of flax are considered obligate and are only found in habitats created by people (Harlan and de Wet 1965). Some of these weeds evolved in the Neolithic fields of the Near East (Fuller and Stevens 2018). Of the traditional weeds of flax in the northern Baltic region, *Spergula arvensis* ssp. *maxima* is the only one missing from the Tjudnäs assemblage (cf. Johansson 2022). *Persicaria lapathifolia/maculosa* and *Stellaria media* could have also grown with flax. The assemblage should therefore be considered a pure example of flax weeds, and as such it is a rare archaeobotanical find.

Previous finds of flax weeds have been discovered in both charred and waterlogged assemblages in rich but not always pure finds of flax. Early Bronze Age flax and *L. remotum* were found at Kastanas in Greece from ca. 2500–1800 BC (Kroll 1979). The Roman Iron Age flax lumps from Uppåkra 2:25 in Sweden contained seeds of *Leontodon autumnalis* or *L. hispidus* (Larsson 2013). Lange (1978) listed the weeds associated with flax from four sites in Germany dating from the La Tène period to the Middle Ages. These sites had floras which included the typical flax weeds *Camelina sativa*, *Cuscuta epilinum* and *Sp. arvensis* var. *maxima*. A bundle of flax was found at Wrzesnica in northern Poland and dated to cal AD 660–980 (Latałowa 1998). There, weeds of arable land, most importantly *Camelina microcarpa*, *C. alyssum*, *C. epilinum* and *Sp. arvensis* were found together with the bundle and interpreted as indicating that the flax was spring sown in a field where *Panicum miliaceum*

(millet) had previously grown, an interpretation based on modern ecological associations. Similarly, mass finds of flax stalks and other uncharred plant remains were discovered in Wolin, Poland, dated to cal AD 900–1200 (Alsleben 1995). The weeds that could be connected with flax growing consisted of *L. remotum*, *Silene gallica*, *Sp. arvensis* var. *maxima* and probably also *Agrostemma githago*, *G. spurium* and *Camelina sativa*. A charred flax bundle, field weeds and some cereals were found in Oldenburg/Starigrad, northern Germany, from layers dated to AD 1000 (Kroll 1987). Here, *L. remotum*, *G. spurium*, *C. sativa* and *Sp. arvensis* were interpreted as having grown together with the flax. These examples presented above show that weed floras similar to the Tjudnäs find grew in the flax fields of the southern Baltic Sea coast around AD 500–1000. It thus appears that the flax weeds had been brought to the islands together with flax seeds intended for cultivation.

The flax weeds found at Tjudnäs have somewhat different survival strategies, but all have similar ecological requirements, similar life-cycles and have evolved to survive intense weeding as well as the post-harvest threshing and winnowing of the flax cop. Flax was traditionally usually sown in rows in well prepared plots. When the flax had grown to around 7.5 cm, or a hand-width, it was weeded (Grotenfelt 1899). At this stage, it would have been beneficial for the flax weeds to avoid being removed by weeding, which they did by closely resembling the flax plants so that they were hard to distinguish from the crop, a phenomenon called vegetative mimicry (Barrett 1983). Flax weeds resemble flax in various ways, such as having slender growth and loose inflorescences (Hjelmqvist 1950). *Cuscuta epilinum* winds tightly around flax stems and *G. spurium* has a scrambling growth, making these plants difficult to weed from flax fields. *Lolium remotum* might resemble flax in its early stages.

Harvesting methods could be different for oil and fibre flax (Viklund 2012). Only the capsules of oil flax were

collected, whereas the whole plant of fibre flax was pulled up (Kaukonen 1946; Ertuğ 2000, p. 176), a method used in the Neolithic (Maier and Schlichtherle 2011). After harvesting, the oil flax plants were usually dried to soften the stalks and allow the seeds to mature. The seed capsules were then removed from the stems, commonly with comb-like flax ripples, though even clubs were used on Åland (Kaukonen 1946). The seeds were then threshed from the capsules with methods similar to those used for cereals and then separated from the chaff by winnowing, sieving or both. Specialised flax weeds had to persist through all of these stages, which they did by mimicking linseed, with seeds that weighed as much as flax seeds and were not separated by winnowing. *Lolium remotum* seeds are almost indistinguishable from the shape of flax seeds (Fig. 10). They are, however, somewhat narrower and shorter (Fig. 7), but could weigh the same by being generally thicker. *Camelina* seeds are smaller, but they are harvested as indehiscent fruits (Barrett 1983, p. 264) that resemble flax seeds in size, but they would probably not have survived charring. *Cuscuta epilinum* seeds are also clearly smaller than flax, but the pairs are attached together so that they are closer to the size of flax seeds. The crop of flax seeds, together with its weeds, would have been used or re-sown in the following year.

Flax use

Flax can be used for its fibres, and its seeds either eaten or pressed for linseed oil. How was the flax found in Tjudnäs used? Here the flax seeds were large compared to other reported flax seeds in northern and central Europe (Fig. 11; Table 6), which suggests that they were used for oil. However, Karg et al. (2021) found it difficult to separate between the oil and fibre forms of the plant. Regardless of seed size, the way in which the seeds were found in lumps also suggests that they were used for oil (Larsson 2013). Flax seeds

Fig. 10 Left, charred *Lolium remotum* caryopsis in ventral and dorsal views; right, two views of a *Linum usitatissimum* seed, showing the similarity between the two. Photo by Santeri Vanhanen



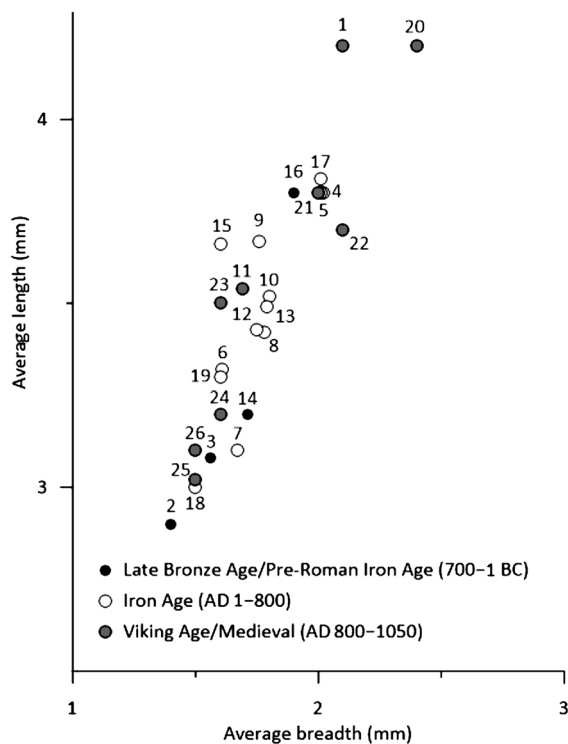


Fig. 11 Average length and breadth measurements of charred *Linum usitatissimum* seeds from northern European sites; numbers refer to “Nr” in Table 6

are often roasted before extracting oil from them by pressing or by other methods, such as heating and the remains fed to farmyard animals (Ertuğ 2000). Sometimes the seeds were ground before they were pressed. Cooking oil was obtained by cold pressing, whereas drying oil used for paints and varnishes was obtained by hot pressing (Zohary et al. 2012, p 101). The varnish could have been used, for example, to waterproof boats and as a finish for other types of woodwork.

The Tjudnäs seeds could have been charred when they were roasted or hot pressed, although it is also possible that they were burned accidentally. The fact that the seeds are tightly packed suggests that the remains were from oil pressing.

Conclusions

Flax seeds and weeds, cereals and peas from two Viking Age sites in Åland were analysed using archaeobotanical and stable isotope methods. These revealed aspects of ancient plant cultivation and use, especially of flax. The large size of the flax seeds and the lumps in which they were found suggest that the flax was probably intended for producing oil. The seeds may have been charred in hot pressing used for producing oil for handicrafts. An assemblage of specific weeds of flax also present in the lumps demonstrates that these weeds had made their way up north to the Åland Islands by ca. AD 1000 together with flax seeds intended for growing. The same weeds, which mimic flax, grew in flax fields until relatively recently, but have disappeared due to more advanced weed removal and reduced flax growing.

Analysis of $\delta^{15}\text{N}$ levels in the ancient plant remains showed that the soil had been considerably altered by manuring with animal dung for growing the crops of cereals, peas and flax. Manuring could have been complemented with resources from the sea, such as seaweed and fish. The large range of crops grown at Kohagen could have been a way of reducing risks such as crop failure. Here, the large amounts of naked wheat suggest prosperity of the settlement. The flax had lower $\delta^{13}\text{C}$ values than the peas and cereals, as also found in other studies, which could be related to the way in which flax was grown or physiological differences between the various crop taxa.

Table 6 A selection of measurements of charred flax seeds from the Iron Age and medieval period in northern Europe

Site	Country	Measured seeds (n)	Length (ø, mm)	Breadth (ø, mm)	L range (mm)	B range (mm)	Dating	Reference	Period	Nr
Tjundnäs	FIN	116	4.3	2.1	3.5–4.8	1.7–2.6	Viking Age	This study	3	1
Bartsgårda	FIN	1	2.9	1.4			Late Bronze Age	Vanhanen report	1	2
Västra Ingelstad	SWE	3	3.08	1.56	2.89–3.45	1.43–1.73	Pre-Roman Iron Age	Strandmark (2022)	1	3
Uppåkra 2:25, pit AG7717 (conglomerate)	SWE	100	3.8	2.02	3.44–4.15	1.81–2.21	Roman Iron Age	Larsson (2013)	2	4
Uppåkra 2:25, pit AG7717 (soil)	SWE	100	3.8	2.01	3.41–4.15	1.74–2.28	Roman Iron Age	Larsson (2013)	2	5
Uppåkra 2:25, House 3	SWE	26	3.32	1.61	2.72–3.94	1.14–1.86	Roman Iron Age	Larsson (2013)	2	6
Uppåkra 2:25, Pit AG11393	SWE	9	3.1	1.67	2.71–3.37	1.44–1.89	Roman Iron Age	Larsson (2013)	2	7
Uppåkra 12:110, House 10	SWE	5	3.42	1.78	3.15–3.7	1.57–1.89	Roman Iron Age	Larsson (2013)	2	8
Uppåkra central place, House 24	SWE	9	3.67	1.76	3.46–3.79	1.63–1.9	Late Roman–Migration Period	Larsson (2013)	2	9
Uppåkra central place, Vifot's house	SWE	59	3.52	1.8	3.09–3.99	1.48–2.17	Late Roman–Migration Period	Larsson (2013)	2	10
Hjärup 9-8	SWE	3	3.54	1.69	3.44–3.65	1.6–1.76	Viking Age	Larsson (2013)	3	11
Trogsta	SWE	16	3.43	1.75	2.41–3.74	1.41–1.99	ca 500	Wennerg (1985)	2	12
Skummeslöv	SWE	5	3.49	1.79	3.34–3.65	1.55–1.99	AD 410–550	Unpublished data	2	13
Eikebakken	NOR	60	3.2	1.71			Pre-Roman Iron Age	Lundberg (2017)	1	14
Ulandhaug	NOR	4	3.66	1.6			Migration period	Lundberg (2017)	2	15
Stoustrup	DEN	10	3.8	1.9	3.6–4.0	1.5–2.3	Pre-Roman Iron Age	Robinson (1993)	1	16
Østerbølle	DEN	50	3.84	2.01	3.11–4.58	1.65–2.56	Roman Iron Age	Robinson (1993)	2	17
Alrum	DEN	50	3	1.5	2.6–3.8	1.3–1.8	Roman Iron Age	Robinson (1993)	2	18
Feddersen Wierde	GER	150	3.3	1.6	2.7–3.7	1.3–2.0	Second century AD	Alsleben (1995)	2	19
Braunschweig	GER	20	4.2	2.4	3.9–4.9	1.8–2.8	12th–13th cent. AD	Alsleben (1995)	3	20
Schleswig	GER	30	3.8	2			13th cent. AD ff.	Alsleben (1995)	3	21
Archsum	GER	50	3.7	2.1	2.9–4.2	1.3–2.4	9th–10th cent. AD	Alsleben (1995)	3	22
Wolin	Poland	40	3.5	1.6	3.0–4.0	1.2–2.1	12th–13th cent. AD	Alsleben (1995)	3	23
Barvas Machair, Lewis	GBR	19	3.2	1.6			Viking Age	Bond and Hunter (1988)	3	24
Pool, Sanday, Orkney	GBR	62	3.02	1.5	2.3–3.5	1.1–1.8	Viking Age	Bond and Hunter (1988)	3	25
Saevær Howe, Orkney	GBR	15	3.1	1.5	2.8–3.4	1.3–1.9	Viking Age	Bond and Hunter (1988)	3	26

1, Late Bronze Age/Pre-Roman Iron Age (700–1 BC); 2, Iron Age (AD 1–800); 3, Viking Age/medieval (AD 800–1050); nr, site number

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Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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