Changing Agriculture

Stable isotope analysis of charred cereals from Iron Age Öland

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Abstract
The Middle Iron Age on Öland (around 200-550 AD) is often regarded as a prosperous period with a wealth based on animal husbandry. In this study charred cereals from several Iron Age sites at Öland are studied to answer questions about prehistoric diet and agricultural practices. The method used is stable isotope analysis of carbon and nitrogen in the cereals, and one further aim of the study is to evaluate this method. The results suggest that there is little need for pre-treatment of cereals before isotope analysis. Most of the grains analyzed were hulled barley and in all sites there are indications of intensive manuring, as would be expected in permanent field agriculture. The ring forts of the period may here have been places where an agricultural surplus was gathered. Concerning human diet, the isotope values indicate cereals may have been an important part. Crops may also have been used to feed the livestock, possibly with secondary products like straws, and likely to a different extent in different animal species. Finally, the sites from the Middle Iron Age all appears to have been abandoned. Heavy dependence on animal manure may have decreased the resilience of agriculture, making it more vulnerable to unexpected changes, for example the climate downturn after 536 AD.

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1. Introduction

1.1. Background
Humans have always depended on both plants and animals for nutrition. Humans may transform the landscape through agriculture practices and domesticate plants and animals for the service of human needs. But this also entangle humans in relationships of dependence. Since these dependencies cannot be reduced to either society or the environment, agriculture have to be conceived as a social-ecological system.

One way to approach such systems in prehistory is to study prehistorical diet. For this purpose, stable isotope analysis has often been carried out on teeth and bones, both on humans and animals. This method may in some cases reveal significant differences in diet between farmers and hunter-gatherers. On Öland, for example, studies have shown shifts in diet from the Mesolithic period to the Iron Age (Eriksson et al. 2008).

A problem however is how variations of isotope values in humans relate to variation in agricultural crops. To correctly interpret human isotope data, that is to determine what humans actually have eaten, isotope data is necessary from both the plants and animals that they may have consumed. Plant isotope values may vary for many reasons and are for example affected by manuring (Bogaard et al. 2007). The infield system in Scandinavia of historical times that is dependent on manuring is assumed to go back to the Iron Age (Welinder 1998:32ff). Isotope analysis have been carried out on Danish material (Kanstrup et al. 2014) and in one Neolithic site in Sweden (Gron et al. 2017), suggesting some level of manuring already in the Neolithic. However, isotope analysis of archaeological plant material is still quite an unexplored area, in particular for Swedish plants.

In this study, the isotope values of charred cereals from Iron Age Öland will be analyzed. First, this a methodological study where the impact of different pre-treatments of the material will be compared. Also, screening methods will be evaluated. Second, the isotope values of cereals will be compared with the isotope values of humans at the same site to estimate the impact of cereals on human diet. This is the ring fort of Sandby Borg, where human remains were left laying after a massacre. Third, the isotope values of plants at different sites will be compared. It has been hypothesized that a form of permanent field agriculture that was heavily dependent on manure was
used in the Early Iron Age in South Scandinavia (Grabowski 2014:20), and this method may reveal if that was the case on Iron Age Öland. The wider implication for the understanding of Öland as well as South Scandinavia during the Iron Age will be discussed.

1.2. Research Aims

The research aims are both methodological and archaeological. The methodological aim is to examine how to best prepare samples for isotope analysis. This involves evaluation of screening methods and pre-treatment. The archaeological aim is to explore the relationship between agriculture, humans and the landscape during the Iron Age, focusing mainly on central Öland. This involves answering the following research questions:

1. How was cereal cultivation practiced in the field? To what extent were the crops manured, what type of manure was used, were fallow years used?
2. How may interspecies variation be understood? Was there some sort of crop rotation?
3. How do these practices relate to place and landscape processes?
4. How is the human and animals consumption of cereal-based foods related to these practices and processes?

1.3. Things and processes

A central problem to archaeology is how to relate material remains to historical process. In the case of domesticated plants and animals, this problems presents itself as how to relate ecofacts to agriculture. Domesticated plants are in the archaeological record traditionally categorized as ecofacts, separating them from artifacts (Welinder 1998:46f, Grabowski 2014:67). As Grabowski (2014:67f) points out however, this boundary is increasingly blurred, as plants for example may acquire many qualities traditionally associated with artifacts. Things may then rather be described as hybrids or assemblages. This means that things are not simply the sum of its parts, but that they have emergent qualities (Hinchliffe 2007:47ff, Witmore 2014). One may then either see things as outcome of processes, or process as the outcome of things interacting. An example of the first perspective in archaeology is traditional systems theory, where agriculture may be conceptualized as energy flows, which is related to an ecological approach (Welinder 1998:32ff, Trigger 2006:386ff). The second perspective is often associated with actor-network theory, here things are seen as primary, process is something that arises from relations between things, rather than from an underlying nature or society. The capacity of things to have effects and create connections is
emphasized, downplaying the central importance given to humans in the formation of the archaeological record (Hinchliffe 2007:47ff, Witmore 2014).

2. The Sites

2.1. Background

Öland is an island in the Baltic Sea, located next to the south-west coast of mainland Sweden. The Middle Iron Age on Öland (Around 200-550 AD) stands out as a period when stone was used as a building material. At least 1000 stone house foundations are known from this period. They are often surrounded by systems of fences, remains of an agricultural systems of enclosures. There are also at least 15 ring forts from this period and they often have stone house foundations inside the walls (Fallgren 2006:25ff, Fallgren 2008).

Fallgren (2006:28f) divides the farms from this period into four size categories, from small farms with a single house up to magnate farms with several houses. A number of the small houses are found on the Great Alvar, a barren limestone plain on the southern part of Öland. Fallgren do not consider these independent farms but buildings related to pastoral practices.

The sites in this study are largely chosen from what material is available (figure 1), as there is a limited number of sites with cereal finds and all of these finds could not be located. The aim however is to give as broad representation of the cultivated cereals of Iron Age Öland as possible. For example, large assemblages of cereals were found in Iron Age Eketorp (Helbæk 1979), but as two ring forts from the same period already were represented in this study, other materials were prioritized.
Gråborg (L1959:7076 / Algutsrum 16:1)

Gråborg is the largest ring fort on Öland, located on the middle of the island. It was in use during the Iron Age and reused during the Early Medieval Period. It is likely that there was some sort of settlement inside the walls, but in later periods however intensive cultivation disturbed much of what remains. A number of minor excavations have been done, most recently 1998-2002 (Tegnér 2008).

A large assemblage of charred cereals and seeds was found during an excavation at the western wall of Gråborg in 2001. Constructions were found believed to be a house, dated by \(^{14}\)C to the period 320-630 AD and destroyed by fire. The cereals may have been stored in wooden bins in this house.
(Tegnér 2008). This area of the fort may be suitable for storing, as it is high up and thus drier, and because it is protected directly by the wall (Hansson & Bergström 2008).

The assemblage is made up of 13,000 grains and seeds. It is dominated by barley, probably mostly hulled barley, but there are also other types of crops (figure 2). There were also remains of flour or bread (Hansson & Bergström 2008, Tegnér 2008). Typical spring crops thus dominates, however the wheat may be autumn sown (Pedersen & Widgren 1998:387, Leino 2017:19). Rye may also be autumn sown, but the low numbers may indicate that is is a weed (Hansson & Bergström 2008).

![Pie chart showing the composition of the assemblage](image)

*Figure 2: The Gråborg assemblage (By the author based on Hansson & Bergström 2008)*

### 2.3. Sandby Borg (L1956:3453 / Sandby 45:1)

Sandby Borg is located at the eastern shore of Öland, a location close to the sea that makes it unique among the ring forts. There are 53 known houses in Sandby Borg, placed in a central block and radially along the wall, a layout found in other ring forts (Viberg et al. 2014). Excavations began in 2011. The results suggest the place was in use during the Migration Period and that it was abandoned following a massacre of the occupants. Skeletal remains of at least 26 individual humans have been found (Alfsdotter et al. 2018). In this case the materials are from the 2016 and 2017 excavations (figure 3).
House 52 is the house at the northwestern end of the central block. Parts of this house were excavated in 2011, 2014 and 2017. Finds of jewelry, gold and glass suggest a high social status of the occupants. They northern section if this house may have functioned as a hall, and the remains of a high seat was found here. There was also skeleton of an elderly man laying in this house had hardly any traces of hard physical labor during life. Parts of the house appear to have burnt and there were a few charred cereals found. The house was built on the top of graves from the Early Roman Iron Age (Papmehl-Dufay & Alfsdotter 2016, Victor personal communication 2019-04-09).

The 2016 excavation took place in and around house 4 in the northern part of the fort. Traces of glass bead production were found in this house. There were also traces around cooking, mostly around a hearth in the middle of the house (context 8679) which may explain the charring of the cereals. There were also other food remains, including an onion which may suggest that some form of gardening was practiced (Heimdahl, In prep).
In 2017 a part of house 1 was also excavated. This appears to have been the lowest part of the ring fort and thus an area subjected to moist (Victor personal communication 2019-04-09). It is thus unlikely to have been a storage area, but a few charred grains of barley were found here.

Figure 4: Sandby Borg, stone fences and house foundations. The white is the area with post-glacial deposition, including the Ancylus and Litorina Ridge (By author based on data from SGU and FMIS).

2.4. Sandby (L1956:2788 / Sandby 37:1)

This house foundation is located about one kilometer northwest of Sandby Borg next to the Litorina ridge. It was excavated in September 2015 and dated to the period 425-600 AD (Papmehl-Dufay & Sandberg 2019). Apparently a single house, it would belong to the smallest category of farms. It may also not have been used as a permanent settlement but only in relation to pastoral practices, as has been suggested about the house foundations on the Great Alvar. This may be supported by the finds of animal bones and a possible location on the outfields (figure 4).

The house had two cultural layers above and below a stone layer. The cultural layers were
interpreted as representing two different phases of the house, where it was destroyed by fire and then rebuilt, and the stone layer was interpreted as a floor. Hulled barley were found in both cultural layers (Papmehl-Dufay & Sandberg 2019).

Figure 5: Detail of Skedstad excavations plans. Edited by author (ATA dnr 6060/1971).

2.5. Skedstad (L1955:2226 / Bredsättra 92)

Skedstad is located east of Skedemosse and slightly east of the Litorina ridge. In 1971 a large assemblage of iron ingots was found here, and 1972-3 the area was excavated. At least three house were uncovered and there were traces of iron working. A hoard with golden rings and other golden objects were also found, including a snake-head similar to that of rings found at Skedemosse. The
finds are from the Roman and Migration periods, a dating that is supported by \( ^{14}\text{C} \) dating of post-holes and hearths. Some of the \( ^{14}\text{C} \) datings from hearths however suggests that the place was already in use during the pre-roman period. Thick occupation layers also suggests a lengthy occupation, as do the complex house plans. (Beskow-Sjöberg 1977:131ff). Because of these rich finds Fallgren (2008) ranks Skedstad as a magnate farm.

Finds suggest that the house had wattle-and-daub walls instead of the dry stone walls typical of the stone foundation settlements on Öland. Similar houses were found in the nearby settlements at Bo and Ormöga, which may indicate a different and more conservative building tradition in the Skedemosse area (Beskow-Sjöberg 1977:109ff) However this may be related to the intensive cultivation in this area, as stone houses foundation and stone fences seen on older maps now have been removed (Fallgren 2006:163ff).

In 1972 an assemblage of mostly hulled barley was found, covering an area of 2,5 m\(^2\) (Hjelmqvist 1979:50). Judging by the line of postholes in the original plans of the excavations (figure 5), the assemblage may have been from the northwest section of a house and may represent a storage context. It is possible that the cereals belongs to an earlier period, as another house overlays this house (ATA dnr 6060/1971).

2.6. **Prästhag (L1955:3207 / Köping 420)**

This settlement excavated in 2009 is located south of the Viking Age and Early Medieval trading port at Köpingsvik. Artifacts and \( ^{14}\text{C} \) datings suggests that the settlement is from the same period, around 900-1250 AD. At least six houses were uncovered (Åstrand et al. 2012). A large assemblage of cereals, around 12,000 grains, were found in a waste pit. These were mostly barley but there were also spelt wheat. Another pit included barley and bread wheat. There were also finds of cereals in constructions interpreted as ovens, but it is possible they are waste pits, and in the post holes of one of the houses (Regnell 2010). The material analyzed was from one of these constructions (A358). The cereals here were heavily charred, but those that could be identified were hulled barley (Leino personal communication 2019-04-15).
3. Agriculture

3.1. Background

As Welinder points out, defining agriculture is a problem in itself. He then settles on a definition of agriculture as the presence of domesticated plants and animals. This has methodological advantages, as it makes the study of agriculture simply a problem of finding traces of domestication (Welinder 1998:44). Unfortunately, this appears as an example of circular reasoning. Such traces are potential outcomes of agricultural practices, but cannot be said to be agriculture. One here has to distinguish between things and processes, things here including biological entities. More reasonable may be to view agriculture as a particular human form of niche construction, where an organism through its activities modifies the environment to create a niche for itself (Eriksson & Arnell 2017). What's more, agricultural practices such as manuring, sowing, harvesting and threshing are not performed independently of each other, but in relation to each other in a system. How systems are conceptualized is therefore fundamental to an understanding of agriculture.

3.2. Social-ecological systems

Welinder (1998:32ff) describes agriculture as an ecological system where energy and nutrients are concentrated to keep the soil fertile, that is to maintain an ecological equilibrium. Using this model, he divides the history of agriculture into four phases.

The concept of equilibrium however is a highly debated issue in ecological theory. In traditional systems theory, ecosystem were perceived as homogeneous and balanced after adapting to the surrounding environment. Nature in itself thus tend towards stability and equilibrium. From the 70's onward however, this view was increasingly questioned. One reason was that empirical data did not match the models of systems theory. In the alternative view, nature is perceived as a place of disorder, struggle and agency. Important concepts in this new ecological thinking were chaos theory and complex systems theory (Worster 1994:388ff). There are here obvious parallels to developments within archaeology, were systems theory was central in processual thinking, and subsequently criticized for environmental determinism and ignoring human agency (Trigger 2006:386ff). In a more recent summary of systems thinking by Meadows (2009), there are no separate systems, as the world is a continuum. Instead of a systemic equilibrium there is dynamic equilibrium, were the inflows balances the outflows.
There thus seems to be little reason to suppose that agriculture ever was a stable ecosystem as envisioned by traditional systems theory. Change may then be thought of as continuous, albeit often slow, and not as a consequence of a disturbed equilibrium. One may then envision agriculture as a complex adaptive system, usually understood as open networks with nonlinear and emergent properties (Presier et al. 2018). An understanding of agriculture will then have to depend on models in line with complex systems theory. An ecological example of this is the resilience theory of Holling (2001), and an example from archaeology is Hodder’s theory of entanglement (2012).

Resilience may be defined as the ability of a system to survive under changing circumstances. It is not to be confused with stability or sustainability, as a resilience depends on flexibility. A rigid system is not resilient, resilience is created by a rich and varied system with feedback loops that restores the system when it is damaged (Meadows 2009:76f). In Holling's model (2001), the system is constantly changing and moving. This change is cyclical, as the system passes through phases of growth (or exploitation, r), conservation (K), collapse (or release, Ω), reorganization (α) and then back to growth, a flow of events that is often represented by a stylized “eight” figure (figure 6). How that happens depends on the wealth or potential of the system, it's internal connections and its adaptive capacity, that is its resilience. Adaptive cycles of different sizes are in turn nested in hierarchies and may affect each other, this is referred to as the panarchy.

Figure 6: The adaptive cycle of the four ecosystem functions: α, r, K and Ω (Source www.resalliance.org).

The idea is that this model should be universally applicable and explain changes in ecosystems as
well as social-ecological systems. Redman and Kinzig (2003) for example uses this model to explain transformations among the Hohokam in pre-columbian North America. The Hohokoma enjoyed a period of prosperity, largely due to investments in large irrigation system in the river valleys of modern Arizona. However, as the system was adapted to relatively stable annual flows of water, this made the system rigid in face of environmental changing conditions. As the variability of the flows increased, the system was stressed, eventually triggering a release phase and reorganization of the system. One here has to be careful, as the model may oversimplify matters. While systems are not static, much of the criticism aimed at traditional systems theory may still apply, that of environmental determinism and ignoring human agency. Also, as the model focuses on temporal change of individual systems, it is unclear how one draws the spatial boundaries of these systems.

Hodder's concept of entanglement is inspired by complex systems theory and actor-network theory. Central to this theory is human-thing relations, were Hodder distinguishes between relations of dependence and relations of dependency. Dependence refers to how humans and things rely on each other, while dependency is the constraints imposed by this relationship. Entanglement is then defined as the dialectical relationship between dependence and dependency (Hodder 2012:88ff). The domestication of cereals is an example of this. As cereals yields more food per land unit, humans come to depend on cereals for food, which require human investment. But cereals also come to depend on humans on survival, in particular if their capacity to seed dispersal is removed. Humans and cereals have become co-dependent or entangled in each other (2012:75f). Once things are entangled, it is very hard to disentangle and go back. Humans thus tend to dig holes for themselves. When things need to get fixed, this is often done by adding more complexity, creating more relations of dependency and making things more entangled. Change is thus not determined by ecology, economy or ideology but by the entanglement itself (2012:206ff).

In both models we find a movement towards a more inflexible and rigid system. A deeply entangled system also appears to be less resilient. In Holling's model however, more definitive predictions are made. A social transformation or collapse appears inevitable. For Hodder on the other hand things are a lot more contingent and open, as it is centered on particular things and humans and not systemic totalities. For this reason it also appears as more grounded in the archaeological material. There is however a tension between the movement towards dependency and the fact that things
breaks down over time, forcing humans to make adjustments (Hodder 2012:211).

3.3. Agriculture in the Iron Age

Prehistorical agriculture may be studied from a number of archaeological materials, including settlements, field systems, agricultural tools, fossilized plants and animal bones (Welinder 1998:46ff). It is an interdisciplinary field and may employ methods such as experimental archaeology, pollen analysis to study landscape change and isotope analysis to study diet change. For the understanding of South Scandinavian agricultural history the interdisciplinary Ystad project was of particular importance, aiming to describe long-term environmental and social change (Engelmark 1992). Since then, however, there has been a growing source material, particularly from settlement archaeology (Welinder 1998:52ff, Grabowski 2014:10ff).

During the Iron Age agriculture underwent a number of changes in south Scandinavia. Permanent field agriculture was introduced towards the end of the Bronze Age. This type of agriculture probably depended on manuring (Engelmark 1992, Pedersen & Widgren 1998:241ff, Grabowski 2014:20f). The term is a bit misleading since the fields moved after being used for some time. Examples of this are the so-called Celtic fields found on Gotland and in Denmark. Eventually the fields were fixed, and the agricultural landscape was organized into the infield system known from historical times (figure 7). This is believed to have occurred around AD 200 and related to the building of stone fences on Öland, Gotland and in central Sweden. It is also related to changing settlement patterns, from single farms to villages (Pedersen & Widgren 1998:277ff, Grabowski 2014:24f).

A second change is what species of crops are grown on the fields. During the Stone and Bronze Age a great variety of crops were grown, including a number och species of barley and wheat. This changes during the Iron Age as hulled barley becomes the dominant crop. During the Iron Age oat and rye also grow in importance, and during the Late Iron Age there is a regional variation what crops are grown beside barley. This is related to the third change, the introduction of crop rotation and fallow years (Pedersen & Widgren 1998:379ff, Grabowski 2014:12ff).

In the Early Iron Age permanent fields the crops were grown year after year on the same field, through they were probably put to fallow when needed causing the fields to migrate, possibly after
being used a few decades. In the historical period it is known that a three field rotation was used in Denmark, Skåne and parts of central Sweden, and that a two field system was used in eastern central Sweden. In the two field system half of the field was put to fallow every year, in the three-field a third of the fields. This was combined with some sort of crop rotation, usually autumn rye after the fallow, then spring barley. In Skåne barley was sown first in the spring after the fallow, then rye the following autumn (Pedersen & Widgren 1998:385ff, Grabowski 2014:20ff, Leino 2017:34f). An obvious advantage of such a system is that it demands less manuring. It also disrupts weed infestations (Grabowski 2014:22).

**Figur 7**: The energy flows of the infield system. The outfields are used for grazing lands and collection of fodder, animal manure is then used to fertilize the infields (Welinder 1998:35).

It is generally accepted that crop rotation was in place in the Late Iron Age. Exactly when it was
introduced and how is connected to the introduction of rye however is uncertain. In Skåne rye was grown in large quantities in the Late Iron Age. In east central Sweden however autumn rye was introduced in the late Medieval Period, though wheat may have been autumn sown. Large finds of rye in Vallhagar at Gotland however suggests that three field rotation may already have been practiced in the Middle Iron Age (Pedersen & Widgren 1998:385ff, Viklund 1998:149f, Grabowski 2014:22ff). Based on his study of Gedved Vest in east-central Jutland, Grabowski argues that rye may have been used as flexible resource that was utilized when necessary (2014:34). One field agriculture without fallow also continued in some places, in Medieval Gotland for example all three systems were used (Pedersen & Widgren 1998:385f, Myrdal 1999:62).

There have been attempts to explain these changes from environmental, technological and social factors. Agriculture may be seen as a form of adaptation, which may change because of for example the climate. A cold period at the beginning of the Iron Age would have impelled people to build byres for the livestock, and this would make collection of manure easier (Pedersen & Widgren 1998:253ff). Cold climate may also have had a negative impact on emmer wheat, millet and naked barley, while the spread of hulled barley during this period has been explained by its resistance to humidity. This does not explain the decrease in spelt wheat, however. Also, as these developments occurs at different times in different regions, climate is unlikely to be the only factor (Pedersen & Widgren 1998:379, Grabowski 2014:17).

One view may be to consider agriculture as a form of technology, which develops because of a compounding of human knowledge and experience. Agricultural change may then be explained by the introduction of distinct technological packages, in what has been described as an agrarian-technical complex (Widgren 1997:19). Byres, manuring, meadows, hulled barley cultivation and iron sickles may thus be considered as innovations that are interlinked, a package solution that would remain fairly stable until around 800 AD (Pedersen & Widgren 1998:241ff, Viklund 1998:138f). Agriculture may then also change because of external technological developments such as iron production (Pedersen & Widgren 1998:261ff).

Finally, because agriculture is practiced by human populations, social factors cannot be ignored. The introduction of permanent fields, stone fences and byres may for example be related to the marking ownership (Pedersen & Widgren 1998:241ff). The fields and enclosures from the Early
Iron Age are different in eastern and western Sweden. Pedersen and Widgren argue that this is because different types of social organization, with a lineage based system in the west and a community based system in the east (1998:316f). Another possible social factor is food preferences, hulled barley cultivation have for example been explained by consumption of porridge and beer (Pedersen & Widgren 1998:405, Grabowski 2014:19f). This may also involve ritual use and deposition (Viklund 1998:153ff).

Overemphasizing one type of factor however may lead to some form of reductionism or determinism that oversimplifies the complexities of these developments. For example, Ingold argues that the concept of technology does not exist in pre-modernity, it only arises with the advent of the machine. This means that the technical is externalized from the human, while in pre-modernity technique and social identity are closely linked (Ingold 2000:312ff). Therefore, when talking about an agrarian-technical complex, this must not be understood as an external package of technology, but the human subject must be thought as a part of it.

According to Ingold (2000:319ff), technique is used to engage both other humans and the environment, and may sometimes involve the use of tools. With the introduction of farming, tools becomes instruments of domination. The technical is thus embedded in the social, as the social is embedded in the landscape, where human dwelling imposes a distinct temporality, what Ingold refers to as the taskscape (2000:189ff). One may here use crop rotation as an example, it imposes a new temporality by introducing a more complex ordering of activities, which may produce a great social complexity. The implication however is that agriculture must be conceived as an independent process that cannot be reduced to its exterior relations.

The impact of agricultural change is also apparent in the landscape. During the first centuries AD, there is an agricultural expansion that is visible in archaeological remains and pollen diagrams (Pedersen & Widgren 1998:267). This may be related to the infield system which was able to support a larger population. It is not clear however, if the infield system caused the demographic change, or if a growing population forced an agricultural reorganization (Welinder 1998:36f). But it also created a more open landscape (Welinder 1998:31f). Eriksson and Arnell (2017) argues that this was a direct consequence of the infield system, through burning and clearing the forests in much of southern Scandinavia were transformed to grasslands, something that also had an impact of
Pedersen and Widgren argue (1998:267ff) that petty kingdoms are formed during this period, leaving traces such as monuments, settlements and treasures. This is related to surplus production in agriculture, which makes it possible for an elite to participate in exchange of artifacts. This would account for some of the regional variation that is visible in agriculture.

### 3.4. The Cereals

Organic materials like plant remains are only preserved under special conditions. Subfossil plants may survive under oxygen-poor conditions, for example waterlogging, where the more resistant plants of the plants may survive. Cereals however are most often preserved as charred, how well depending on factors such as the type of plant, temperature, the surrounding material and how long they burn. It is also likely to change the texture och shape of the plant materiel. It is usually the grain that is preserved, but other part of the plants may also be found. These includes the rachis, that is the central axis of the cereal ear, as well as stems and roots (Viklund 1998:29ff, Fraser et al. 2011).

The cereals grown in Scandinavia during the Iron Age includes species of barley, wheat, rye and oat. Barley has been the most common crop in long periods, and its ability to grow on poor soils and resistance to cold make it suitable for northern climate. It is generally assumed that the barley grown during the Iron Age was six-row barley (Pedersen & Widgren 1998:379, Leino 2017:185ff). During the Iron Age hulled barley (Hordeum vulgare var. vulgare) became the dominant crop, largely replacing naked barley (H. vulgare var. nudum). As discussed, a number of reasons for this have been suggested: It responds better to manuring, is may be stored longer, its use in beer brewing and cooking. Possibly this is a situation of entanglement, as sowing depends on what has been previously harvested. It would therefore be difficult to go back once a particular crop had become dominant.

Rye (Secale cereale) was domesticated in Anatolia, but when it spread to Europe it was as a weed. This does not mean it was a wild plant but a hybrid form, acquiring features typical of domesticated plants like enlarged grain size and touch rachis. It is known from the Pre-Roman Period in Scandinavia and the first evidence of intentional cultivation is from Halland and Jutland (Viklund
It does not become widespread until the Late Iron Age however, despite being a plant suitable for colder climate. Rye is generally autumn-sown and the plantlets survives during the winter. This makes it suitable in systems of crop rotation (Behre 1992, Leino 2017:15ff).

It has been proposed that the spread of hulled barley and rye may be explained by introduction of iron sickles that cut low to the ground. As straws and weeds also were harvested, the outflow of nutrients would increase the need for manure. Increased manuring would favor hulled barley (Viklund 1998:139), though there is little evidence of this (Grabowski 2014:18). Meanwhile, Behle (1992) argues that the harvesting of weeds means that it would be more difficult to separate weed rye from other crops, making it spread faster, eventually being accepted as a crop plant.

Wheat no longer had the prominent role it had during the Stone Age but was still cultivated. It generally has higher nutritional demands than barley however and is less suitable for colder climates. Wheat is either hulled or naked, in hulled wheat the hulls have to be removed from the grain after threshing. Naked wheat include bread wheat (*Triticum aestivum*) and club wheat (*T. compactum*), while emmer (*T. diococcum*), spelt (*T. spelta*) and einkorn (*T. monococcum*) are hulled (Welinder 1998:72f, Leino 2017:125ff). Wheat may be both spring sown and autumn sown, autumn sown being more common in historical periods (Leino 2017:142ff).

Like rye, oat appears to first have occurred in Scandinavia as a weed. Cultivated oat (*Avena sativa*) is often hard to tell apart from other species of oat. It appears that it was first cultivated in Halland during the Late Bronze Age, also not being common in other regions until the Late Iron Age. (Viklund 2004, Grabowski 2014:15f, Leino 2017:217ff). Oat has lower nutritional needs than other cereals, but is more sensitive to drought (Leino 2017:36).

Following the harvest, cereals were threshed, which would separate the grains from the straws. In Scandinavia, this was likely performed indoors using clubs and sticks. This was followed with steps of cleaning and sieving involving for example the removal of weeds, and then storage of the grains before they were used in cooking and baking (Viklund 1998:49ff). The bread finds from the Early Iron Age mostly contain hulled barley. All cereals may be used for bread, however only wheat and rye may be used for fermented bread. Barley was also likely used for beer brewing. All cereals may
also be used as fodder, but most often oat have been used for this purpose (Leino 2017:36, Pedersen & Widgren 1998:398ff). Why some cereals were cultivated may thus also be related to their social significance.

3.5. Manuring

As shown above, manuring was of central importance in Iron Age agriculture. Manuring is a flow of energy and matter in a social-ecological system. It also makes humans more dependent on animals, and crops more dependent on both humans and animals for their procreation. Manuring is thus a practice that generates deeper entanglements.

As manuring leaves few direct traces however, very little is actually known about prehistoric manuring. The presence of manuring has often been inferred from preserved weeds, but this does not provide direct evidence, as it rather reflect overall growing conditions (Fraser et al. 2011). Based on weed finds in south Skåne, Engelmark (1992) argues that manuring is related to the spread of hulled barley during the Late Bronze Age and Early Iron Age. This would be because hulled barley has a greater need for soluble nutrients, in particular nitrogen. This would also be related to the introduction of byres, which would have made the collection of manure easier (Pedersen & Widgren 1998:253ff, Grabowski 2014:17f). However, it has been argued that there are traces of manuring in Western Europe dating back to the Neolithic. It may have started with the introduction of the ard (Bakels 1997), or even been a factor in the first domestication of animals (Hodder 2012:78f).

One may here emphasize the materiality of manuring. Waste disposal is likely to always have been a problem that had to be solved somehow. As animals were domesticated, accumulation of fecal matter may have posed a hygienic problem that have to be solved, a problem that must have grown with the number of animals and the closer humans and animals lived together. Manuring turned this problem into an advantage. Bakels (1997) suggests that manuring was an unintended consequence of milking and stalling.

The advantage of stable isotope analysis is that it may provide direct rather than indirect evidence of manuring. Kanstrup et al. (2014) did a long-term analysis of danish cereals from the Neolithic to the Early Iron Age. The results supports that manuring of some sort was used as early as in the
Neolithic, though the results indicate an increase in manuring for naked barley during the Late Bronze Age and Early Iron Age (figure 8).

Figure 8: Nitrogen isotope values suggesting increasing manuring intensity in danish naked barley during the millennia BC (data from Kanstrup et al. 2014).

Manuring is related to the question of how one should understand the changes in agriculture during the Iron Age, if it was primarily caused by technological innovation or other factors. Since much suggests manuring was already known, the change may have been one from a more flexible use to one of stronger dependency, that is one of more entanglement. One may then ask what elements and which agents played a more important role in this development. The social consequences may have been significant if agriculture became more labor intensive, which implies greater social control and social complexity. In the eddic poem Rígsþula, which may go back the Viking Age, manuring is a task allocated to thralls, and it is likely that there were already thralls in the Early Iron Age (Pedersen & Widgren 1998:436ff).

Concerning the sources for manure, the roman writer on agriculture Columella says in De re rustica that there are three main sources, birds, humans and livestock. Of these he ranks manure from some birds highest, including chickens, followed by manure from humans. Of livestock manure, manure from donkeys is the best, followed by manure from sheep, goat, cattle and finally pigs. The low
ranking of pig manure may not be justified, but it may be true for cattle manure. That cattle manure was more important in Scandinavia is most likely related to that cattle was more numerous than in the Mediterranean area (Myrdal 2009). Other historical sources mentions seaweed being used as a fertilizer (Blanz et al. 2019), and peat is known to have been used in Scandinavia during the Medieval Period (Myrdal 1999:64).

Columella also describes the actual practices of manuring, but how this applies to Scandinavia during this period is of course unclear. There must have been an operational chain involving gathering, storing, transportation and fertilization. Byres are known from most of South Scandinavia from the Early Iron Age, usually as a section in the long house. This would make feeding the livestock and collecting the manure easier, but this would also create a dependence on hay meadows for the supply of winter fodder (Engelmark 1992:372f, Pedersen & Widgren 1998:253ff). According a model by Viklund (1998:113ff) based on a reconstruction of an Iron Age longhouse at Gene in northern Sweden, hay and manure may have been stored in different sections next to the byre. Also, the stones fences found in eastern and central Sweden sometimes forms cattle paths along which grazing animals may daily have been brought to the byre for the collection of manure (Pedersen & Widgren 1998:294).

The extent to which animals were stalled during the Iron Age is a debated issue however. A reason for this that identifying sections were animals were kept may be difficult. Methods for identification may include phosphate or element analysis. Central pits in some houses are sometimes interpreted as places were manure may have been collected, but these may have been storage pits (Viklund 1998:124ff, Welinder 1998:124f, Isaksson et al. 2000, Petersson 2006:68f). For some houses in Östergötland, Petersson (2006:82ff) interprets some high phosphate values and cultural layers as manure heaps outside a byre section. She thinks however that byres were a high status phenomena during this period in Östergötland, and that animals were mostly kept outside even during the winter. This does not mean manure was not collected, as animals may have been kept in enclosures during the night for this reason (2006:249ff).

In permanent field agriculture, the same arable land may have been used year after year without fallow if the manure supply was big enough to compensate for the loss of nutrients. Eventually however the people may have to abandon the field because of leaching or because of weeds, pests
or parasites. It would also create a dependency on large supplies of manure, even if peat or seaweed could be added. Crop rotation may decrease leaching of the soils, and the introduction of a fallow year decreases the need for manure (Engelmark 1992:372f, Eriksson et al 2013:293ff).

Because of the complexities of these flows of matter and energy, it is unclear if human trial and error could ever establish a dynamic equilibrium. Intensive cultivation leading to soil degradation have also been proposed as a reason for changing settlement patterns during the transition to the Late Iron Age (Beskow-Sjöberg 1977:129, Pedersen & Widgren 1998:314). However, other evidence suggest that this does not occur or that soil fertility may actually increase in the long term (Widgren 1997:50). One may then not assume a linear relation between intensive manuring and soil degradation.

It may be more relevant to discuss the relative resilience of these forms of field agriculture. Permanent field agriculture without crop rotation do not appear as a very resilient system, as it depended heavily on manuring and a single crop, hulled barley. Two-field och three-field systems reduced the need for manure and crop rotation introduced more diversity by adding more cereal species, making it a more resilient system. This may partly explain why this system replaced permanent fields. A question is how this change occurred, if there was a slow transformation because of daily problem fixing or if there was a systemic crisis that triggered a reorganization.

During the migration period the agricultural expansions appears to slow down. There is a change in settlement patterns as many farms are abandoned. Pollen analyses also suggests a regrowth of forests in some areas. This may be because settlements are concentrating into fewer villages (Pedersen & Widgren 1998:309ff, Grabowski 2014:25). These developments fit well with the model of the adaptive cycle in resilience thinking, one may identify phases of growth, conservation, collapse and reorganization. Instead of searching for external causes like wars, climate or pestilence it may thus be possible to explain these changes from the internal dynamics of the system, where agricultural practices are central. That is not to downplay the importance of external causes, as such an event may trigger the transition from the conservation phase to the release phase (Holling 2001).
4. The Social Ecology of Iron Age Öland

4.1. Background

The purpose of this section is to trace the web of relationships between landscape, humans, livestock and crops on Öland during the Iron Age, the spatiality of this network, how it changes with time and what elements and agents shape these changes.

4.2. The Landscape

The landscape of Öland have been shaped by many processes: geological, climatological, biological and antropogenic. For example, the movements of ice sheets and changing sea levels have shaped the landscape, creating the ridges known as landborgar running north to south along the island, a large escarpment in the west and the smaller Ancylus and Litorina ridges (Köningsson 1968:12ff, Fallgren 2006:121f).

Öland is one of few areas in Sweden where a limestone bedrock is preserved. This impedes acidification and contributes to the forming of brown earth soils that are suitable for cereals (Welinder 1998:21ff, Eriksson et al. 2013:225ff). Agriculture was introduced during the Neolithic, increasing the human impact on the landscape. It has long been the view that animal husbandry was central and crop cultivation secondary as once claimed by Stenberger (1933:106). One impact was that of deforestation, as the coastal areas and much of the southern part of the island was cleared of forest by humans, for the collection fodder, fuel and building material as well as expanding grazing land (Stenberger 1933:104ff, Königsson 1968, Pedersen & Widgren 1998:298ff).

It is likely that the crop fields and single farms firsts moved around in the landscape, although very little is known about agriculture or settlement patterns from early periods. During the Iron Age, however, the landscape would be divided into stable infields and outfields and farms would conglomerate into villages, an organization that would remain into the historical period. The remains of stone fences and stone house foundations from the Middle Iron Age are seen as related to this change. These settlements begin to be built around 200 AD, though they sometime overlays earlier remains (Fallgren 2006:27).

Stone fences appears as the remains of what once was a human taskscape. Their dating is problematic, but they are often linked to the stone house foundations. The stone fences form large
systems of partitioning around the settlements. There are small enclosures around what may once have been crop fields, and larger enclosures for meadows or cattle. The stone fences also enclose cattle paths from the outfields to the settlements (Herschend 1988, Fallgren 1997, Pedersen & Widgren 1998:294f). That these settlements often are placed on dense soils supports the view that animal husbandry still is primary (Widgren 1997:42).

The stone fences form the border to the outfields, which should not be understood as wild nature. As grazing lands they are what one may call a domesticated landscape, possibly commons between the villages and farms. This is also the place were ring forts dating to the same period as stone house foundations have been built. Fallgren (2008) interprets them as joint projects of the surrounding farms and villages, so one may see them as a heterarchical rather than hierarchical elements. Other features of the landscape also seem to have served as social nodes. There is the fen of Skedemosse, during this period still a lake, where sacrifices took place from the Pre-roman Period into the Viking Age. The Ancylus ridge runs next to its eastern edge (Monikander 2010). These ridges seems to have served as important roads of communications and cemeteries have been placed along them (Fallgren 2006:121ff).

The Great Alvar of south Öland has a number of stone house foundations that are not connected to the stone fence system. Königsson (1968) used pollen analysis to study history of this landscape. He concludes that people could not have lived on the barren landscape of today, but that this landscape was created by human activities, especially intensive grazing. These transformations would have started with the introduction of agriculture, but the pressure increased during the Roman Iron Age. Eventually these settlement would have become unsustainable and the people would have to abandon them, possibly because of worsening climate conditions. During the Late Iron Age however the agricultural expansion seem to have resumed. Because of overgrazing, the grassland at Öland's southern end now developed into a heath (Alm Kübler 2001).

Eventually stone houses and ring forts were abandoned all over Öland. This have often been connected to some sort of catastrophic event, possibly involving a demographic collapse. Stenberger (1933:211f) believed that the island was devastated by war, possibly related to the Slavic migrations. More recently it has been connected the the “dust veil event” of AD 536 causing a climate downturn (Gräslund & Price 2012). Fallgren (2006) however points out the continuity
between the stone house foundations and historical settlements and that some stone houses remain in use unto around AD 700. So the change would be one of a slow transformation instead of a catastrophic event. On the other hand, this does not explain why these changes occurred. The discovery of the massacre at Sandby Borg (Alfsdotter et al. 2018) shows that war was an actuality. The dust veil event is also likely to have had a real impact on the landscape (Gräslund & Price 2012).

### 4.3. The Humans

Human remains from Iron Age Öland are preserved in a large number of graves, both cremations and inhumations. These have an unequal temporal distribution. From the Early Roman Iron Age there is a large number of burials, after that the numbers decrease, leaving much fewer burials from the Migration period. From the Vendel period there is only a handful, then there is a large number again from the Viking period. It is uncertain if these distributions reflect demographics or changing burial traditions (Stenberger 1933, Fallgren 2006:136ff, Wilhelmson 2017:56ff). Human remains have also been deposited in Skedemosse (Monikander 2010:86ff) and at Sandby Borg (Alfsdotter et al. 2018).

The remains in the landscape suggest agricultural practices were central in the life of the people on Iron Age Öland, both animal husbandry and crop cultivation. This is supported by finds of animal bones (Pedersen & Widgren 1998:364) and fossilized cereals (Hansson & Bergström 2008). In a number of graves from the Early Roman Iron Age there are half-moon knives that may have been used for leather preparation. As these are female graves, these practices may have had a particular social significance (Räf 2001). The importance of wool textile production is indicated by finds of combs, spindle whorls, spindle shafts and loom-weights, for example at Sandby Borg (Victor 2014:53). As a coastal population, fishing also seems to have been of importance. In the ring fort Gråborg there is a large number of fish bones, mostly herring. There were also bones from sea birds that must have been hunted (Vretemark & Sten 2008). Other practices leaving traces in Iron Age settlements are handicrafts such as metal working and pottery (Beskow-Sjöberg 1977).

As for what people have eaten, a number of isotope analyses have been done on human remains from the Iron Age showing relatively high $\delta^{15}N$ values and low $\delta^{13}C$ values (Eriksson et al. 2008, Howcroft et al. 2012, Wilhelmson 2017:149ff), indicating that people mostly depended on either
freshwater fish or a terrestrial protein sources which were $^{15}$N-enriched. Here are several possibilities, including pastoral animal products and manured cereals. There is also some temporal variation with relatively higher $\delta^{15}$N values from the Roman Iron Age. One possibility is that this reflects the increase in manuring from the Iron Age observed by Kanstorp et al. (2014). From the Late Iron Age, analyses sometimes give lower $\delta^{15}$N values and sometimes suggest a higher dependence on marine food (Howcroft et al. 2012, Wilhelmson 2017:149ff).

It is apparent that the people from Iron Age Öland participated in far-reaching social networks. This is demonstrated by finds of roman artifacts and treasures of *solidi*. There are the Torslunda plates with motives found at helmets from Central Sweden and Sutton Hoo. There are also finds of *Sternfussfibula*, a type of brooch mostly found in the Eastern Baltic region (Stenberger 1933:14ff, Hagberg 2008). Strontium and oxygen isotope analysis of human remains also suggests the presence of non-locals (Wilhelmson 2017:167ff, Calleberg 2019). It appears likely that participation in such networks was part of processes of identity formation and of distinguishing an elite, something that from around AD 400 would materialize in the Animal Art Style that appears for example on fibulas and the Torslunda plates (Hedeager 2011:61ff). These processes may explain be visible in settlement hierarchies from this period on Öland (Fallgren 2006:143).

It is also apparent that connections were not only peaceful but that war was a reality. During the Roman Iron Age, people are often buried with weapons (Stenberger 1933:14ff). In Skedemosse, several depositions of weapons are made during this period, similar to the danish depositions (Monikander 2010:13ff). From around AD 200, ring forts are being built (Fallgren 2008). At least one ring fort, Sandby Borg, have been attacked and the occupants massacred. Alfsdotter et al. (2018) believes this relates to an internal conflict on the island. Other ring forts are abandoned during the Vendel period (Fallgren 2008).

Violent conflict may thus played a role in a social reorganization during this period. Possibly there is a relationship to the turbulence surrounding the fall of the Western Roman Empire. It has been suggested that because of the importance of these social connections where an elite benefited from the exchange of artifacts, this would have caused social destabilization (Herschend 1988).

From the Vendel Period there is a boat grave in Nabberör where a man appears to have been buried
with two thralls (Pedersen & Widgren 1998:438). While this does not prove there were slavery in earlier periods, the seizing of thralls may have been a part of warfare (Andrén 2014:98f). A thrall would have been totally dependent on his owner for food and housing, while for the owner, owning a thrall would maximize the labor output in relation to energy investment in the form of food. It thus appears likely that social relations involved relations of domination. It is also likely that such relations were ritualized, as in Skedemosse humans also have been deposited (Monikander 2010:77ff).

4.4. The Livestock

In a number of graves from the Iron Age there are animals have deposited from a wide variety of species (Räf 2001). In Skedemosse animals have been deposited throughout the Iron Age, and horses are the most common animals. A well outside the ring fort Eketorp appears to have been used in a similar way (Monikander 2010:58ff). These ritual practices suggests that the entanglement of human and animals was therefore not only a matter of functionality, but also had a social dimension. In slavery, there is a dependency on humans that is instrumental, slaves have a status closer to that of domesticated animals, as the relationship is one of domination (Ingold 2000:72ff). The animal style art is introduced during the Migration Period, for example the Torslunda plates. Here warriors are associated with wild animals like wolves, bears and boars, and not with any domesticated animals (Hagberg 2008, Hedeager 2011:61ff, Andrén 2014:98ff). One may envision an elite maintaining domination over human and animal populations to control the flows of matter and energy in the landscape.

Domesticated animals that are known from Iron Age Öland are cattle, sheep, goat, pig and horse. Of these sheep seem to have been most numerous, and their importance grew during the Early Iron Age (Pedersen & Widgren 1998:364ff). The sheep on Öland appears to have been relatively large and it appears that they evolved into a local landrace (1998:378). The excellent grazing land may have contributed to this, but also selective breeding and other conditions created by human practices. It may therefore be described as a particular nature-culture hybrid. The demand for wool is often seen as reason for the importance of sheep husbandry (1998:368f), and a surplus of wool may have allowed people to participate in exchange networks (1998:313).

After sheep, the material is dominated by different types of cattle; cows, bulls and oxen (Pedersen
& Widgren 1998:364f). The cattle also seems so have become usually large because of the good grazing lands and breeding (1998:378). Beside wool people may have depended on a surplus of hides and leather. Half-moon knives is found in some graves may have been used for leather preparation (1998:313).

An advantage of having both sheep and cattle is that the species occupy different niches in the landscape and do not compete with each other. For example, cattle eat the tips of the crass while sheep the bases of the grass (Pedersen & Widgren 1998:368, Hodder 2012:78). A downside would be that this increases the energy outflow of the pasture, increasing the risk of overgrazing.

Stone fences have most likely been built to keep livestock away from cultivated fields and meadows (Fallgren 2006:38ff). In farms with only one long-house, part of the house may have served as byre. Most farms however had more than on house and the byre was a separate house. The houses remains on the Great Alvar may not have been separate settlements but houses related to herding practices. The ring forts also appears to be related to grazing practices on the outfields. Some of the houses of the ring forts seem to have been byres (Herschend 1988, Fallgren 1997, Pedersen & Widgren 1998:298f, Vretemark & Sten 2008, Peterson 2009).

While archaeology usually have focused on human dependency on animals, it can also be argued that animals depend on humans to propagate. In this view, the relationship appears as one of co-dependency or mutualism (Hodder 2012:79). Growing animal population would have an impact on the landscape, as grasslands expands and forests retreats. Humans would have to protect cultivated fields and meadows by building fences, and the loss of forest may have been a factor in the choice of stone as a building material. One way to decrease the impact on the landscape would be to keep the animals inside and feed them (Petersson 2006:250), but it is unclear to what extent this happened in the Early Iron Age. Soil degradation may have increased the need for manure, increasing human dependency on the animals, as well as meadows for fodder, although a coastal population like that of Öland may have been able to add seaweed to the manure. Eventually however this generates a transformation of the landscape, forcing human and animal populations to readapt. This may involve a change from extensive to more intensive animal husbandry practices, involving for example a greater degree of feeding and stalling.
4.5. **Cultivated Plants**

Charred cereals from Iron Age Öland have been found in ring forts and settlements. The most common species of plant is hulled barley. Several large assemblages of cereals have been found, most likely from storage context were the cereals have been charred for one reason or another (Hansson & Bergström 2008). There are also stray finds, for example from post holes, hearths or floor layers (Peterson 2009, Larsson 2012, Papmehl-Dufay & Sandberg 2019).

In both Gräborg and Eketorp storage assemblages from the Migration Period and the Vendel Period have been found, usually placed in locations close to the wall of the forts (Helbæk 1979, Hansson & Bergström 2008). As these ring forts are located on outfields, it is unlikely that there was any crop cultivation in their vicinity. The cereals must then have been brought to forts from somewhere else, most likely the nearby contemporary settlements where they were cultivated. But it is also possibly that cereals have been brought in from outside Öland, which must have happened at least as some occasions as new cereals and weeds were introduced (Helbæk 1979, Hansson & Bergström 2008).

In the settlements a large assemblage of cereals was found in Skäftekärr in the northern part of Öland, in a storage pit below a charred wooden cover in the western section of a long house (Fallgren 1997). As it composed almost totally of hulled barley, the grains appears to have been cleaned (Viklund 1998:84). The Skedstad assemblage may have had a similar context. A large finds of charred cereals is also reported from Ormöga, possibly in a house foundation according to Stenberger (1933:144).

From the pattern of stone fences in the settlements, it appears that the crops grew on infields right next to the houses (figure 9), today visible as concave surfaces cleared of stone. These fields were not very large, often no more than one or two hectares (Fallgren 1997). The practices of crop cultivation thus appear concentrated to a small area, manure possibly being collected and stored in the byres and then brought to the nearby fields, crops sowed, harvested, threshed and cleaned and then stored in the longhouse.
Figure 9: The agricultural landscape at Gillsättra north of Gråborg (By author based on FMIS data).

It is assumed that this was a form of permanent field agriculture with no crop rotation (Pedersen & Widgren 1998:301), something that may have been feasible in the brown earth soils of Öland. However as farms may sometimes have more than one field, some sort of two-field or three-field systems may not be excluded as a possibility. This is related to the occasional presence of rye in the material, in Eketorp (Helbæk 1979), Gråborg (Hansson & Bergström 2008), Skäftekärr (Viklund 1998:84) and Sandby Borg (Larsson 2012). This could indicate crop rotation, though one may then expect larger amounts of rye (Grabowski 2014:22). Engelmark (1992:373) thinks rye could have worked well in the permanent field system as the last crop before abandoning the field. Flax, being intolerant of weeds, would have been used as the first or second crop. Hansson and Bergström (2008) believes that rye in Gråborg is a weed. Helbæk (1979) however thinks the rye from Eketorp is cultivated, as it appears in larger amounts here and may have been used for cooking and brewing purposes. It may of course have been used as food resource without being intentionally sowed. Larger scale cultivation of rye is first known from the Late Medieval period in northern Öland (Myrdal 1999:38f).
Human dependency on cereals was one simply one of nutrition. Beer and bread was likely associated with feasting and social status (Pedersen & Widgren 1998:400ff, Hansson & Bergström 2008), and traces of bread and beer brewing were also found in the ring forts. These may have been important nodes for an elite controlling the flow of crops in the social landscape.

4.6. **Hypothesis**

Approaching agriculture on Iron Age Öland as a social-ecological system, one may describe its function as that of producing subsistence and surplus. The surplus contributes to the emergent properties of the system, leaving material remains such as ring forts and imported artifacts. Applying resilience theory, one may try to identify the phases of the adaptive cycle (Holling 2001, Redman & Kinzig 2003), even if it is problematic to pinpoint exactly when they start or end:

- **Growth (r):** The agricultural expansion during the Early Iron Age.
- **Conservation (K):** The stabilization of infields and enclosures and the building of ring forts, indicating a more rigid system. Growing human and animal populations increases the pressure on the landscape and decreases the resilience of the system.
- **Collapse (Ω):** Starts in the Migration Period, possibly with the dust veil event of 536. Stone house foundations and ring forts are abandoned and the number of graves decreases, indicating a loss of wealth and connections.
- **Reorganization (α):** In the Vendel period as new settlements patterns and practices are introduced.

A prediction is that the flows of nutrients are changing, and thus are different in different phases. A method to estimate these flows is isotope analysis, as isotope values vary because of factors such as diet, feeding, manuring and grazing. This makes it possible to produce testable hypotheses. For example, intensive permanent field agriculture should generate high $\delta^{15}\text{N}$ in cereals, as it depends heavily on manuring, and intensive grazing may result in high $\delta^{15}\text{N}$ values in animals (Szpak 2014). The reorganization and exploitation are characterized by flexibility, which suggests variation in isotope values. One should be able to tell from human isotope values if humans have depended on a single type of food or utilized a number of different resources.
5. Methodology - Stable Isotope Analysis of charred plants remains

5.1. Background

Stable isotope analysis of archaeological bone and teeth have often been used as a method to study palaeodiet. This is based on the assumption that "you are what you eat", basically that tissue in the body is synthesized during life from what the body consumes. For this reason, the isotopes in food is going to have an impact on the isotopic composition of the body. Archaeologists may then extract collagen from bone and teeth and use mass spectrometry to measure isotope values, looking at the isotope values of both light and heavy elements. This makes it possible to reconstruct diet patterns. Migration may also be studied, as some elements show variation of isotopes because of geography (Schoeninger & DeNiro 1984, Pollard et al. 2007:176ff). The methodology applied here analyzes the isotopes of the light elements carbon and nitrogen.

5.2. Nitrogen isotopes

The stable isotopes of nitrogen are \(^{14}\)N and \(^{15}\)N. The \(\delta^{15}\)N value expresses the ratio between these isotopes relative to a standard based on the ratio in the atmosphere where \(\delta^{15}\)N is 0‰. It is calculated by this formula (Schoeninger & DeNiro 1984, Fraser et al. 2011):

\[
\delta^{15}N = \left( \frac{\text{^{15}N}}{\text{\text{^{14}N}}_{\text{sample}}} \right) - 1 \times 10^3
\]

In the study of palaeodiet \(\delta^{15}\)N values are usually used to measure trophic levels, where there is a 3 - 5‰ raise for every step in the food chain. In other words, collagen isotope values of herbivores should be 3-5‰ higher than those of the plants they consume (Schoeninger & DeNiro 1984, Fraser et al 2013). Some plant species may absorb nitrogen from the air, but most species take up nitrogen from the soil in the form of nitrate or ammonium. In animal manure, there is a loss of \(^{14}\)N because of processes such as volatilization of ammonium (Bogaard et al 2007, Fraser et al. 2011, Szpak 2014). The \(\delta^{15}\)N values of the plants will thus depend on the soil conditions, were for example manuring may raise the \(\delta^{15}\)N level. Other types of fertilization may also have an impact, for example sea-weed fertilization have been shown to raise \(\delta^{15}\)N values (Blanz et al. 2019)

5.3. Carbon isotopes

The stable isotopes of carbon are \(^{12}\)C and \(^{13}\)C. The \(\delta^{13}\)C value expresses the ratio between these
isotopes and is calculated in the same way as $\delta^{15}$N except that the so-called PDB standard is used instead of the atmospheric standard. This standard based on particular geological conditions in South Carolina, and the $\delta^{13}$C value of the atmosphere is around -7‰. Carbon is absorbed by plants through photosynthesis, with fractionation according to different metabolic pathways giving rise to different $\delta^{13}$C values. $C_3$ plants are most common and give rise to $\delta^{13}$C values between -19‰ and -29‰. The $C_4$ pathway, mostly used by tropical grasses, gives values between -12‰ and -6‰. A third pathway called CAM is used by succulents and combines the other two pathways (O'Leary 1988, Pollard et al. 2007:169ff). Water status also has an impact on $\delta^{13}$C values, were water stress produce higher values, and they may thus be related to drought, rainfall or irrigation practices. The $\delta^{13}$C value relative to that of the atmospheric CO$_2$ at the same time in history may be expressed as $\Delta^{13}$C, the isotope discrimination (Ferrio et al. 2005).

Marine plants have other sources for carbon than the atmosphere, and thus the isotope values are different in marine environments. For this reason $\delta^{13}$C analysis is used in archaeology to differentiate between terrestrial and marine diet. A problem is that the values in marine plants may overlap with terrestrial $C_4$ plants. For $\delta^{13}$C a trophic level elevation like that for nitrogen is also observed, but for $\delta^{13}$C this is only around 1‰ (Schoeninger & DeNiro 1984, Pollard et al. 2007:176ff). It has been suggest that fertilization with sea-weed would have an impact on $\delta^{13}$C values of crops, but this has not been observed, suggesting little take up of carbon from the soil (Blanz et al. 2019).

### 5.4. Isotopes in charred plants remains

Interpretation of isotope data is dependent on reference values. Usually faunal material have been used, but it has been argued that the amount of animal protein in human diet have been overestimated (Bogaard et al. 2007). In recent years the technique is increasingly applied to charred plants remains, as a method to solve the problem of animal- versus plant-based food. Nitrogen isotope values are influenced by soil conditions, and manuring has been shown to have an impact, so the approach can also be used to study land management and agricultural practices (Bogaard et al 2007, Fraser et al. 2011, Szpak 2014). This mainly applies to plants that absorb nitrogen from the soil, like cereals (figure 10). Carbon isotope values are related to water status which depends on climate conditions and irrigation practices (Ferrio et al. 2005). In conclusion, stable isotope analysis of charred plants remains can be used to study relations between humans, animals, plants and the
One here has to consider some differences between isotope values in plants and those in humans or animals. Isotope values in the latter usually reflects an average of longer periods. Isotope values in individual cereals however reflects a single year, were the may be variation because of temperatures, rainfall or agricultural practices (Bogaard et al. 2007). One may therefore expect larger variation of isotope values in cereals than in humans or animals. Also, nitrogen isotope values in plants are not directly related to trophic levels as in humans or animals.

Archaeological cereals are usually charred. Experiments have shown that charring does not seem to affect isotope values to any greater degree, though it may raise $\delta^{15}$N values slightly (Kanstrup et al. 2012, Fraser et al 2013). Short-term burial experiments have not shown to have an impact on isotope values either. Charring may result in so-called Maillard reactions, where protein and starch form large molecules called melanoidins that are resistant to degradation and may preserve isotope
signals. Long-term burial for thousands of years poses an obvious problem since it cannot be studied experimentally. The isotope signal may change because of diagenetic processes and contamination from the soil. For this reason, it may be necessary to clean the material using some sort of pre-treatment, as well as using methods for investigating the biochemical composition (Fraser et al. 2013, Styring et al. 2013).

5.5. Screening

FTIR may be used to study the chemical composition of charred grains, as it uses infrared radiation to detect chemical bounds which makes it suitable for organic materials. It has been used to study the effects of charring and pre-treatments (Styring et al. 2013). Vaiglova et al. (2014) performed contamination experiments on various plants and were able to connect particular peaks to particular contaminants. Brinkkemper et al. (2018) also applied XRF for elemental analysis and suggests it may be more effective for detecting humic acid contamination, leading to higher concentrations of iron and manganese. FTIR however offer practical advantages, as very small samples may be tested quickly.

5.6. Pre-treatment

The acid-base-acid (ABA) protocol is the conventional pre-treatment of plant material for radiocarbon dating. The fist acid step is intended to remove non-structural carbon (carbonates and organic acids), the base treatment removes humic acids. As the material absorbs CO$_2$ during this step, a second acid step is necessary (Fraser et al. 2013, Vaiglova et al. 2014).

Several studies has been done comparing ABA to untreated material and other treatments, for example an acid-only wash. While there is a difference in isotope values it is usually no more than 1‰, which suggests that the impact of contamination is rather low and that materials may be analyzed untreated. Generally the difference is bigger for nitrogen than carbon. A downside particularly of ABA treatment is that involves quite a large mass loss, which in some cases may not leave enough material for isotope analysis (Vaiglova et al. 2014, Brinkkemper et al. 2018).

A possible way to estimate the success of pre-treatment and the archaeological preservation is the C:N ratio. Fraser et al. (2013) analyzed the atomic C:N of modern plant material, comparing uncharred and charred material. Well-preserved archaeological grains should have a similar ratio. In
cereals this ratio was between 20.9 and 33.3.

5.7. Mass spectrometry

Stable isotope analysis is performed with a mass spectrometer. The principle of mass spectrometry is that individual ions are separated by atomic masses and counted. The analyzed substance first have to been ionized, then they are sent into the mass spectrometer through an electric or magnetic field where they follow different paths depending on mass. Different methods are used in studying light or heavy isotopes. Light elements like carbon and nitrogen are generally vaporized into gas that may be ionized by different methods (Pollard et al. 2007:160ff). In this case the isotope and atomic values were measured by elemental analysis isotope ratio mass spectrometry (EA-IRMS). The analysis was performed at SIL in Department of Geological Sciences at Stockholm University. The samples were combusted in a CarloErba NC2500 elemental analyzer connected to a Finnigan DeltaV advantage mass spectrometer. The precision for isotope values is ±0.15‰ or better.

5.8. Method

The grains were homogenized and then treated according to a protocol following Brinkkemper et al. (2018). First, they were put to dry at 60°C for 48 h and untreated samples were taken for isotope and FTIR analysis. Then followed the A-treatment of the ABA-treatment. First, they were treated with 1M HCl at 85°C for 30 minutes. The acid was removed, then a washing procedure followed. Deionized water was added, then the samples were centrifuged for 15 minutes at 5000 rpm, after which the water was removed by decantation. This was done five times, then the samples where then again put to dry at 60°C for 48 h. The A-treated samples where then taken for isotope and FTIR analysis. Then followed the base treatment, 1 M NaOH at 85°C for 30 minutes. The washing procedure was then repeated, then the HCl treatment and then the washing treatment again. Finally they were put to dry for a last time, after which the ABA-treated samples were taken for isotope and FTIR analysis (figure 11). For the isotope analysis with EA-IRMS, 1 mg of each sample where weighed into tin capsules.
5.9. Material

The materials analyzed were of two types: Large cereals assemblages and isolated finds of single grains (table 1). For this reason, different sampling methods were used. From the large cereals assemblages, a number of cereals (usually ten) were sampled randomly and homogenized to get an isotope value. Each sample was analyzed three times in order to estimate the standard deviation. For the single finds, each grain was analyzed separately. To compare these sampling strategies, both strategies were employed to the Skedstad material. Of ten available grains, seven were analyzed as a bulk and three were analyzed separately.

In the case of Gråborg, the large amount of seeds made this assemblage appropriate for comparing the effect of different types of pre-treatments. For this purpose, 10 seeds of hulled barley, 10 of naked barley and 10 seeds of emmer or spelt wheat were sampled. For further species comparison, 10 seeds of bread wheat and 10 seeds of oat were sampled. Of rye only 5 seeds were sampled because of the low abundance.

<table>
<thead>
<tr>
<th>Assemblages</th>
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<td>Site</td>
</tr>
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<tr>
<td>Skedstad</td>
</tr>
<tr>
<td>Prästhag</td>
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</table>

<table>
<thead>
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<th>Single grains</th>
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<tr>
<td>Sandby</td>
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</table>

| Low C/N value and deviating δ¹³C in the cereals analyzed casts doubt on this dating. |

6. Results

6.1. Screening

Visual comparison of FTIR spectra reveal a varying level of absorption but similar peaks (see appendix). The level of absorption increases with pre-treatment, and in the pre-treated material there is a new peak around 1200 cm⁻¹. The cereals from the house foundation Sandby 37:1 also stand out as there is a peak around 1020 cm⁻¹. Cluster analysis of the spectra shows a low linkage distance, indicating little difference between cereals (figure 12). The material cluster into two major groups. Cereals from the house foundation Sandby 37:1 have a close distance, others sites are divided between the groups. Pre-treated material is also clustered. There seems to be little differentiation between plant species, as hulled barley is found in all clusters.
Figure 12: Cluster analysis of FTIR spectra.

Table 2: Isotope data of all samples.
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<th>StDev % C</th>
<th>δ¹⁵N vs air (‰)</th>
<th>StDev % N</th>
<th>StDev C/N</th>
<th>Sample</th>
<th>Context</th>
<th>Pre-treatment</th>
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6.2. Pre-treatment

The samples from Gråborg that were subjected to different pre-treatments showed a mass loss below 20% following the first acid-treatment. The following base-acid treatment resulted in a much larger mass loss, in particular for hulled barley (figure 13). Isotope values (table 2, figure 13) tend to be lower δ¹³C values for ABA-treated material, but never more than 0,5‰. The δ¹⁵N values may fluctuate up to 1‰ but less consistently. Concerning variation in isotope values, the results are contradictory. In naked barley, the standard deviation for isotope values decreases with each treatment, but in emmer and spelt this variation increases.

Concerning carbon and nitrogen content there is a consistent increase in the proportion of both elements after the A-treatment. The correlation between carbon and nitrogen content increases with each treatment and is very strong in the ABA-treated material (R²=0,98), suggesting the mass loss is related to removal of exogenous material (figure 15).

![Mass loss %](image)

*Figure 13: Mass loss from the pre-treatment in the Gråborg samples compared to untreated samples.*
Isotope values in untreated and pre-treated cereals

Untreated Mean
A-treated Mean
ABA-treated Mean

δ13C

Figure 14: Comparison of isotope values for untreated, A-treated and ABA-treated cereals from the Gråborg assemblage.

Carbon and Nitrogen content

Gråborg untreated Trend
Gråborg A-treated Trend
Gråborg ABA-treated Trend

Figure 15: Carbon and nitrogen content in untreated, A-treated and ABA-treated material from the Gråborg assemblage.
6.3. The sites

Comparison of both $\delta^{13}C$ and $\delta^{15}N$ values in charred cereals from the Gråborg assemblage shows that the values from the different species fall within a quite narrow range, mean $\delta^{13}C$ values are between -23.1‰ and 24.5‰ and mean $\delta^{15}N$ values between 7.5‰ and 10‰ (Figure 16). Rye and oat seem to be somewhat different. The same is true when comparing the hulled barley with assemblages from Skedstad and Prästhag. Here the $\delta^{13}C$ values are in a slightly higher range, between -22.7‰ and 23.9‰, while the $\delta^{15}N$ range is the same (Figure 17). The values from Prästhag and Gråborg are very similar, while Skedstad is somewhat different. If these values are normally distributed, which may be likely as the assemblages represent a single context, these differences between sites and species may be seen as statistically significant (p < 0.05 in a paired t-test).

![Gråborg - Species comparison](image)

*Figure 16: Average carbon and nitrogen isotope values and one standard deviation for different species of crops from the Gråborg assemblage.*
Figure 17: Average carbon and nitrogen isotope values and one standard deviation in hulled barley from assemblages at different site and their standard deviation, compared with the means of single grains from different sites.

Single grain analysis of barley results in a much larger range of both δ¹³C and δ¹⁵N values (Figure 18). The δ¹³C are in the range between -26‰ and -21‰ and the δ¹⁵N values between 4‰ and 16‰. The variation in Sandby Borg appears related to context. Applying a χ² test shows that this difference is statistically significant, for example between barley in the contexts 8238 and 10200 (p = 0.007) and the contexts 8645 and 8679 (p = 0.015).

The carbon and nitrogen content of all cereals from assemblages shows a fairly linear regression (R²=0.58), grains with high carbon content also tend to have a high nitrogen content (figure 19). The same relationship is not as clear in single grains however, and the nitrogen content is often higher. There is also a slight tendency of grains with a high nitrogen content to have high nitrogen isotope values (figure 20).
Figure 18: Carbon and nitrogen isotope values in individual grains of barley.

Figure 19: Carbon and nitrogen content in untreated material.
Nitrogen

\[ R^2 = 0.13 \]

Figure 20: Nitrogen isotope values and content in all samples.

7. Discussion

7.1. Methodological issues

The results clearly suggest that the pre-treatment has an effect on the Gråborg material, related to what is removed during the procedure. This is visible in the carbon and nitrogen content and in the FTIR spectra. A peak around 1200 after pre-treatment was also observed by Styring et al. (2013), performing ABA-treatment of archaeological charred cereals. They attributes this to OH deformation of carboxyl groups and C-O stretching. This also supports their conclusion that it is primarily the acid treatment that effects the biochemical composition, and that the mass loss during the base treatment is related to removal of endogenous material.

However, concerning isotope values, it rarely had an impact larger than 1‰ for both $\delta^{13}$C and $\delta^{15}$N mean values. This is in accordance with previous studies (Kanstrup et al. 2014, Vaiglova et al. 2014, Brinkkemper et al. 2018). No evidence of contamination was found in the FTIR analysis of the material. In this case, analyzing untreated material would therefore be enough to answer the research questions, as the impact of manuring has been shown to far exceed 1‰ in $\delta^{15}$N values. The rest of the material was therefore analyzed untreated.
Still, it has to be considered as a potential source of error to what extent one may generalize this assumption. In the case of the cereals from the house foundation at Sandby 37:1, the FTIR analysis detected a peak around 1010-1020 cm$^{-1}$. This may reflect starch content and low level of charring (Styring 2013). However, the contamination experiment by Vaiglova et al. (2014) contamination with humic acid also produced a peak around 1010. An acid treatment or full ABA treatment of this material would have been preferable, unfortunately not enough was left to allow this. Based on Vaiglova et al., this should not have a big effect on isotope values however.

The atomic C/N ratio may also be used to estimate how well preserved the cereals are. Fraser et al. (2013) for example measured values between 22.6 and 28.2 in bulk samples of modern hulled barley after charring. In the present study the ratios very usually lower, and the pre-treatment raised the ratio, indicating some removal of possibly exogenous material, an effect also observed in previous studies (Fraser et al. 2013, Brinkkemper et al. 2018). In the analysis of individual grains, the ratio could fluctuate widely, from 11.2 up to 29.6 in hulled barley. This may be partly expected as the values in bulks represent that of an average of a number of grains. However, the difference seem mostly to be in the nitrogen content and not in the carbon content. In the bulks the relationship between carbon and nitrogen is fairly linear, but in some individual grains the nitrogen content sometimes is higher. There was also a slight tendency of grains with high nitrogen content to have high nitrogen isotope values. This may be because of distortion of the isotope signal because of diagenetic processes in these grains, but it may also be an effect of manuring (Fraser et al. 2011).

In the Skedstad material, the different sampling methods were compared (table 3). Both produced very close isotope value averages, but single grain sampling generated a much larger standard deviation. This suggests that there is considerable variation between grains grown under the same conditions. The mean values for carbon and nitrogen content were more different, indicating either that these values varies more than the isotope values, or the unreliability of these measurements. It is also known that while grain size may vary within the same cereal ear, according to a study by Kanstrup et al. (2012) this does not appear related to nitrogen isotope variation.
Table 3: Sampling methods at Skedstad.

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<td>7.84</td>
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<tr>
<td>SD</td>
<td>0.26</td>
<td>1.83</td>
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<tr>
<td>Mean $^{13}$C</td>
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<tr>
<td>SD</td>
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<tr>
<td>Mean %N</td>
<td>1.72</td>
<td>2.70</td>
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<tr>
<td>SD</td>
<td>0.24</td>
<td>0.70</td>
</tr>
<tr>
<td>Mean %C</td>
<td>33.29</td>
<td>41.33</td>
</tr>
<tr>
<td>SD</td>
<td>6.32</td>
<td>9.01</td>
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</table>

How useful is then the C/N ratio as a measure of quality of the preservation? It appears that it is to some degree, as pre-treated material has a ratio closer to that of modern charred grains. However, this did not affect the isotope values very much. This may be that most of the material removed was not just exogenous contamination, but endogenous material in the grain that had degraded because of diagenetic processes. Possibly what is preserved after the pre-treatment are structurally intact melanoidins. This may also be observable in FTIR spectra, were the level of absorbance tend to increase with each pre-treatment, indicating this may be useful as quality indicator.

To sum up, the results supports the conclusion by Brinkkemper et al. (2018) that charred cereals tend to be well preserved and isotope analysis may be carried out without pre-treatment. However, one have to consider that there may be exceptions for this, indicating the importance of screening methods. In this case FTIR was able to detect a deviation. This points to the importance of continuing to test this assumption in future research.

7.2. Manuring on Iron Age Öland

The $\delta^{15}$N values from the cereals are generally in the range between 7.5‰ and 10‰. Corresponding $\delta^{15}$N levels on Öland are found in domesticated terrestrial herbivores in the Iron Age. In wild herbivores the values are likely lower. Although from the Stone Age, $\delta^{15}$N values in moose, roe deer, hare, and beaver from the same area are in the range between 1.8‰ and 7.4‰ (Eriksson et al. 2008). If one subtracts one trophic level of 3-5‰, one should get value for wild plants, which would be far below what is found in the cereals. As discussed in the methodology section, the most likely explanation for this deviation is manuring. Manuring experiments have produced similar high
values (Bogaard et al. 2007, Fraser et al. 2011, Kanstrup et al. 2012), and the values are generally higher than what is observed from earlier periods in Scandinavia (Kanstrup et al. 2014, Gron et al. 2017). It is also known that slash-and-burn agriculture will result in higher $\delta^{15}$N values, but this appears unlikely in this context, and the effect is usually not as large as for manuring (Szpak 2014).

According to Fraser et al. (2011), values above 6‰ is a result of long-term annual manuring of 35-37 t/ha cattle manure per hectare. Whatever this applies to the local ecological conditions on Öland it is in accordance with the common understanding of Early Iron Age agriculture as intensive permanent field cultivation. That amount of manure would under modern conditions be produced by three cattle annually (Bogaard et al. 2007). According to estimates based on the numbers of stalls in the byres of Eketorp, one farm on Iron Age Öland would have around 13 cattle (Edgren & Herschend 1982). While Iron Age cattle were smaller than modern cattle (Pedersen & Widgren 1998:377), they would likely produce enough manure for annual fertilization, as most farms only had one or two hectares of cultivated fields. These numbers thus appear perfectly reasonable. Also, there would be little incentive to add sea-weed or peat to the manure. A more likely source of manure was sheep dung, which is better than cattle manure (Myrdal 2009), and experiments have shown that this produces similar values (Fraser et al. 2011). Pig manure may also have been used to a lesser extent, which have been shown to produce very high $\delta^{15}$N values (Szpak 2014). Human manure may of course have been used, the infields being located next to the dwellings.

In Skedstad, lower $\delta^{15}$N values and higher $\delta^{13}$C values were observed. There may be many potential causes for this differences and the values still indicate significant manuring. Lower $\delta^{15}$N values were also observed in some Sandby Borg contexts. This indicates spatial variation in manuring practices or ecology. It cannot be excluded however that the Skedstad material belongs to an earlier period. Long term increase in $\delta^{15}$N values during the Iron Age was observed by Kanstrup et al. (2014).

Crop cultivation appears to have been practiced in fields enclosed by stone fences next to the houses, and the settlements seems to have been occupied for several centuries (Fallgren 2006:27), but if permanent field agriculture was carried out, a field is likely to have to be abandoned or put to fallow after a few decades of cultivation. This does not necessarily mean there was a long-term decrease in soil fertility, but the dependency on manure from the livestock as well as the pressure on
the landscape by growing human and animal population as well as social investments in stone enclosures and ring forts likely introduced rigidity that decreased the resilience of the overall system. Possibly it was the same process that created the Great Alvar landscape of today.

The dust veil event of 536 may have turned this into a crisis. The four sites from the Middle Iron Age all show signs of intensive manuring and are abandoned during this period. It is known that other settlements on Öland also are abandoned. Possibly settlements were moved to soils more suitable for crop cultivation (Widgren 1997:42). The cold and loss of sunlight would strike hard against crop cultivation, by impeding growth as well as decreasing available manure, possibly generating negative feedback processes. Two-field och three-field systems would in this case be more resilient, being less dependent on manure. There is no evidence of changing manuring practices however, as the Late Iron Age $\delta^{15}$N values from Prästthag indicates the same level of manuring. However, one has to take into consideration that the relative distribution of livestock have changed, possibly increasing the number of pigs (Vretemark & Sten 2008, Åstrand et al. 2012:94). $\delta^{15}$N values may therefore not automatically be translated to manuring intensity.

7.3. Species variation in Gråborg
All species from the Gråborg assemblage have $\delta^{15}$N values that suggests a high level of manuring. The different species of barley and wheat cluster, indicating similar growing conditions, as experiments have shown that different species of cereals grown under the same conditions have similar values (Fraser et al. 2011). Oat and rye however deviate somewhat, both species that are known to have grown as weeds (Grabowski 2014:14). Both have lower $\delta^{13}$C values and oat have a lower $\delta^{15}$N value. As oat made up 7% of the assemblage it is however unlikely to have occurred as a weed. The deviating values may here rather be caused that different agricultural practices, oat possibly being grown for fodder. From later periods in western Sweden it is known that extensive cultivation of oat have been practiced beside intensive cultivation of barley (Pedersen & Widgren 1998:387), and oat is also a plant with less nutritional needs than other plants.

By contrast, the amount of rye was very low. Hansson and Bergström (2008) thought that it was a weed. Rye may have grown as a weed in the wheat, which also may have been autumn sown. This is supported by the similar $\delta^{15}$N values. Rye may have had the lowest $\delta^{13}$C values, but this is likely related to the biological properties of the plant, it being less dependent on water and resilient against
fluctuations in temperature (Leino 2017:36). However, this does not exclude the possibility that rye was intentionally cultivated and that some sort of crop rotation may have been practiced. This does not mean that the fields were put to fallow, agriculture with spring barley and autumn rye without fallow is known to have been practiced in southern Sweden (Pedersen & Widgren 1998:386, Leino 2017:34f).

7.4. Temporal and spatial variation at Sandby Borg

Significant variation depending on context was found in the isotope values of barley from Sandby Borg (figure 21). In two contexts (10200 and 8645), the average $\delta^{15}\text{N}$ value exceeded 11‰, suggesting very intensive manuring. In cereals found in a spot with soot (context 8238) however, the value was below 6‰. This may reflect lower level of manuring, the early years of cultivation on a field or the residual effects after a period of intensive manuring (Fraser et al. 2011). It is also possible that different types of manure have been used, as pig manure give higher $\delta^{15}\text{N}$ values than cattle manure (Szpak 2014). Both cattle and pig have been found in Sandby Borg. These finds of barley thus seems to originate from different harvests.

These variation may be conceived as both temporal and spatial. In temporal terms, isotope values may vary because of short-term factors such as weather, livestock and labor (Bogaard et al. 2007), as well as of the long-term impact of manuring. The variation in $\delta^{13}\text{C}$ values may be more likely to reflect temporal variation, as it depends on weather conditions. The barley found in Sandby Borg may then be conceived as the remains of a continuous flow to the ring fort, as there would be a dependence on food for its occupation and upkeeping. This is the line with the conception of the ring fort as a hierarchical and rigid element, as part of a system of domination. It has been suggested that house 03 in Eketorp is a small hall building with special status (Herschend 1988). In Sandby Borg house 52 may have played a similar role (Papmehl-Dufay & Alfsdotter 2016:57).

If one conceives this variation as spatial however, one may consider the barley originating from different farms, and the variation in isotope values is then caused by differences in the landscape and different agricultural practices. Sandby Borg then rather appears as a heterarchical element or a network node, contributing to social organization. It adds flexibility and resilience by working as a positive feedback loop, for example by providing storage and defense.
Figure 21: Carbon and nitrogen isotope values in single grain analysis of barley from different contexts in Sandby Borg.

7.5. Cereals in humans and animal diet

Human collagen $\delta^{15}N$ values from Iron Age Öland tend to fall within the range between 10‰ and 16‰, while the $\delta^{13}C$ values fall within the range between -21‰ and -18‰ (Eriksson et al. 2008, Howcroft et al. 2012, Wilhelmson 2017:149ff). Assuming the trophic level fractionation of 3-5‰, it is likely that the cereals was a source of protein. It could not have been the only source however, as human $\delta^{13}C$ values tend to be slightly higher than those of terrestrial herbivores.

The $\delta^{15}N$ values of livestock such as cattle, sheep, goat, horse and pig are usually in the range between 3‰ and 10‰ (Eriksson et al. 2008). These values may be a result of grazing combined with feeding with crops. From later period it is known that horses have been fed with barley and oat (Myrdal 1999:81). It is possible that cereal straw was used as fodder. Fraser et al. (2011) found that the $\delta^{15}N$ values of the rachis were consistently lower than in the grain. A value around 9‰ in the grain would correspond to a value around 6‰ in the rachis. There seems to be significant intraplant variation in $\delta^{15}N$ values, with some studies showing higher values in stems and leaves compared to the grains. The implication however is that animals feed on agricultural byproducts are likely to have higher $\delta^{15}N$ values than animals that are only grazing (Szpak 2014). It has been claimed that
collection of the straw began with the introduction of iron sickles, as the cereal then was cut closer to the ground (Viklund 1998:36ff). Another possibility is that the animals consumed the straw by grazing on the fields after harvests (Leino personal communication 2019-04-29). This increase in fodder was beneficial for the collection of manure. But as this also increased the output of nutrients from the field, increasing the dependency on manure (Viklund 1998:139). In other words, this created a particular entanglement of humans, animals, crops and tools were it would be very difficult to go back to an older form of cultivation.

A consequence of this is that higher $\delta^{15}N$ values should be observable in livestock during the Iron Age. Such elevation is also observable at Sandby Borg (Figure 22), where $\delta^{15}N$ values are higher than animals from earlier periods (Eriksson et al. 2008). Particularly high values are observable in horse and pig, and while there are too few animals for the differences to be considered statistically significant, this is line with what has been observed in other studies (Eriksson et al. 2008, Wilhelmson 2017:301). This would suggest different feeding practices than for sheep and cattle, possibly including cereal grains, at least for horses, as pigs are omnivores. It may thus be related to what extent the animals were kept indoors, though it is known that intensive grazing also may raise $\delta^{15}N$ values (Szpak 2014).

Figure 22: Isotope values of collagen in humans and livestock at Sandby Borg (Eriksson et al. In prep).

A consequence of this is that higher $\delta^{15}N$ values should be observable in livestock during the Iron Age. Such elevation is also observable at Sandby Borg (Figure 22), where $\delta^{15}N$ values are higher than animals from earlier periods (Eriksson et al. 2008). Particularly high values are observable in horse and pig, and while there are too few animals for the differences to be considered statistically significant, this is line with what has been observed in other studies (Eriksson et al. 2008, Wilhelmson 2017:301). This would suggest different feeding practices than for sheep and cattle, possibly including cereal grains, at least for horses, as pigs are omnivores. It may thus be related to what extent the animals were kept indoors, though it is known that intensive grazing also may raise $\delta^{15}N$ values (Szpak 2014).
This may then be related to sheep and cattle being the most common animals, connected to everyday needs, while horses and pigs are more rare and possibly associated with an elite. Horse sacrifices are known from Skedemosse and Eketorp and is the only domesticated animal depicted in the Scandinavian Animal Style. It is also likely related to martial practices (Pedersen & Widgren 1998:372f, Monikander 2010:58ff, Hedeager 2011:61ff). In Sandby Borg spurs have also been found, rare in Scandinavia during this period (Victor 2014:53f). Spurs here may indicate roman style of riding, but other finds in Scandinavia indicate hybrid traditions (Sundkvist 2017). On the continent this is a period of mounted warfare, Sandby Borg for example being contemporary with the hunnic migrations, and hunnic influence in Scandinavia during this period have been suggested (Hedeager 2011:191ff). Pigs are close related to wild boars, which also are known to be associated with war during this period, for example on the Torslunda plates. One may then here trace the network of a warrior elite.

7.6. Implications

The results support the hypothesis that permanent field agriculture was practiced on Öland, a form of agriculture depending heavily on manure. It is likely that this kind of agriculture was not very resilient, and that the resilience decreased with time because of increasing pressure on the landscape, were the need to feed the animals was likely the most important element. From historical periods it is also known that the meadows were the weak link in the infield systems, as their fertility would decrease (Welinder 1998:35f). This social-ecological system would therefore be vulnerable. According to the model of the adaptive cycle, it is this low level of resilience that pushes the system from the conservation phase (K) to the collapse phase (Ω). This may then related to the abandonment of the stone house foundations, as the population may have moved to more fertile soil. They need not to have moved very far however, as crop cultivation had been practiced in small fields next to the houses. This may also be related to the abandoning of the ring forts, as these must have depended on an agricultural surplus.

If one looks at the wider implications, it is likely that a similar type of permanent field agriculture was practiced in most of South Scandinavia during this period. As the limestone landscape of Öland was particularly suitable for agriculture, it is possible that the system was even more vulnerable in other regions. It is also known that settlements were abandoned during this period, agriculture
apparently being consolidated to the best soils (Gräslund & Price 2012, Grabowski 2014:25).

A problem when applying resilience thinking to archaeology have been to define the parameters of connectedness and potential. They are merged into the single parameter of complexity, which may be interpreted through proxies such as type of subsistence, social organization or demographic trends (Bradtmöller et al. 2017). It may here be argued that manuring intensity is a measurement of connectedness, that is the connection between the practices of crop cultivation and animal husbandry. A trend of increasing manuring may thus correspond to the increasing connectivity during the transition from the growth phase (r) to the conservation phase (K). However, this may still be hard to separate from potential, as it may be related to wealth in the form of animals or crops. Also, one has to keep in mind that this is only following a single variable whose importance may depend on the archaeological context.

It may here be of interest to compare the situation in Öland with that in Östergötland. In Östergötland during the Middle Iron Age few farms seems to have had byres, and it is likely that the livestock were grazing all year around (Petersson 2006:249ff). On Öland however most farms may have had some sort of byre, which may partly explain manuring levels as this would make the collection of manure easier. A possibly reason for this may be the variation in the landscape. If areas such as the Great Alvar became increasingly unsuitable for grazing, this may have generated a need to grow fodder for the livestock.

8. Conclusion

The aim of this study to was to explore agriculture on Iron Age Öland, which may be conceived as a process generated by the relations between humans, plants, animals and the landscape. The methodology applied was stable isotope analysis of charred cereals, and an important part was to evaluate the methods involved. The results support the hypothesis that stable isotope analysis of charred cereals may produce relevant results without pre-treatment, though FTIR may be useful for screening.

Nitrogen isotope levels in almost all cereals suggest annual manuring, as would be expected in a permanent field system, likely used on Öland during the Early Iron Age. It is likely animal manure was used, probably mostly from sheep and cattle. In the Gråborg assemblage, the nitrogen levels in
oat deviated from the other species, which suggest different growing conditions. Rye and wheat likely grew during the winter on the permanent fields. Concerning Sandby Borg, the cereals found appears to come from different harvests. Possibly this and other ring forts were places where an agricultural surplus was gathered.

The isotope values indicate that cereals may have played a significant part in human diet, but also that it could not have been the only protein source. It is also likely that the livestock to a varying extent were fed with cereals, possibly with byproducts like straw. This may apply more to horses and pigs than sheep and cattle, which may tell something about the social significance of these animals.

The sites from the Middle Iron Age all show signs of intensive manuring and are abandoned during this period. From the perspective of resilience theory, it is likely that the heavy dependence on animal manure introduced an element of rigidity into agriculture. With time, as pressure on the landscape increased, this would make it more difficult for the system to adapt to unexpected changes, for example the dust veil event of 536 and the climate downturn that followed.

9. Further research

Concerning isotope analysis of cereals, important areas of further research are how values are affected by different types of field systems and crop rotations, by the source of the manure used, and by alternative means as fertilization such as slash-and-burn cultivation. This can be achieved by experimental archaeology as well as analysis of cereals from historical periods were there is detailed textual information about agricultural practices. It is also of interests to study variation in agricultural practices depending on the landscape. Here it is of relevance to collect isotope data from animals, as crop cultivation and animal husbandry are entangled practices.

10. Summary

During the Iron Age in Scandinavia humans, plants, animal and the landscape were entangled in systems of agriculture. With the aim of exploring these relations, stable isotope analysis were performed on cereals from five site from central Öland. Of these four had remains from the Middle Iron Age: Gråborg, Sandby Borg, Sandby and Skedstad. From this period a rich agricultural
landscape is preserved, including systems of stone enclosures, and animal husbandry were of central importance. These site were abandoned around the 6th century, and a number of reasons have been suggested for this: Changing traditions, warfare, a social crisis related to the fall of the Roman Empire and the climate downturn after 536 AD. In the case of Sandby Borg, the fort was attacked and the occupants massacred. The fifth site, Prästhag, is from after this period, dated to the Late Viking Age and Early Medieval Period.

The $\delta^{15}N$ values in hulled barley from these sites suggest intensive manuring, as would be expected in permanent field agriculture. In the Gråborg material, species of barley, wheat, rye and oat were compared, all showing indications of manuring. They were slightly lower in oat, suggesting different conditions of cultivation. Rye had slightly lower $\delta^{13}C$ values, likely related to the biological properties of the plant, but it is unclear if it was intentionally cultivated. Some sort of crop rotation involving barley, wheat or rye may not be excluded however. In Sandby Borg, barley in different context seems to come from different harvests, suggesting an agricultural surplus was gathered at the site.

Altogether, the results indicate that cereals were an important part of human diet, but it must also have been supplemented with other food sources. Cereals or agricultural byproducts such as straw was also likely used to feed the livestock. This may be relation to variation in different animals that may reflect their social significance, for example the high $\delta^{15}N$ values in horses. Finally, dependence on manure suggest a high degree of connectivity between animal husbandry and crop cultivation practices. This may have introduced rigidity into the system, making it less resilient and vulnerable to unexpected changes, for example the cold period following 536 AD. In the model of the adaptive cycle, this may have triggered a transition of the system from the conservation phase to the collapse phase, which may partly explain why the sites were abandoned.

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12. Appendix – FTIR Analysis

FTIR analysis was continuously carried out on the charred cereal material after pulverization. The instrument used was a Nicolet iS 10 FT-IR spectrometer connected to a PC using the OMNIC software. 64 scans were used per sample using 4 cm$^{-1}$ resolution. The collected spectra were subjected to a cluster analysis based on correlation using Statistica, following the protocol of Isaksson (1999).