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New potential in old varieties

Using landrace cereals to meet food production challenges

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Cover: An illustration of the cyclic process of learning and understanding that has been used in this thesis: From interviews and discussions with farmers, to agronomical studies in field experiments and in the farmers' own fields, on to analysis of crop traits, and then going back to farm interviews to discuss and deepen the understanding of the findings. Photos by Tove Ortman and by Anna Börjesson.

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New Potential in Old Varieties. Using Landrace Cereals to Meet Food Production Challenges

Abstract

Landrace cereals – historical varieties characterised by high genetic diversity – have long been considered obsolete, and have almost completely been replaced by high yielding but high input-dependent cultivars. However, the need for increased multifunctional and low-input farming, and for finding varieties that can be robust to environmental stresses, has meant that these old varieties have been revalued. The aim of this thesis was to investigate the potential of landrace cereals in modern farming, and how landrace performance is influenced by environmental conditions and farmers' management practices. By using a transdisciplinary perspective involving farmers' experiences and motivations as well as field experiments and on-farm experiments, the results indicate that landraces have traits that can contribute to multifunctional farming systems and be used for farming on marginal lands, i.e. lands with poor soil fertility. Landrace spring wheat was shown to be providing similar yields as modern varieties under low-to-medium input organic conditions, and landrace of spring wheat and rye are shown to provide additional ecological services beyond yield, such as weed suppression and a high straw yield. These additional services were found to be valued by farmers that use landrace cereals, and be important for their cropping systems. However, challenges like lack of knowledge on landrace management, e.g. seed borne diseases, and restrictions in seed legislation hinder a further expansion of the landrace cereal cultivation. In conclusion, this study shows that, with appropriate management, landraces can have potential in organic farming, or for farming in environmentally challenging conditions, and can contribute to increased food security and sustainability of food production.

Keywords: Agroecology, Heritage cereals, Agrobiodiversity, Participatory plant breeding, Farmers' management, GxExM interactions, Seed commons

Ny potential i gamla sorter. Att använda kulturspannmål för att möta matproduktionens utmaningar

Abstrakt

Kulturspannmål, eller lantsorter av spannmål, är historiska sorter som kännetecknas av hög genetisk mångfald. Lantsorter har länge ansetts vara föråldrade och har nästan helt ersatts av moderna sorter med hög avkastning men som kräver höga nivåer av insatsmedel. Behovet av ökad multifunktionell och extensiv växtodling, och att hitta sorter som kan vara robusta mot sämre odlingsförutsättningar, har dock inneburit att dessa gamla sorter har omvärderats. Syftet med denna avhandling var att undersöka potentialen hos lantsorter i modernt jordbruk, och hur lantsorter påverkas av miljöförhållanden och lantbrukares skötsel. Genom att använda ett transdisciplinärt perspektiv som involverar lantbrukarnas erfarenheter och motiv samt fältexperiment och gårdsstudier, indikerar resultaten att lantsorter har egenskaper som kan bidra till multifunktionella jordbrukssystem och till jordbruk på marginella marker, d.v.s. marker med dålig markbördighet. Vårvete från lantsorter har visat sig ge liknande skördar som moderna sorter under låg till medelhög kvävetillgång under ekologiska odlingsförhållanden, och lantsorter av vårvete och råg har visat sig ge ytterligare ekosystemtjänster utöver skörden, t.ex. god ogräskonkurrens och hög halmskörd. Dessa ekosystemtjänster visade sig vara uppskattade av lantbrukare som använde lantsorter, och vara viktiga för deras odlingssystem. Men utmaningar som bristande kunskap om odling med lantsorter, t.ex. utsädesburna sjukdomar och restriktioner i utsädeslagstiftningen hindrar en ytterligare expansion av lantrasspannmålsodlingen. Sammanfattningsvis visar denna studie att lantsorter, med lämplig skötsel, kan ha potential i ekologisk odling, eller i odling under miljömässigt utmanande förhållanden, och kan bidra till ökad livsmedelssäkerhet och hållbar livsmedelsproduktion.

Nyckelord: Agroekologi, Kulturspannmål, Biologisk mångfald, Deltagande växtförädling, Lantbrukares skötsel, GxExM-interaktioner, Utsädesallmänningar

Nytt potensial i gamle sorter. Bruk av kulturkorn for å møte matproduksjonens utfodringer

Abstrakt

Kulturkorn, eller landsorter av korn– historiske varianter preget av høyt genetisk mangfold – har lenge vært ansett som foreldet, og har nesten blitt fullstendig erstattet av sorter med høy avling, men som er avhengig av høyt bruk av innsatsfaktorer. Behovet for økt omfang av multifunksjonelt og ekstensivt jordbruk, og for å finne sorter som kan være robuste mot mindre optimale miljøforutsetninger, har imidlertid gjort at disse gamle sortene har blitt revurdert. Målet med denne avhandlingen var å undersøke potensialet til landsorter av kulturkorn i moderne jordbruk, og hvordan landsorters prestasjon påvirkes av miljøforhold og bønders skjøtsel. Ved å bruke et transdisiplinært perspektiv som involverer bøndenes erfaringer og motivasjoner, samt felteksperimenter og gårdsstudier, indikerer resultatene at landsorterne har egenskaper som kan bidra til multifunksjonelle jordbrukssystemer og jordbruk på marginale jorder, dvs. land med lav jordkvalitet. Landsorter av vårhvete viste seg å gi tilsvarende avlinger som moderne varianter under økologiske dyrkningsforhold med lav til middels tilgang av nitrogen, og landsorter av vårhvete og rug viste seg å gi flere økosystemtjenester utover avling, som f.eks. god ugresskonkurranse og høy halmavling. Disse økosystemtjenestene ble verdsatt av bønder som dyrker landsorter av korn, og var viktige for deres dyrkningssystemer. Men utfordringer som mangel på kunnskap om skjøtsel av landsorter, f.eks. såkornsbårne sykdommer, og restriksjoner i såkornslovgivningen hindrer en ytterligere utvidelse av dyrkingen av kulturkorn. Avslutningsvis viser denne studien at landsorter med riktig forvaltning kan ha potensial i økologisk landbruk, eller i dyrking under marginale dyrkningsforhold, og kan bidra til økt matsikkerhet og bærekraftig matproduksjon.

Nøkkelord: Agroøkologi, Kulturkorn, Agrobiodiversitet, Deltakende planteforedling, Bønders skjøtsel, GxExM interaksjoner, Såkornsallmenninger.

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This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Ortman T, Sandström E, Bengtsson J, Watson CA, Bergkvist G. (2023). Farmers' Motivations for Landrace Cereal Cultivation in Sweden. Biol Agric Hortic, Vol.ahead-of-print (ahead-of-print), 1–22.

II. Ortman T, Bengtsson J, Watson CA , Gerhardt K, Breland TA, Sandström E, and Bergkvist G. Landraces Outperform Modern Spring Wheat under Low-Input Conditions (submitted)

III. Ortman T, Bengtsson J, Watson CA, Nkurunziza L, Sandström, Chopin P, Bergkvist G. Farmer´s Management, Experiences and Networks More Important Than Environmental Conditions in Explaining Performance of Landrace Rye (manuscript)

IV. Sandström E, Ortman T, Watson CA, Bengtsson J, Gustafsson C, Bergkvist G. Saving, Sharing and Shaping Landrace Seeds in Commons: Unravelling Seed Commoning Norms for Furthering Agrobiodiversity (submitted)

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The contribution of Tove Ortman to the papers included in this thesis was as follows:

I. First author. Designed study with the co-authors. Performed all data collection, interview transcriptions and analysis. Wrote the manuscript with contributions from co-authors.

II. First author. Contributed to the design of the study. Collected the data with help of field assistants, and analysed all data. Wrote the manuscript with contributions from co-authors.

III. First author. Designed study with GB, CW, ES and JB. Collected the data, with help from field assistants and contribution from PC. Analysed the data with support from LN. Wrote the manuscript with contributions from the co-authors.

IV. Shared first authorship. Designed study with ES, GB, CW and JB. Collected and transcribed the data, with contributions from CG. Analysed data and wrote the manuscript together with ES, with contributions from co-authors.

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Abbreviations

LAI	Leaf area index
TKW	Thousand kernel weight
NUE	Nitrogen use efficiency
HI	Harvest Index
LPIS	Land Parcel Identification System
NORDGEN	Nordic Genetic Resource Centre
CV	Coefficient of variation
SD	Standard Deviation
SE	Standard Error
PCA	Principal components analysis
PLS	Projections to Latent Structures analysis
VIP	Variable Importance for the Projection

1. Introduction

Food production has been a constant challenge for human societies since the dawn of agriculture. In the aftermath of the agricultural revolution, the solution seemed simple to many – helped by cheap pesticides, irrigation and application of mineral fertilisers most problems could to be solved, and food production could be made efficient and economical. The last decades have shown us that it is not that simple – food production comes at a price, which can be very dear to pay (Ramankutty et al. 2018). Loss of biodiversity is emptying our ecosystems, and climate change – induced by human activities including agriculture – threatens the very existence of our societies, as concluded in a recent IPCC report (Bezner Kerr et al. 2022). Food production has again manifested itself as a problem without a simple solution – some would call it a wicked problem, see e.g. Lawrence et al. (2022). It has become a balance between the production needed for human survival and comfort – food, fuel, raw material – and what the agroecosystems can bear. As it turns out, there is an urgent need to increase the production of other services than simply food from the ecosystems (Tanentzap et al. 2015; Grass et al. 2021). As part of this, there is a need to reevaluate many agricultural conceptions, for example what a productive farming system looks like and what values that it produces, or what traits a good crop variety should have (Shahzad et al. 2021).

The goal of modern plant breeding of cereals has long been to maximize the yield potential. By introducing dwarf genes, it has been possible to develop varieties with shorter and stronger straws, which can utilize high applications of nitrogen into high grain yields (Foulkes et al. 2011). The motivation for this has been simple – the need to produce as much food as possible for a growing population. However, this is not the only driver. The market demands of richer countries in the global north, and increasingly also in the rest of the world, has raised the demand for wheat, especially wheat with high baking quality that can be used to bake white wheat bread (Mergoum et al. 2009). Wheat is a demanding crop, and modern wheat varieties need fertile soils, favourable weather conditions and high input of nitrogen fertilisers to reach high yields with good baking quality, and it is vulnerable to environmental stresses (Foulkes et al. 2009). Another driving force in crop production, and thereby also in plant breeding, has been the increased concentration of meat production in large and labour-efficient facilities, where profitability is determined by low cost of nutritionally satisfactory feed. As the demand for meat such as beef, pork and chicken has risen with the higher living standards of industrialised countries, this has meant an increase in cereal feed production. Animal feed production has developed from being mainly dependent on grazing and food residues in pre-industrialised agriculture, to taking up more and more agricultural land for feed cereals and pulses (Martin et al. 2020). Around 70 % of the world's agricultural land is currently used for animal feed production (Rauw et al. 2023). The raised demand for wheat- and cereal-fed meat has meant a rising demand for cereal products, at the same time as cereal production has become more and more vulnerable and problematic because of extreme weather caused by climate change (Shahzad et al. 2021; Marone et al. 2021).

Even though the intensification of cereal production for both bread baking and feed has suited the current market demands, there are many grounds to question the sustainability in the long run. The increased intake of refined wheat flour has many documented health hazards, while a more varied diet with different types of cereals in whole grain products provide important health benefits (Poutanen et al. 2022). Livestock is an important part of many integrated farming systems, producing food from residues and plants that we humans cannot utilize directly as food, and in addition enhancing biodiversity by grazing, and providing many benefits to sustainability by introducing perennial grass-clover leys in the crop rotations (Martin et al. 2020). However, there is strong evidence that livestock production needs to scale down and change in order to decrease its emissions of climate gasses (Bellarby et al. 2013). Instead, more crops need to be produced that can be consumed by humans directly, including cereals, for food production to be sustainable (Willett et al. 2019; Poutanen et al. 2022).

Apart from changing our diets, we also need to change our landscapes to increase resilience to climate change, and to enhance biodiversity. Intensification of agriculture has meant a simplification of agricultural landscapes and cropping systems, with a heavy dependence on a few – often cereal – crops. This leads to multiple environmental problems; loss of biodiversity through lower species richness of plants and birds is one example (Birkhofer et al. 2018). While the most fertile plains become biodiversity deserts dominated by cereals and a few other high-producing crops, agricultural lands in more marginal areas instead become used for extensive production of animal feed, such as leys, and not for production of crops directly for human consumption (Peyraud et al. 2014). Marginal lands are generally defined as areas which economically and biophysically are less optimal for agriculture (Peterson and Galbraith 1932; Csikós and Tóth 2023), but have been identified as an important resource for agriculture in order to ensure food security, for example recently in a report by FAO on the subject (Ahmadzai et al. 2023). Especially agriculture following ecological/organic principles, and High Nature Value farming, are suggested as suitable for marginal lands since the farming system needs to be resilient to harsher environments, with lower levels of in-put (Ahmadzai et al. 2023; Csikós and Tóth 2023). Another related challenge for crop production is the dependence on high levels of inputs. The simplified cropping systems are not only dependent on high levels of fertiliser, but also on pesticides to treat weed problems, and protect the crop from diseases or pests. The application of herbicides in turn contributes to the loss of biodiversity, by reducing the number of e.g. pollinating insects (Williamson and Wright 2013; Goulson et al. 2015; Uhl and Brühl 2019), particularly when combined with a simplification of the agricultural landscape with less semi-natural habitats (Potts et al. 2016). The over-use of pesticides has resulted in a selection of weeds that can become dominant and difficult to get rid of (Petit et al. 2010), especially in the face of pesticide resistance that has evolved due to over-dependence on chemical weed treatment (Gould et al. 2018). This specialisation of cereal production not only creates environmental crises, but also socio-economic insecurities and vulnerability for farmers due to dependence on a few income sources (Prokopy et al. 2020). In order to overcome these challenges, more diversity is needed in cropping systems and in the landscape (Bezner Kerr et al. 2022). There is also a need for more diversity in the plant material. In a changing and more extreme climate, crops need to be more robust, and farming not only focused on producing high yields under optimal conditions, especially in order to utilize marginal lands for the cultivation (Lopes et al. 2015; Marone et al. 2021).

How can then a change in diets, landscapes and plant material be carried out to facilitate the development of sustainable farming systems? By, for example, replacing simplified crop rotations with more diverse ones to a larger extent, this could enable diversification of both diets and cropping systems at the same time. A higher proportion of perennials on more fertile land would need to be introduced (Davis et al. 2012; Martin et al. 2020), while marginal lands could be better utilized for producing more crops that can be consumed directly by humans (Ahmadzai et al. 2023). At the same time, sustainable food systems would need to be less dependent on high levels of inputs, and more resilient to challenging environmental conditions (Garibaldi et al. 2017). The combined change in cropping systems and diets could be addressed by applying an agroecological perspective on food production, taking into account a wider spectrum of ecological services than just yield (Wezel et al. 2020).

In order to create sustainable food systems, there is also a need for robust crop varieties that are able to utilise less optimal conditions and which rely less on inputs (Janni and Pieruschka 2022). These are factors that plant breeding has disregarded during the last 100 years, while instead focusing heavily on high yields under high input conditions (Lammerts van Bueren et al. 2018). However, estimations of future yields show that due to climate change it will be very challenging to upkeep yields for varieties demanding stable and optimal environmental conditions, and that we will be forced to adapt cropping systems to be able to withstand a greater degree of environmental stress (Lobell and Tebaldi 2014). The increasing climate crisis leads to higher temperatures, more extreme weather with drought or heavy rainfall and flooding, all which will put crop production under severe pressure (Shahzad et al. 2021; Bezner Kerr et al. 2022).

In relation to these challenges to our food systems, landraces have been suggested as a way forward (Newton et al. 2009; Lopes et al. 2015; Marone et al. 2021). This may seem counterintuitive, since landraces consist of historical varieties which have been largely abandoned for more high yielding modern varieties. However, landraces are both a potential source for plant breeders when introducing traits that, for example, can make crops more resilient to changing climates (e.g. Lopes et al. 2015; Ayed et al. 2021; Marone et al. 2021), but also a source of plant material for direct use in cropping systems (Dawson et al. 2013; Migliorini et al. 2016; Martin et al. 2023).

1.1 Definitions of landraces

In this thesis, landraces are defined as: *a dynamic population(s) of a cultivated plant that has historical origin, distinct identity, and lacks formal crop improvement, as well as being genetically diverse, locally adapted and associated with traditional farming systems* (Camacho Villa et al. 2005). The adaptability, genetic diversity and dynamic nature of the landraces means that the distinct identity is not always distinguishable (ibid), and that definitions are challenging (Wolfe and Ceccarelli 2019). Evolutionary mixes of landraces and more modern varieties are sometimes called "modern landraces", and share many features with historical landraces, such as the heterogeneous nature, and the connection to farmers' management systems (Murphy et al. 2005; Döring et al. 2011). Mirroring the variability of the landraces, the terminology of landraces in the literature is somewhat inconsistent, and many different terms are used, for example heritage cereals, heirloom varieties, old or traditional varieties. The term ancient cereals is often used for Einkorn, Emmer, Spelt etc., and heritage cereals can be used as an overarching term (Boukid et al. 2018). The term landraces is used in this thesis and is the most established for the dynamic populations with historical origin that are propagated by farmers (ibid).

1.2 Landrace cereals: history and present usage

Today´s landrace cereals originate from varieties grown before the agricultural revolution. Following the increasing industrialisation of societies all over the world during the 19th and 20th centuries, attention was turned towards increasing agricultural production and making farming as efficient as possible, in order to feed the growing population and free labour to the emerging industries. Plant breeding became an important way to increase yields and to adapt the crops to the new cultivation methods

(Kingsbury 2009). The genetically heterogeneous landraces were regarded as too low producing and undependable – robust generalists rather than specialists when it came to crop performance, and could produce a small but certain yield even under stress (Newton et al. 2009). This robustness was an advantage in the pre-industrial agriculture, but the new effective agriculture had other demands on the plant material, and plant breeding became more focused on finding specialized crops that gave high yields under optimized conditions. For example, between 1892 and 1994, Nordic varieties of spring wheat were developed towards shorter straws and more dense spikes, with a decreased risk for seed shattering and with an increased resistance toward diseases, e.g. mildew, yellow rust, and bunt (Diederichsen et al. 2012). Through plant improvement by selection of landrace material, more uniform varieties were developed – varieties with landrace parents. These early varieties had similar traits as the old landraces, also characterized by robustness rather than high yields (Leino 2017). As plant breeding became more and more precise, landraces were, and are still, used as indirect parents or sources of specific traits to specialized modern cultivars (Mondal et al. 2016).

The landrace potential as a source for diverse genes in modern plant breeding is one of the driving forces for landrace conservation, and has meant that a number of landraces have been preserved in gene banks as a resource for the future – so called ex-situ conservation (Zeven 1998). However, ex-situ conservation is not sufficient to conserve the genetic diversity of landraces – the conserved sample is just a small snapshot of the variation within the landraces. An important complement to the gene banks is in-situ conservation, where the landraces are grown on active farms, preferably in systems resembling the traditional cultivation associated with the landrace, both in terms of environment and management (Newton et al. 2009; Bellon et al. 2017). In countries in the Global South, landraces are often still used actively in farming, despite the efforts made during and after the Green revolution to replace them with modern varieties (Smale 1997; Atlin et al. 2017). In the Global North, a majority of farmers in for example Europe replaced landraces with modern cultivars during the 20th century, but some farmers, especially in more marginal growing regions, kept using the landraces. Many varieties were preserved in this way and have continued to be grown on-farm (Raggi et al. 2022). In Sweden, which is the geographical location of the studies that are the basis for this thesis, only a few instances of continued growing of landrace cereals have been recorded, and in the majority of cases landraces were replaced by modern varieties during the first half of the 20th century (Leino 2017). Material from these few remaining active farmers was collected during the latter half of the 20th century, and was preserved in the Scandinavian gene bank NordGen (Olsson 1997; Leino 2017).

During the last 20 years, the interest for local food through short food supply chains (SFSC) has increased all over Europe, from both producers and consumers, and a multitude of ways to sell products have evolved (Aggestam et al. 2017; Halkier et al. 2017; Slámová et al. 2021). Alongside this trend, the interest for products from organic farming and other special food has increased in Scandinavia, although the market for organic products in Sweden is slowing down somewhat (Halkier et al. 2017; Diagourtas et al. 2023). A recent survey among consumers in Sweden shows that there was a large demand for products from landrace cereals (Wendin et al. 2020). The number of farmers that are growing landraces and participating in in-situ conservation is increasing in Sweden from just a handful in the early 1990s, to over 50 in 2020 (Larsson, 2020). In the national landrace seed swapping association Allkorn, founded in 1995, farmers spread and propagate cereal landraces (Allkorn 2023). This pattern of landrace re-emergence is not unique for Sweden, but accruing all around Europe and many other parts of the Global North (Colley et al. 2021; Raggi et al. 2022). Examples of this can be found in Italy and in the UK, where an interest for local landrace products has led to increased landrace cereal cultivation (Varia et al. 2021; Martin et al. 2023)

By their very nature, landraces are linked with farmers' seed saving and swapping, thus forming continuously evolving populations of landraces which reflect the available gene pool, local environment and the farming system they are gown in (Casañas et al. 2017). This means that the seed exchange in farmers' seed swapping associations, or through participatory breeding projects, is an important factor in the development of the landraces and their traits (Mazé et al. 2021; Colley et al. 2021). Farmers' seed exchange can be regarded as a form of commoning system, as seed commons, where a resource – landrace seeds – is shared within the common (Pautasso et al.

2013; Sievers-Glotzbach et al. 2020). Even though there have been many efforts to incorporate landraces in formal and/or commercial seed systems, e.g. the European union's conservation list 2008/62/EC (Batur et al. 2021), the resulting legislation often removes the initiative and ownership from the farmers, which can be considered contradictive to the nature of landraces (Casals et al. 2019; Peschard and Randeria 2020).

When landraces and modern varieties of cereal have been compared in field experiments, landraces often perform less favourably than modern varieties, especially in regard to grain yield (Newton et al. 2009), and the conclusion is often that landraces are obsolete and not suitable for modern cultivation. This is partly in contrast to farmers' experiences; they find that landraces can produce a more stable yield in low-input management and/or harsh environmental conditions, in regard both to quantity and quality, e.g. protein content (Negri 2003; Bocci et al. 2020; Wada et al. 2022). Apparently, the landraces have something that makes certain farmers prefer the landraces to modern high-yielding varieties, and a key to understanding the values created by landraces is to take farmers' perspectives into account.

1.3 Marginal lands – robustness and adaptability.

One important value ascribed to landraces is an ability to cope with harsh environmental conditions (Zeven 1998; Newton et al. 2009; Ficiciyan et al. 2018). Landrace cultivation is often associated with marginal growing conditions, and recently, the interest for investigating landraces' ability to adapt and tolerate more marginal growing conditions has increased. Findings supporting the notion of yield stability of landraces in harsher environments have been observed both in field experiments (e.g. Yahiaoui et al. 2014; Daaloul Bouacha et al. 2014) and in on-farm trials (e.g. Serpolay et al. 2011; Bocci et al. 2020). Farmers cultivating landraces in Europe have been found to appreciate the ability of adapting to local and variable environmental conditions (Raggi et al. 2021). The ability of landraces to produce stable yields under variable and marginal environmental conditions has been reported as a motivation for landrace cultivation by farmers in Ethiopia (Wada et al. 2022), Italy (Negri, 2002; Bocci et al., 2020), Scotland (Mahon et al. 2016) and Germany (Peratoner et al. 2015).

Tolerance to variable and extreme environmental conditions is often associated with certain plant traits. Landrace bread wheats have been found to have larger root systems than modern varieties, which enable the landraces to store and access more resources (Siddique et al. 1990; Bektas et al. 2016). High total biomass in landraces increases the stress tolerance by providing greater potential to store resources in the straw, and enables the plant to fill the grain even during stressful e.g. dry conditions (Lopes et al. 2015). An ability to grow rapidly early in the growing season has also been shown to increase heat tolerance in landraces (Pinto et al. 2017; Lan et al. 2022). The response of landrace cereals to different environments has been investigated (e.g. Serpolay et al. 2011; Dawson et al. 2012) but seldom by taking management factors, such as fertilisation or sowing rate, into account. Much is yet unclear concerning how different kinds of management affect landraces in different environments.

1.4 Low-input and organic management

Landraces are also closely associated with certain management systems. In a recent meta-analysis, more than 80% of European farmers growing landraces were found to be using either organic or low input management (Raggi et al. 2021). These findings were partly linked to farmers who were farming marginal lands; however, more than half of the farms (56 %) were not situated in what was considered to be marginal lands. It has been observed that organic farmers, for example on Sicily and in Scotland, value landraces of durum wheat and barley, since these crops suit their management methods (Mahon et al. 2016; Varia et al. 2021). In an investigation of landrace cultivation among farmers in central Italy, Negri (2003), it was found that landrace cereal cultivation was associated with larger farms and modern technology, and that organic farmers were particularly interested in landrace cereals.

Traits of the landraces that can make them of interest for organic and low-input management include an ability to produce a high-quality crop under low-input conditions, e.g. with good baking quality i.e. high protein and gluten content, and an ability to cope with diseases, pests and weeds

(Lammerts Van Bueren et al. 2011). Nitrogen is usually a limited resource in organic farming, and therefore it is an advantage with varieties that can perform well also when nitrogen availability is limited. In field studies in Mediterranean conditions, wheat landraces have been shown to produce similar yields as modern varieties at low nitrogen doses, with some variations between landraces (Ruiz et al. 2008; Daaloul Bouacha et al. 2014; Giunta et al. 2019). Nevertheless, other findings – also from the Mediterranean region –– indicate that modern varieties utilize nitrogen more efficiently than landraces also under organic/low-input conditions (Motzo et al. 2004).

Nitrogen use efficiency (NUE) is related to different genetic and agronomic traits under different types of fertilisation management – low-input management often requires a different kind of genotype than high-input management (Lammerts van Bueren and Struik 2017), which means that there might be differences in NUE between landraces too (e.g. Asplund et al. 2013). Since landraces are mainly used in conditions with low availability of nitrogen, it is more relevant to investigate differences in NUE in landraces at low nitrogen doses than at high. Nitrogen use efficiency is indeed increasingly a goal even for conventional plant breeding, because of environmental concerns related to excessive use of mineral fertilisers; furthermore, farmers need to reduce input-related costs (Foulkes et al. 2009). This means that findings of these traits in landraces can be of interest also for conventional plant breeding.

In field experiments, landraces have moreover shown a better ability than modern varieties to compete with and suppress weeds (Murphy et al. 2008; Konvalina et al. 2010; Lazzaro et al. 2017). Weed suppression of cereals can be affected by e.g. leaf area index (LAI), straw biomass, number of tillers per plant and early vigour, but also by the plants' nitrogen use efficiency and allelopathic abilities (Andrew et al. 2015). The response of landrace cereals' ability to weed suppression, to fertilisation, or different environmental factors is not well known.

1.5 Landrace cereals - interactions with farmers' management and environmental conditions

Despite the fact that landrace cereals were abandoned by most farmers in favour of higher yielding varieties, there are modern farmers who value the traits of the landraces; this appears to be related to both management systems and the environmental conditions of the farms (Raggi et al. 2021). This indicates that in order to investigate landrace potential for organic/low-input systems, or for more marginal growing areas with marginal agricultural lands, there is a need to examine the interactions between the landraces, the environment they are grown in and the management of the farmers. This in itself is nothing new – the Genotype x Environment x Management interaction is much studied in agronomy. However, since landraces are so closely linked and formed by local diverse management and environment through the farmers' seed saving and the ability for local adaptation, the interactions become more complex to disentangle. Desclaux et al. (2008) argue that to study complex interactions in these types of dynamic and diverse landrace populations, which are managed in diverse environments and propagated through seed saving in e.g. seed commons or participatory plant breeding projects, the reductionistic GxExM model needs to be put in a holistic context. The different motivations and driving forces of the farmers need to be taken into account, for example the knowledge of the farmer, what products and other values the farmers aim for with the production, and the regulations surrounding the seed exchange (ibid). Farmers have been shown to value more functions than yield when growing landraces (Ficiciyan et al. 2018). This is a point that also should be taken into account when designing research projects about landrace cereals in order to increase the relevance, i.e. including the multifunctional values generated by landrace cereal cultivation. All in all, this calls for a broader perspective when studying the complex realities of landrace cereal cultivation, and its potential to make farming more sustainable and robust.

2. Thesis aim and objectives

The aim of the thesis is to explore how landrace cereals interact with environment and management factors, how this interaction affects yield quantity, quality and other functions within farming systems, and to discuss how landraces can be of relevance for future sustainable farming.
The main aim was investigated through four research questions, representing the different sub-studies of the thesis work:

1) What motivates farmers to use landrace cereals and how do these motives affect the crop management? (Paper I)

2) How do environmental factors and fertilisation management affect agronomic performance and baking quality of landrace spring wheat compared to modern varieties? (Paper II)

3) How do management factors and environmental conditions affect agronomic performance and baking quality of landrace rye? (Paper III)

4) How is landrace cereal cultivation affected by landrace seed exchange, management and legislation? (Paper IV)

3. Methods and materials

3.1 Methodological approach

The material that this thesis builds on was collected through a mixed methods approach. Qualitative data were used in order to design, form hypotheses and to discuss results of quantitative studies, but also for stand-alone studies.

3.1.1 Transdisciplinarity and agroecology

This project was designed with a transdisciplinary ambition. Transdisciplinarity is often defined as spanning not only over different research disciplines, but also including stakeholders and actors from outside academia for participation in the research (Lawrence et al. 2022). However, transdisciplinarity can also be seen as a holistic way of doing research, a mindset of how to investigate research questions, and indeed a discipline of its own (Rigolot 2020). Although this project has its base in crop production ecology and agronomy, the ambition has been to reach further than the field scale, and include the entire farm – and in some cases also the entire food system – connected with landrace cereal production. By using a transdisciplinary approach, I have aimed at overbridging disciplines in order to answer complex farming and seed system related questions. This project can be regarded as positioned within the broader discipline of agroecology, a discipline that has been argued to be closely intertwined with transdisciplinarity (Ernesto Méndez et al. 2013). The idea is that complex problems need a multifaceted approach, and in order to study intertwined interactions between varieties, farm management and environment, it is necessary to include the farmers and their experiences and motivations in the analysis. Social science methods and analysis have been integrated together with agronomic research methods with the purpose of including the experiences of farmers (and others as well).

Transdisciplinary research has many challenges, as well as many benefits. To combine methods and stakeholders from different disciplines of academia, as well as actors from outside, can be difficult not least methodologically, but can be useful for addressing entangled interactions and relationships between many different aspects, e.g. both social and environmental (Fritz et al. 2019; Lawrence et al. 2022). By combining different methods in a mixed methods approach, the findings can feed into each other, and contribute to addressing complex questions (Östlund et al. 2011). In this thesis, I have worked with both qualitative and quantitative methods in order to study landrace cereal from a more holistic perspective than would have been possible by for example only relying on agronomic field trials. Using a transdisciplinary and mixed method perspective in research projects is not new, especially not within the research field of agroecology. Within agroecology, the ambition is to study not only what happens on the field scale, but how the field relates to the farm- and food-system scale. This perspective can imply a cyclic approach to learning and understanding – using one kind of findings or observations to enrich the understanding of another, and reflecting over the acquired knowledge and letting that inspire further experiments or actions etc. (Kolb 1984; Francis et al. 2013).

The thesis project was part of a larger transdisciplinary research project focused on Swedish heritage landrace cereals. Grains of spring wheat and rye collected as part of agronomical studies were used for nutritional and sensory analysis, making it a project spanning from farm to fork, overbridging several disciplines. The project was funded by FORMAS, the Swedish Research Council for Sustainable Development, project no 2018-02393.

3.1.2 Participation

By involving participants, most importantly farmers, in this research process, the ambition was to increase the applicability and relevance of the results. Since landraces are so closely linked to farmers' management and to the environmental conditions of the farms, the choice to involve farmers in the process seemed natural and indeed necessary. Some other studies of landrace cereal cultivation have involved farmers' experiences in designing field experiments, for example in Scotland (Martin et al. 2010), South Africa (Jankielsson and Miles 2016) and Germany (Peratoner et al. 2015). A few studies of landrace cereals have been conducted on different farms, in order to study the effect of different on-farm conditions on landrace performance (e.g. Serpolay et al. 2011; Migliorini et al. 2016; Bocci et al. 2020). These studies have inspired the design of this research project, by showing the potential of involving farmers in the research both for helping designing and interpreting field experiments in order to increase the relevance of the findings, or to enable studies in varying farm conditions in order to study interactions between e.g. environments and genotypes.

Participation was imbedded in the project in two main ways. One part was to use participation in the design process, mostly by consulting farmers when designing experiments and data collection for paper II and III. A considerable part of the participatory approach has been to incorporate farmers' experiences in the development of hypotheses and in discussing the results in all four papers. The idea has been to let farmers' knowledge not only guide the design and hypothesis forming, but also give an indication of what traits and performance indicators that farmers value in the landraces, and to discuss the results in relation to farmers' experiences.

3.2 Research design

The thesis consists of four interrelated studies. The first study, an interview study encompassing the majority of farmers in Sweden with experience of landrace cereal production, was used to guide the hypotheses and the design of the following studies (Figure 1).

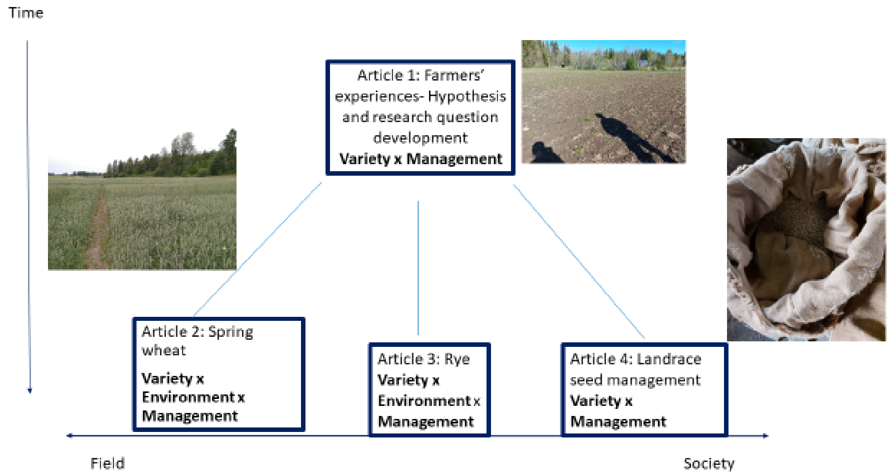

Figure 1. Design of the PhD project. An initial interview study with farmers (Paper I) formed the basis for hypotheses investigated in agronomical experiments (Paper II and III) and for a deeper study of the farmers' experiences of seed exchange and management (Paper IV). Photos by Tove Ortman.

In practice, however, the process was not as linear as Figure 1 suggests. The data collection for the different studies (i.e. the interview study and the agronomic data collection) were carried out partly in tandem, feeding into each other. There was a certain overlap of participants in the different studies, since the number of farmers that have experiences of repeated landrace cereal cultivation in Sweden is limited. The farmers that were most engaged and experienced in landrace cereal cultivation were often part of both the interview- and the on-farm study.

The first experiments to be set up – the spring wheat experiments discussed in paper II – were designed with input from a small group of farmers who had long experience of landrace cereal cultivation. These farmers were members of the Swedish landrace cereal seed swapping association Allkorn. They assisted by sharing their experiences, especially recommendations for fertilisation strategies that suit landrace spring wheat, and helped provide landrace seeds for the first year of the experiment. Another important knowledge resource when designing and setting up the experiment was that the staff at the university field experiment farm in Uppsala, SLU Lövsta Field Research Station, had long experience of growing landraces. They had, for example, hosted a field scale Allkorn landrace propagation scheme for several years.

3.2.1 Recruiting farmers

A starting point for this project was to involve farmers who cultivate landrace cereals, and to learn from their experiences. Beyond farmers, other actors involved in the landrace cereal food system were part of the project; for example, as bakers, consumers, and employees at Swedish governmental bodies (e.g. the Swedish Board of Agriculture). The purpose was to understand the context that the farmers were acting in. At the commencement of the project, I started building up a network around landrace cereal production in Sweden, with the motivation to recruit farmers for the interviews and on-farm studies, but also to be able to take part of activities around landrace cereals and gain a broader understanding of the context.

In parallel with building a network among the Swedish landrace cereal community, my ambition was to find and survey as many as possible of the farmers in Sweden that cultivated landrace cereals, and to recruit farmers for the on-farm rye study. A natural starting point was the association Allkorn. By first contacting representatives from the board of Allkorn, I was put in contact with farmers that received seeds regularly from the association and were active in the association. I then received further contacts from these farmers, using the snowball method (Noy 2008). Since landraces are primarily exchanged through seed swapping, I was able to backtrace the seeds, i.e. ask farmers who they had exchanged seeds with, and thereby find farmers who were in the outskirts of the Allkorn association. Another way to broaden the search, and avoid the bias of only recruiting farmers engaged in the Allkorn association, was by advertising about the study in the newsletters of the association “Ekologiska lantbrukarna”, an association for Swedish Organic farmers. An advertisement was posted in the social media group “Spannmålsbönderna” (“The cereal farmers”) with over 24 000 members, which is a platform for Swedish farmers who produce cereals. In this way I met with farmers who had a partly different perspective on landrace cereal cultivation than farmers with an engagement in Allkorn (see paper I). Another way to meet farmers was by participating in events about landrace cereal, and orally inform about the study. Examples of events were field days arranged by Allkorn, and workshops about landrace cereal cultivation arranged by SLU, Allkorn, Ekologiska lantbrukarna and the Swedish Board of Agriculture.

I contacted and held short phone interviews with all farmers I could get in touch with for an initial survey. The goal was to find 1) farmers that were interested in being further interviewed about their experiences of landrace cereal cultivation, and 2) farmers growing landrace rye and who were interested in taking part in the on-farm study. In the initial phone survey, I first informed the farmers about the project, asked if they were interested in taking part, and if so, asked a few questions about their landrace cereal cultivation (e.g. what landraces do you grow, how long have you been growing landrace cereals) in order to map the farmers' experiences and find out more about their type of production. In total 47 farmers were part of the initial phone survey.

3.3 Qualitative methods: data collection and analysis

Qualitative methods – semi-structured interviews and participatory observation – were used to collect data for paper I and IV, and as part of the data collection for article III; qualitative data was used to inspire and inform the investigations for paper II.

3.3.1 Semi-structured interviews

After the initial phone survey, I asked farmers who had repeated experience of landrace cereal cultivation on a commercial scale if I could do a longer face-to-face interview with them. The aim of this study was to explore farmers' experiences with landrace cereal cultivation on a field scale (i.e. not in home gardens), and to understand what motivated them to use landrace cereals instead of modern varieties. I spoke to a few hobby farmers during the initial survey, but they stated that they did not have enough repeated experience of landrace cereal cultivation. Consequently, the focus became farms growing landraces commercially, i.e. selling products and not only using the produce for their own consumption. In addition, the farmers that were included in the interview study had repeated experience of landrace cereal cultivation. At least two years' experience was included in the selection criteria; this was a limit which evolved naturally – often farmers with less than a couple of years' experience declined to be interviewed further anyway, saying that they did not have much experiences to relate. Out of the 47 farmers from the initial survey, ten were excluded based on the selection criteria. Five farmers declined to be interviewed further. These five farmers were all elderly, and the fact that the ongoing Covid-19 pandemic made physical meetings impossible for persons in a risk group this might have affected this decision. In total, 32 farmers consented to be interviewed in more depth and took part in the interview study which is the basis for paper I and IV. Many of these farmers grew landrace rye, and also participated in the on-farm study that is the basis for paper III in this thesis (Figure 2).

The entire fieldwork took place during the Covid-19 pandemic, and due to restrictions and safety for everyone involved, the interviews generally took place outside or in, for example, a barn. In three cases when the interview was not performed in person, telephone or video calls were used, depending on the method with which the farmer felt comfortable. Physical interviews were not possible in any of these cases, either because of the weather (making it impossible to sit outside) or because the farmer belonged to a risk group for Covid-19 and had to keep isolated. Instead, I was able to come back and visit the farm at a later date, when the weather was better, and get a tour around at the farm. The interview was often preluded by some small talk about the weather, the state of the roads, about the farmer's (and my own) workload etc., which in itself was an excellent way for me to get a feeling for the context. Before the interview started, I informed about the study, and asked for consent to record and use the transcripts for publication. I informed that the recordings and transcripts would only be used by myself and my co-authors, and would be stored in a safe manner in the university servers.

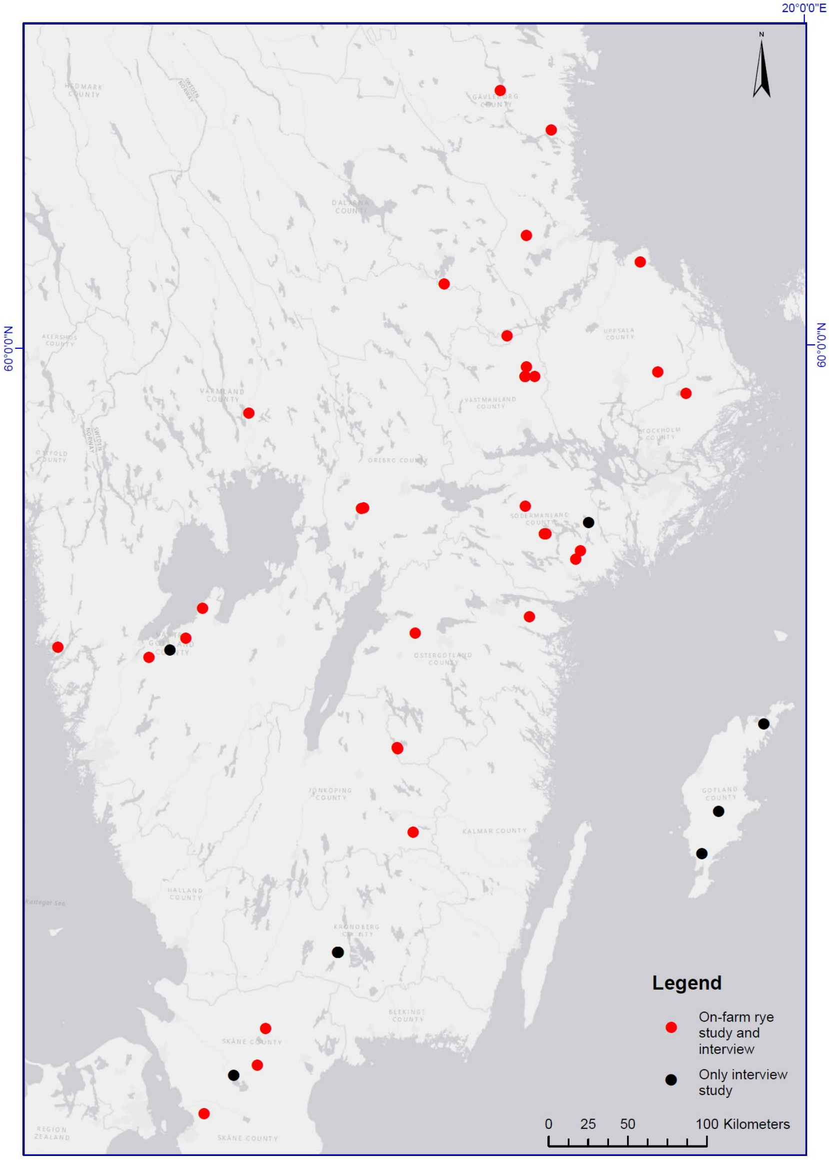

Figure 2. Map showing approximate locations for the farms included in the on-farm study and the interview study (Source: Esri)

The interviews were in a semi-structured format with a structured part. (See Appendix A). The main part of the interviews was conducted in a conversation-like manner around different themes, such as the origins of the landrace seeds, or the history of how and when the farmer started using landrace cereals. The structured part consisted of a number of questions about, for example, the farm size, management and lines of production. The semi-structured format aims at making the interviewees feel relaxed and able to expand in their own words on different themes introduced by the interviewer. This is a common qualitative method for understanding the background, ideas and motivations of the interviewee (Kvale and Brinkmann 2014). The interview was usually accompanied by coffee and cakes, and I often brought a tin of homemade cookies to contribute. The interviews took between 30 minutes and 2 hours, depending on the farmer's experience of landrace cereal cultivation. Most interviews took around one hour, not including small talk, interruptions and a walk around the farm. In many cases there were other persons involved in the farm management present for all or part of the interview, for example the spouse of the farmer, the farmers' children or employees. When more than one person was active in the landrace cereal production, for example if the farm was run by a couple together, or if there were two generations active at the farm, I tried to include all these persons in the interview. In many cases the various farmers at the farm were involved in different tasks – one person might be responsible for the cultivation, and another for the milling and sale of the products. To ensure anonymity, all farmers have been allocated an alias, e.g. Farmer A or Farmer B. In the cases of several persons being actively involved in the landrace cereal production, numbers have been used, e.g. Farmer A1 and Farmer A2.

Part of the data collection for paper IV was done by a master student who I supervised in collaboration with the other main author. These interviews (12 additional) were conducted by using a similar method, partly with the same farmers, but more focused in depth on seed exchange and including other actors than farmers (see Gustafsson 2022).

3.3.2 Participatory observation

An important part of the qualitative fieldwork was participatory observation. This consisted of two main parts, observations at the farms and observations at events, Allkorn activities and social media discussions. The purpose was to complement interviews and provide an understanding of the broader context and community around landrace cereal cultivation in Sweden.

Observations at farms were carried out in connection with the interviews, but were also combined with the on-farm rye study. After or before the interviews, I asked the farmers to give me a tour around the farm, to see some of the fields, machines and buildings used in the cultivation. This was an excellent opportunity for me to understand the context described in the interviews, but also to ask follow-up questions, and for the farmer to expand on themes from the interviews or relate things that they had forgotten to mention. An important stop was usually the farm shop, since a majority of the farmers used some sort of direct sale. An important purpose in looking at the farm shop was to form an idea of the types of produce of the farm, and how these were marketed. In itself, visiting the farm shop was a useful experience, where I could obtain an insight into the customers' experiences, and also buy landrace cereal products to taste for myself afterwards. In the cases where the farm was also hosting an on-farm experiment, I had many opportunities for gaining an even fuller picture of the farm.

The fieldwork for the on-farm landrace rye study (Paper III) required 4-7 visits to each farm during the growing season. Most of these (4-5) were to collect data, but I often had to make extra visits in order to check the development stage of the rye, or for additional interviews. These visits offered an opportunity to talk to the farmers several times, and see the farm at different times of the year. I often parked the car at the farmyard and the farmers would often take time and come to the field for an update on the field experiment. These talks were usually focused on the rye cultivation. The farmers frequently reflected together with me on how the rye was growing, and the cause of different conditions in the field, for example weed growth, disease occurrence or lodging, and how they planned to adapt the management to these circumstances. The farmers would for example express how confident they felt in the management (i.e. in the success of the rye cultivation), and describe what type of support and knowledge they had access to when they encountered problems in the cultivation. These reflections and discussions with the farmers were the basis for formulating qualitative factors to include in the multivariate analysis for paper III, and were also used for discussing the findings of that study.

Part of the data collection was performed by taking part in activities and events concerning landrace cereal cultivation. In particular, much of the data about the seed exchange for paper IV was collected at these types of events. The types of activities that I attended included field walks, study visits to farms and mills, annual meetings, workshops and seminars. Many of the events were arranged by the Swedish seed swapping association Allkorn. I became a member of Allkorn (the association is also open for researchers and people from the public with a general interest for landrace cereals), and in order to understand how the propagation was carried out and the work it entails for farmers and hobby growers, I also attempted to contribute to the seed propagation of the association's seed bank. This consisted of sowing ten different spring sown landraces in a field in your home garden, then selecting ten healthy ears and sending these to the Allkorn seed bank. I also joined events and practiced both home baking and straw handcraft myself, using landrace cereal material. These experiences were of particular use to gain a fuller understanding of the cultural and social values created by the landraces.

An important part of the seed exchange, discussions and knowledge transfer about landrace cereals took place in social media groups, and I followed the discussions as part of the participatory observation. It was a good opportunity to obtain updates on news and see discussions among the members about the cultivation, sale and propagation of landrace cereals, in order to gain a fuller understanding of the farmers' motivations to use landraces and for how the seed exchange worked. In addition, I was able to keep the stakeholders updated on our research progress, and to invite them to events arranged by us at the university, so that they could give me feedback on methods and discuss the implications of my research results.

I documented all participatory observations, both from farm visits and from events, Allkorn activities and social media discussions, in field diaries. One special diary was used for continuous reflections during the entire process, from data collection to analysis and writing. In the field observation diaries, I documented both the informal conversations I had with e.g. farmers standing by the rye fields, but also of impressions, descriptions of environment and atmosphere in order to understand the context for e.g. statements or field observations. The field notes were included in the analysis for paper I and IV, and were the basis for formulating the qualitative variables that are included in the analysis for paper III. In the cases where quotes from field diaries were used for analysis or in publications, they were translated and transcribed.

3.3.3 Methods for analysis - qualitative data

All interviews were transcribed, which in itself became an opportunity for me to go through the material again and do an initial coding, i.e. identifying common themes and marking them by using colours. Field diary entries from participatory observations were used to complement the interview data, and were included in the coding. The analysis of the qualitative data for paper I was inspired by inductive theory, an analysis method which is closely related to grounded theory (Thomas 2016; Bowen 2016), where the material guides the analysing process rather than an already conceived analytical framework (Figure 3). All quotes used in the publications were translated from Swedish to English.

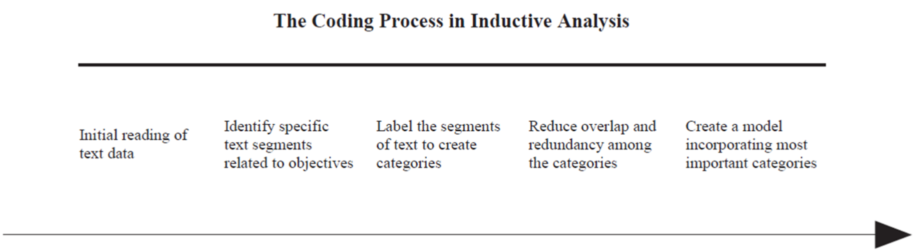

Figure 3. The coding process in inductive analysis of data, adapted from Thomas (2016).

Since the conceptualisation of paper IV was based on the findings of paper I, the analytical process can rather be said to be abductive, i.e. that former perceptions and ongoing empirical observations informed the analysis in a more circular manner (Bryman 2016).

3.4 Quantitative methods: data collection and analysis

Quantitative methods were used to collect data for paper II and III. Two types of studies were the basis for these papers, field experiments (paper II) and an on-farm study (paper III).

3.4.1 Spring wheat experiments

At the start of the project, a field experiment comparing landrace and modern varieties of spring wheat grown under organic conditions was set up. The aim was to study how the modern varieties and landraces responded to different fertilisation levels, to environmental conditions and interaction between these factors. Before setting up the experiments, farmers with experience of landrace cereal cultivation were consulted. They recommended a low and late fertilisation, aiming at protein content rather than yield, in order to reduce the risk for lodging in the landraces. The fertilisation level of the organic biodigestate fertiliser was at the lowest level recommended for Swedish organic cereal production with modern varieties (Lantmännen Lantbruk 2023), but was deemed by the experienced farmers to be comparably high for the landraces. With the inclusion of treatments comprising both no-fertilization and a relatively high dose of biodigestate applied late, our objective was to mimic the range of conditions relevant to farms that grow landrace spring wheat. The experiment was run for three years, 2019-2021, at the organically managed part of the university (SLU) property outside Uppsala, Sweden. The experiments were located at two locations each year, at Ekhaga (59.8305, 17.8083) and Krusenberg (59.7362, 17.6827). In the first year (2019) low initial seed quality led to germination problems in the landraces. Therefore, the first year of the experiment is regarded as a propagation year, and only the two last years were included in the analysis. The seeds of each variety used in 2020 and 2021 were taken from a pooled and mixed sample of the harvested grains from the previous year. The experiment was designed in randomized complete blocks, with four replications and two levels of fertilisation in main plots, and seven different varieties in subplots (Figure 4).

Block I

B3 22	B7 23	B1 24	B5 25	B2 26	B6 27	B4 28
A7 15	A1 16	A5 17	A4 18	A6 19	A3 20	A2 21

Block III

A1 50	A5 51	A7 52	A6 53	A2 54	A4 55	A3 56
B2 43	B6 44	B4 45	B1 46	B3 47	B5 48	B7 49

Block II

B6 8	B3 9	B2 10	B4 11	B5 12	B7 13	B1 14
A4 1	A5 2	A3 3	A2 4	A7 5	A1 6	A6 7

Block IV

B2 36	B1 37	B3 38	B6 39	B7 40	B4 41	B5 42
A5 29	A1 30	A6 31	A4 32	A7 33	A3 34	A2 35

Figure 4. An illustrative example of the spring wheat experiment design, using split-plots in randomised complete blocks. The letters A and B represent the different fertilisation levels in the main plots (A = 0 kg N7 ha, B = 100 kg N/ha), and the numbers 1-7 represent the varieties. The numbers 1- 56 represent the individual subplot numbers.

The fertilisation used was organically certified biodigestate, which consisted of cow manure from the nearby SLU livestock research farm (Lövsta Swedish Livestock Research Centre) combined with ley grass, which had been processed in the research station's biogas plant. The fertiliser was spread in liquid form, and applied late, after sowing but before stem elongation, growth stage BBCH 30 (Lancashire et al. 1991), according to farmers' recommendations (Figure 5). Half of the main plots were unfertilised, and half of the main plots were fertilised with biodigestate equal to 100 kg N/ha, of which approximately 60% was available as ammonium-N.

Figure 5. Application of the biodigestate fertilisation at the field experiment at the site Krusenberg 2020. Photo by Tove Ortman.

The two locations of the experiments were chosen to represent a fertile clay soil with a high organic matter content (Ekhaga), and a more sandy and less fertile soil (Krusenberg). At the Ekhaga site, PH was generally lower than at the Krusenberg site, and the level of soil mineral nitrogen was generally higher (Table 1) At Ekhaga in 2021, the levels of mineralised nitrogen were exceptionally high. According to the manager of the field research season, this is not unusual for this specific field at the Ekhaga site, especially after heavy rainfalls early in the season, reflecting its high organic matter content. In 2021, the sowing was delayed at Ekhaga due to large amounts of rain, allowing a long time for mineralisation of nitrogen. The dominating weeds differed between the sites. The Krusenberg site was infested with thistles (*Cirsium arvense*) and Baldr’s brow (*Matricaria maritima*), while the prevailing weeds at the Ekhaga site were white clover (*Trifolium repens* L.) and common hemp-nettle (*Galeopsis* spp).

Table 1 Field properties at the two sites Ekhaga (E) and Krusenberg (K), used for the comparison between spring wheat landraces and modern varieties. Presenting dates for sowing and harvest at the different sites (month-day), mineralised soil nitrogen (Mean N min) measured before sowing at 0-90 cm depth, pH and proportion of soil organic matter (SOM), clay, silt and sand from top soil samples (0-30 cm depth). Adapted from Paper II

Location	E	E	E	K	K	K
Year	2019	2020	2021	2019	2020	2021
Mean N min	301	115	413	263	112	232
Sowing date	04-29	04-22	05-14	04-28	04-21	04-30
Harvest date	08-27	08-20	08-24	08-28	08-21	08-31
pH	5,8	6,0	6,8	6,1	6,0	6,3
SOM %	8,9	7,1	6,4	2,4	2,2	1,9
Clay, %	40	51	44	20	22	24
Silt, %	47	33	47	35	31	37
Sand, %	4	9	< 4	43	45	38

Seven varieties were compared in the experiment: three modern varieties and four landraces. The modern varieties were Skye, a relatively recently released variety in Sweden (2015), and two older varieties, Quarna and Dacke (released 2005 and 1990), which are still popular in organic farming. Dacke is more or less exclusively used in organic farming. Both the latter varieties are well known for producing high protein levels and to be well suited for producing spring wheat with high baking quality (Karlsson et al. 2022). The landraces were of two types: two historical landraces, Dala and Ölands lantvete, dating from the mid-19th century (Diederichsen et al. 2012; Leino 2017), and two recently produced evolutionary mixes. One of the mixes, Källunda mix, came from a farm in the south of Sweden, and the other was mixed by the former field research station manager at Lövsta research station, and is called Ekhaga mix (named after the oldest organic part of the research farm). Because of problems with low germination in the landraces in the first year of the experiment (2019), the germination was tested before sowing in 2020, and seeds that showed low germination and fungal growth were treated with the organically certified heat treatment Thermosseed® before sowing in 2020.

The data collection included plant-counting, biomass sampling at anthesis and before harvest, leaf area index measurement at stem elongation and early anthesis, and soil samples post-harvest. The biomass samples included weed biomass, and were divided in straw, ears, annual & perennial weeds, which were then dried and weighed. Grain samples from the harvest and soil samples were sent for chemical analysis, which was performed through NIR transmittance (Pojić and Mastilović 2013) at Agrilab in Uppsala, Sweden. The kernels were run though a photo analysis tool, Cgrain Value®(Leiva et al. 2022) in order to measure thousand kernel weight (TKW) and kernel form. Yield components were calculated using plant counts, biomass weight and TKW, and biomass/ears ratio; NUE and adjustments to Lai for biomass weight were calculated based on crop and soil data.

3.4.2 On-farm landrace rye study

For studying the interactions between landrace rye and environment, an on-farm study was set up with farmers contacted in the initial farmer survey. The ambition was to include all Swedish farms growing organic landrace rye during that specific growing season on a commercial scale, i.e. not on museum farms or in home gardens. By a thorough search and backtracking of seeds, we consider this ambition as good as fulfilled. All farms that were growing landrace rye were organically managed, except one. This single conventionally managed farm was excluded from the study, since pesticides and mineral fertilisers were expected to make this farm an outlier and make interpretation of the results more difficult. The main data collection was carried out during the field season 2020-2021, with harvest 2021. Spring rye cultivation was included for two growing seasons, 2020 and 2021, since only a small number of farmers grew landrace spring rye.

In total, 37 fields were included in the study. These fields were located at 28 different farms (See figure 2). Some farmers cultivated two different landraces of rye, and several grew both spring rye and winter- or midsummer-sown rye. It was common to grow different types of rye for different purposes. The spring rye was often grown for its baking quality or on frost-prone fields, while the midsummer-sown rye could be specifically used as weed sanitation or to sell the straw for thatching or straw handicraft. In several cases farmers were, for example, cultivating one favourite landrace, and then one additional landrace used for a special purpose. In the cases when a farmer grew more than one landrace of rye, the two rye landraces were grown at different parts of the farm with at least one kilometre apart, in order to avoid cross-pollination of the landraces. Since landraces of rye are so dynamic and change over time due to cross-pollination and farmers' seed exchange, landrace rye should be regarded as part of meta-populations with locally adapted subpopulations, rather than seen as separate varieties (Larsson et al. 2019). Therefore, instead of focusing on differences between landraces, the landraces grown by the farmers were instead grouped according to sowing time (spring-, winter- and midsummer rye). For a list and description of all included landraces, see paper III.

Data was collected 4-5 times from the fields during and after the growing season (see paper III). In connection to the first visit, an interview was held (usually at the rye field) with a few structured questions about the rye cultivation (see interview guide in paper III, appendix A). Six observation plots (2 x 2 m) were randomly placed in the field, and marked by a field flag in one corner. The data collection in the plots included plant counting, visual weed assessment at tillering (around BBCH 21) and at early anthesis (around BBCH 61), leaf area index measurement at anthesis, rye biomass sampling at medium dough stage (around BBC 85) and soil samples after harvest (0-30 and 30-60 cm depth). The biomass was separated in ears and straws, the ears were counted and the biomass was then dried and weighed. After weighing, the ears were threshed, and the grains were weighed, and the TKW was determined by using Cgrain value® (Leiva et al. 2022). The grain samples were then sent to chemical analysis at Agrilab, Uppsala, to determine protein by using dry combustion on a LECO CN928 machine (modified method of SS-ISO 13878), and mineral content by using Spectro Blue ICP machine (modified method of SS 028311), see paper III for detailed descriptions. Soil samples were analysed for chemical and physiological properties at Agrilab (see paper III). Yield components were calculated using data from plant counts, biomass weights, and TKW; harvest index and NUE were calculated using crop and interview data. In order to asses weed occurrence in the plots and in the field generally, visual weed assessments were used. The weed assessments were performed in two ways, plot-wise at two occasions and in four transects at two occasions across the fields to better estimate the occurrence of e.g. spot-wise perennial weeds, which tend to grow in clusters. To avoid the risk for bias in the assessment (Parker et al. 1995) the same person (Tove Ortman) carried out all assessments, after training in the spring wheat experiment in order to make as correct assessments as possible. At each assessment both weed species and weed cover of the difference species were noted, and these data was used to calculate diversity indexes (see paper III).

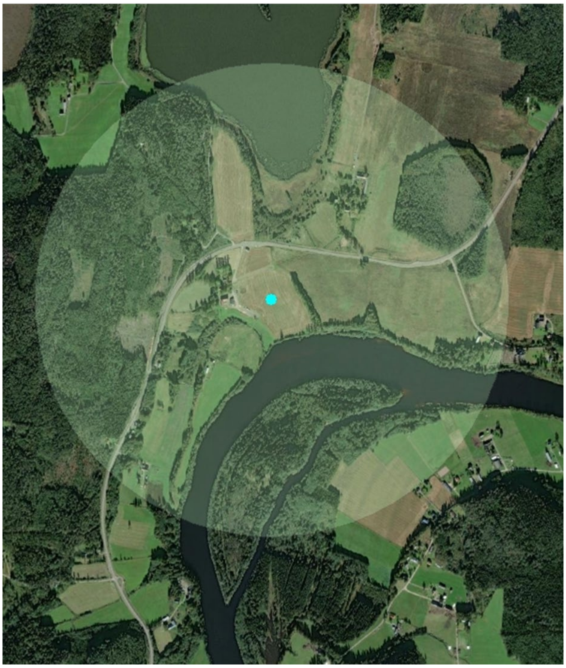

Figure 6 Example of a 1 km buffer around a rye field that was used to assess the proportion of landscape types applying Land Parcel Identification System (LPIS) data (Reumaux et al. 2023) (Source: Esri).

In order to investigate the landscape structure around the field, Land Parcel Identification System (LPIS) data (see Reumaux et al. 2023) were collected for buffers in 1 and 5 km, in order to calculate the proportion of different land use (Figure 6). In addition, LPIS data were used to calculate the diversity of the historical crop rotations and the proportion of e.g. leys and cereals. The proportion of high-quality leys in crop rotations was categorised using agricultural crop codes, see paper III, Table B2. All geographical analyses were performed in ArcGIS (version 10.4.1)[1].

[1] All maps included in this thesis have been created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and copyright © Esri. All rights reserved.

3.4.3 Method of analysis: quantitative data

The agronomical data from the field experiments with spring wheat were analysed by using a mixed model, with variety, fertilisation and environment as fixed factors, and blocks and split plots (fertilisation * blocks) as random factors. The two factors location and year were combined under the term environment, in order to simplify and increase the relevance of the model. The model was fitted using the lme4 package in R (Martin Machler et al. 2015). This model was used for analysis of variance, and pairwise comparisons, using the emmeans package in R (Russell V. Lent 2023). In the cases when there were significant interactions between variety and environment, the environments were tested separately in a simplified version of the main model, consisting only of variety and fertiliser and random effects. All analysis was done in R software (R x64 4.0.5). Response variables were chosen in order to test three hypotheses that had been formulated inspired by farmers' experiences, and which were themed around 1) Yield of grains and straw, 2) Baking quality and 3) Weed suppression (Paper II, Table 1).

For the analysis of the on-farm rye data, Projections to Latent Structures analysis (PLS) was employed; this is a multivariate analysis which can handle both quantitative and qualitative data. The PLS analysis made it possible to combine both the agronomical data from the on-farm study and the qualitative data from farmer interviews, participatory observations and reflections at the farm for an overall analysis. In addition, PLS is a method which can handle datasets with few numbers of observations but a high number of variables (Ferrer et al. 2008; Nkurunziza et al. 2020). The qualitative data collected from the farmer interviews and from participatory observation added depth to the on-farm study, by providing information about farm management and the farmers' experience, making it possible to assess the farmers' knowledge about landrace rye cultivation. The qualitative variables were transformed into rankings, see paper III Table B1. The initial dataset (consisting of 119 variables, see paper III, Table B3) was explored through PCA analysis and Pearson's correlation analysis (Venables and Ripley 2002). Three models were analysed in a first PLS analysis; these models contained variables associated with 1) rye yield and general performance, 2) rye nutritional quality and 3) rye weed suppression effect. Variables with a VIP value (the Variable Importance of the Projection) lower than 1 were filtered out and excluded, in order to increase the fit of the model and the prediction, and the models were then re-analysed through a second PLS analysis. Spring rye is biologically different to overwintered rye, since it has no winter dormancy. Consequently, spring rye and the winter-sown rye types were analysed separately since spring sown types reacted distinctly differently than the other types to the included determinant variables. The PLS analysis was performed in SIMCA (17.02), and all other analysis were performed in R (R x64 4.0.5).

3.5 A note on positionality – my role as researcher in relation to participants

Reflecting on my own role as researcher in relation to the participants is important part of a transdisciplinary fieldwork, since this can affect the data collection (Dalgaard et al. 2003; Fritz et al. 2019). In this case, it turned out to be an advantage that I was relatively new to both landrace seed swapping and cereal cultivation. The farmers seemed not to primarily regard me as an expert coming from the university, but more as a student – someone who wanted to learn and understand. My agronomist training and background – having worked at a farm for many years in parallel with my studies – made it possible for me to still know enough to ask well-informed questions, and be able to have an approximate understanding of the realities of farming life. Being able to use a common language and terminology as the participants is an advantage in transdisciplinary projects, enhancing understanding on both sides (Fritz et al. 2019). All interviews were conducted in Swedish, all the farmers' first language as well as mine, which can be an advantage when conducting e.g. interviews or observations, reducing the risk for misunderstandings (see e.g. Winchatz 2006). Not being formally involved or experienced with landrace seed swapping made it possible for me to have an outside perspective. A challenge, however, was to communicate my role as researcher, and that it meant taking a neutral standpoint with regard to landrace cereals. Nevertheless, most participants approved, often saying that an unbiased observer would make the results more valid, and make the impact greater. For my part, I felt some pressure from the stakeholders to find positive results that could be communicated to consumers – e.g. health benefits. In order to be able to distance myself and keep a neutral and open mind, I actively distanced myself from the participants' context during the analysis- and writing processes, still keeping in contact with my key informants and participating at events, but taking a less active part, and more taking the role of relating results from the studies.

4. Results

4.1 What motivates farmers to use landrace cereals, and how do these motives affect the crop management? (Paper I)

The farmers that were included in the study were all except one certified organic. A majority of the farms were situated on what the farmers themselves described as less optimal growing conditions for cereal – e.g. forested areas with less fertile soils and wildlife problems with wildlife damaging the crops. Many of these farmers described how they were the only farm in the area growing cereals for direct human consumption. The farms were diverse, usually with more lines of production than cereal cultivation. More than half of the farms also kept livestock, for example dairy cows, sheep or suckler cows. The farms represented a broad range of agricultural activities, from apple cultivation to organic broiler production (for detailed descriptions of the farms, see table 1 in Paper I, Ortman et al., 2023).
Farmers' motivations to grow landrace cereals grouped around three themes: Ideals about sustainable farming, agronomic properties and market opportunities. The first theme can be regarded as an overarching theme, while the other two can be seen as sub-themes, providing the rationale for the broader theme of ideals about sustainable farming.

4.1.1 Ideals about sustainable farming

The farmers generally described landrace cereal cultivation as a common ground to meet other farmers with similar interests as their own: an interest for ambitious innovative organic practices. One farmer described how his neighbours regarded him as an UFO, with all his ideas about organic farming and landraces, while the networks around landraces gave him a place to meet others who think in the same lines (Ortman et al. 2023). The landrace cultivation was described as part of a broader ambition to make the farm "outstandingly organic" ("spjutspets-ekologiskt"), a common expression among the interviewed farmers. Landrace cereal cultivation was presented as a means to grow high-quality cereals in low-input organic farming systems. Indeed, the farming associated with landrace cultivation was often described as an antipole to conventionalisation of organic farming, i.e. organic farming relying on high in-put levels and intensive methods, similar to conventional farming.

Not all farmers shared these the sustainability ideals to the same degree. A number of farmers, who were often newer to landrace cultivation than the more engaged farmers, rather saw the landraces as a way of being able to grow cereals on marginal lands, and to be able to keep up farming traditions in their – more marginal – regions. Here, low-input management tended to be more motivated by the situation, i.e. that the properties of the marginal lands make high-input management costly and uneconomical.

4.1.2 Agronomic properties of landraces

One important reason for the farmers to use landraces was the agronomic properties – that the landraces suited the type of farming systems that the farmers had and the type of management they wanted to use. The farmers described how a number of traits of the landraces enabled them to use lower levels of fertilisation, less intensive weed management and to use the landraces in intercropping systems. The yields were generally described as somewhat lower than for modern varieties, with higher bread baking quality and more straw. This meant that the grains could be sold on a niche market as high-quality products, and that the straw could either be used as feed and bedding for livestock at the farm, mulched in the soil to increase soil health or sold for a good profit to other farms

Table 2. Crop performance indicators of landrace cereals, farmers' experiences of management and agronomic properties of landraces, and the implication this has on the farming system. Adapted from Ortman et al. (2023)

Crop performance indicators	Farmers' experience of management and agronomic properties of landrace cereals	Implication of experience in the farming system
Low demands on nutrient availability	Requires little or no application of nutrients, a too high nitrogen rate causes early lodging. Can reach good protein levels at low nitrogen doses (especially wheat).	No or reduced need to buy fertilizers. Better possibility of reaching acceptable protein levels for baking and therefore be able to sell to a better price than as animal feed. Possible to grow on poor soils. Avoid sites with much available nitrogen.
Prone to lodging	Early lodging can cause lower quality of the grains, but late lodging is generally not regarded as a problem, since landraces lodge in "vaults".	Special techniques for harvesting lodged crop necessary.
Low harvest index	High straw production.	The straw can be used as feed and bedding. Reduced need to buy straw.
Long straws	The long straws make the landraces outgrow weeds.	Need less mechanical weed control – enables a less intense weed strategy. Can be used as weed cleaning crop.
Rapid establishment of the crop	Strong early growth of spring sown crops, easier to reach a satisfactory establishment than with modern cultivars	Rapid establishment is associated with weed suppression, adds to yield, and is an advantage in intercropping.
Pest resistance	Long distance between ear and flag leaf reduces spread of fungi infection. Good general resistance because of genetic diversity.	Less damage from disease. Genetic diversity is further enhanced by using evolutionary mixtures.
Resistance against extreme weather	A robust crop, hardy. Deep roots of landraces give improved water uptake during droughts.	Less vulnerability to extreme weather, especially drought.
Local adaption and genetic diversity	The genetic diversity of the landraces enables local adaptation, i.e. adaptation to management and environmental conditions. Local adaptation effect within 3-4 years. The adaptation process can be facilitated by using evolutionary mixtures.	A crop that performs well according to conditions of the farm, especially an advantage when the soil is poor. The market value of a locally adapted landrace named after the farm or the village might be higher than other landraces.

The farmers described how they had had to build up knowledge about how to grow the landraces, and often shared this knowledge with each other (see paper IV). One example of how landrace cultivation requires new and different kinds of skills is harvesting a lodged crop, with long straws getting stuck in the combiner (Figure 7).

Example: Farmers' experiences of harvesting a lodged crop

A common experience is to "drive the combiner from the right direction" i.e. from the side of the lodged crop. This takes some skill and patience. Several farmers use special tools on the combiner, for example rapeseed knifes or torpedoes. One farmer describes his experiences with lodging and how he manages the harvest:

They (the landraces) almost never lodge close to the ground, they form vaults. Then you can use so called torpedoes on the combiner – long spears that disentangle the straws so that they don't get stuck, but steer them towards the table (...) and you get a tolerable feeding to combiner. Farmer C

Figure 7. Examples from the farmers' descriptions of landrace cereal management: harvesting a lodged landrace crop

4.1.3 Market opportunities

For most of the farmers, an important prerequisite for landrace cereal cultivation was that they were able to sell their products at an advantageous price. What the farmers described as a demand for local products of landraces made landrace cultivation part of a viable business model. The motivation to cultivate landraces was closely linked to producing for and selling to niche markets. All of the farmers had some sort of direct sale channel, i.e. a shorter way to the consumers than in the standard farmer-mill-retailer-shop structure. Often, the farmers sold directly to consumers through farm shops, farmers' markets, Reko rings (see Daving Götberg 2018), or at most they sold to mills specialised in landrace or other niche products, who then sold directly to consumers or bakers. For a detailed account of the farmers' direct sale of landrace cereal products, see Table 1 in Ortman et al. (2023). Direct sale meant that the farmers compete for consumers, and needed to communicate the values they associate with landraces. As a way of doing this, farmers often portrayed landraces as a healthy alternative to other cereal products, nutrient dense and good both for yourself and for the environment at the same time. All farmers report an increased consumer interest for landrace products, and that many customers associate it with high nutrition content, sourdough baking and other traditional and/or trendy products (Figure 8).

Öland wheat and the rising demand for landrace products

Farmers with longest experience of landrace cereal cultivation relate that the first real consumer rush for landrace cereals for spelt came at the beginning of the 21st century. A couple of years later, a Danish TV-chef started baking with Öland wheat, which created a great interest from consumers to buy Öland wheat. This occasion is pointed out by many of the farmers as the real start for the current landrace cereal trend.

Suddenly we started to get a totally different kind of feedback from the customers in the farm shop. That's when the Ölandsvete hype really got started. After that Danish TV-show the customers were mad for it… and since the mid-00s it's just gone upwards! (Farmer K)

Figure 8 Examples from the farmers' descriptions of landrace cereal management: Ölands wheat and the rising consumer interest.

To produce a high-quality product – i.e. landraces with high baking and nutrition quality – was important because of the market. It was also important for the farmers and millers that landrace cereal products should be associated with health benefits and with artisan baking. Often landrace cereal products were marketed as a healthy alternative to "industrially" produced bread (Figure 9). This means that a high content of nutrients, such as minerals and vitamins were of interest for the farmers and their consumers. Motivated by the reported nutrient content, many farmers specifically choose to grow different landraces of so called ancient cereals, like emmer and einkorn, despite the fact that the yields are reported as lower than for other types of cereals. Since consumer demand is high for these types of cereals, consumer prices are also high, and this meant that it could be profitable for farmers to grow e.g. emmer wheat, even though the yields are low.

Figure 9 “There’s a difference between flour and flour!” Advertisement for local mill that sells landrace cereal products. Photo by Tove Ortman.

As the market is increasing, the farmers with longer experience of landrace cereal cultivation often expressed a worry about the need to keep conventionalised organic farmers away from this market. If larger organic farms start to grow large volumes of landraces, using a higher degree of inputs (for example bought fertilisers such as bone meal etc.), the farmers are worried that this will dump the market and lead to a drop in prices for landrace products. These farmers therefore want to protect the market, keep the connection with direct or on-farm sale, and ensure that larger actors (e.g. large-scale mills and retailers) are kept away from the landrace market. This view partly contrasts with the ideas of some of the farmers who are newer to landrace cereal cultivation, and who would prefer an easier way to create sale channels for the products. They state that they would welcome more large-scale actors – although preferably locally based. In essence, there is a common wish among all the interviewed farmers to ensure that landrace cereal production continues to be associated with low-input organic farming. The present restrictions in the selling of landrace seeds partly acts as a threshold, making landrace cereals a crop only for the dedicated farmers, who are members of a seed sharing group, e.g. Allkorn or regional networks, and are able to propagate the seeds for themselves (see Paper IV).

4.2 How do environmental factors and fertilisation management affect agronomic performance and baking quality of landrace spring wheat compared to modern varieties? (Paper II)

Based on the experiences of farmers from paper I (Ortman et al. 2023), we hypothesised that landraces of spring wheat would perform well in terms of baking quality, weed suppression and straw yield, but give lower grain yield than modern varieties (see table 1 in paper II). However, the results from the field experiment show that this is not always the case. There were no differences in how landraces and modern varieties responded to fertilisation, and the fertilised plots gave higher yield and protein content. Despite primarily aiming at increasing the protein content, the late fertilisation also had a positive effect on yield for both modern varieties and landraces of spring wheat.

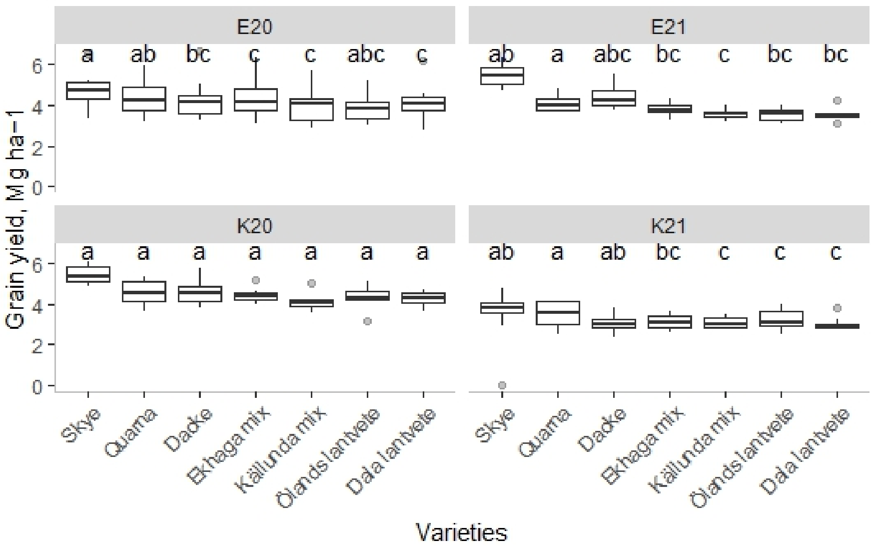

Figure 10 The grain yield at the four experimental environments for the varieties (Interaction between Variety and Environment, P >0.001). The varieties range from the most recent modern variety (Skye) on the left, to the historical landraces Öland and Dala lantvete on the right. Significant differences between varieties (P>0.05) indicated by letters.

The mean landrace yields at three of the experimental environments (all except the environment E21) were similar to the modern varieties Quarna and Dacke (Figure 10). The baking quality indicators protein and gluten content were significantly correlated (p<0.001), and the protein levels of the landraces were high. The landraces showed equal or higher protein content as compared to the two modern varieties Quarna and Dacke (Figure 11). The modern variety Skye gave considerably higher yield than all other varieties, but with low protein and gluten content. The landraces gave higher straw yields than the modern varieties, especially the two evolutionary landraces, the Ekhaga and Källunda mixes (Figure 12).

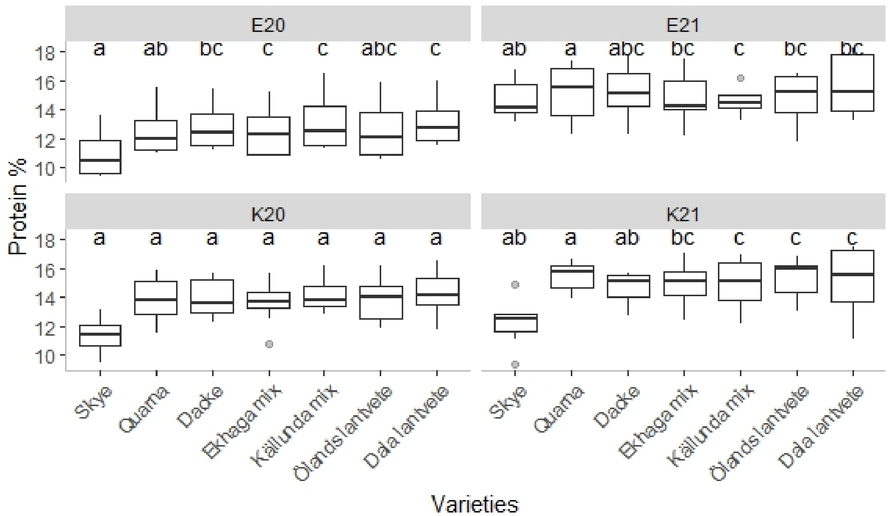

Figure 11 The protein content at the four experimental environments for the varieties (Interaction between Variety and Environment, P<0.001). Significant differences between varieties (P<0.05) indicated by letters.

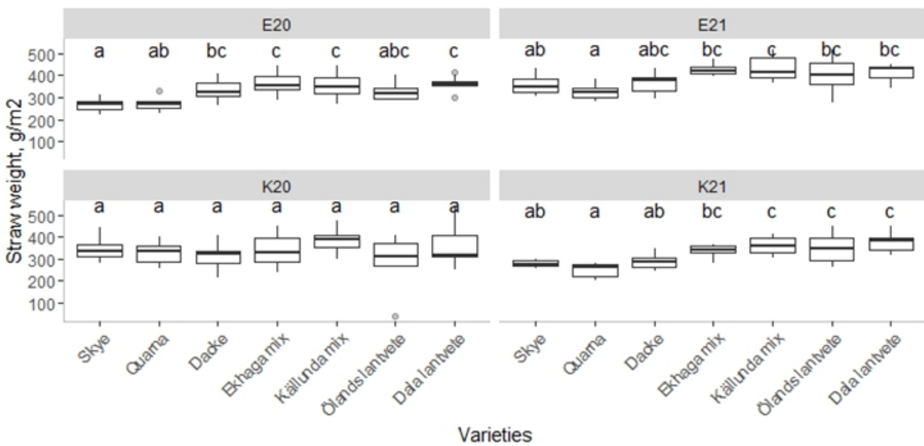

Figure 12 The straw yield at the four experimental environments for the varieties (Interaction between Variety and Environment, P <0.05). Significant differences between varieties (P<0.05) indicated by letters.

Generally, the landraces gave equal grain yields and equal protein content to two of the modern varieties, and higher straw yields than all modern varieties. The exception from this pattern was the experimental environment at Ekhaga 2021 (E21), where the initial available nitrogen was very high, due to an unusually high level of soil mineralised nitrogen before sowing. Therefore, this environment unintentionally mimicked conventional farming conditions, where the plants have access to high levels of nitrogen from the start of the growing season. In this environment, with a high degree of initial nitrogen, the landraces were outperformed by the modern varieties. The landraces yielded less grains in this environment, and all modern varieties gave as high protein content as the landraces. At the E21 environment, the landraces still produced higher straw yield, but did not seem to be able to utilise the extra nitrogen. This environment was also an exception in nitrogen use efficiency, where the NUE of the landraces was lower than the modern varieties. At the other environments, there were no significant differences in NUE between varieties.

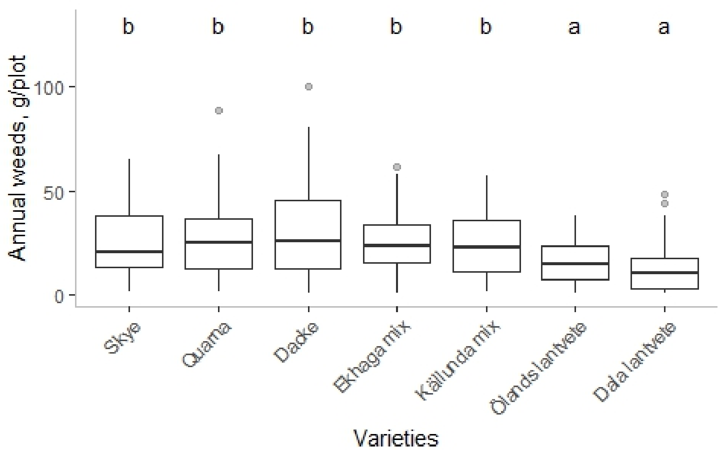

Figure 13 Mean biomass of annual weeds (g/plot) for the varieties (P<0.001). Significant differences between varieties are indicated by letters.

The two historical landraces, Dala lantvete and Ölands lantvete, suppressed the annual weeds better than all the other varieties (Figure 13). The straw yields and the leaf area index were higher for the landraces, suggesting that the landraces have a strong ability to compete for sunlight. The connection is not clear, however, since the two evolutionary landraces also exhibited these traits but still did not differ significantly in weed suppression ability from the modern varieties.

4.3 How do management factors and environmental conditions affect agronomic performance and baking quality of landrace rye? (Paper III)

The results of the on-farm study of landrace rye show that the most important factors for rye yield performance were primarily related to farmers' management and experience, rather than environmental conditions. The most important factors for grain yield and other performance indicators were related to the scale of operations at the farm, i.e. the farm size in terms of arable land and animal density (many animal units per hectare). Farms with a certain size of cereal production, with large areas of arable land and a high number of livestock or other animals, tended to have higher yields of grains and straw, with a lower weed cover. There was no clear connection to environment. Neither production zones (based on predicted yields of agricultural annual crops) nor growth zones (based on hardiness for perennials and trees) had any importance for overall landrace rye yield performance. High yield was not related to the extent of cereal production or arable land in the surrounding landscape. However, the proportion of forest in the surrounding landscape (5 km buffer), was of importance for rye yield, and was related to lower and more variable rye yield, and a higher degree of winter damage of the overwintered rye (Figure 14).

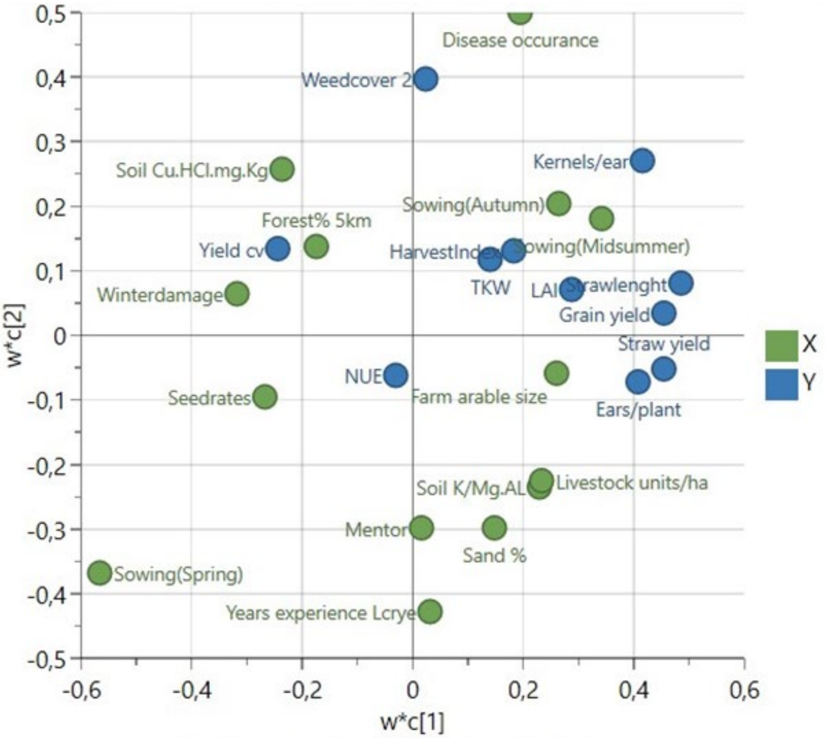

Figure 14 The relationship between yield performance indicators of landrace rye (Y), and management and environment variables (X), in a model with all rye fields (n= 37), shown as PLS scores (R2x[1] = 0.172; R2x[2]= 0.201) Variables included in the model are presented in full detail in Paper III, Table B2.

When analysing subsets of the different rye types, the robustness in less optimal environmental conditions seems to be partly caused by the midsummer-sown rye. When landraces of this rye type – mainly variants of the landrace Svedjeråg ("Swidden rye") – were grown, even farmers with less experience of landrace rye cultivation, with farms located in less optimal environmental conditions, could obtain high and stable yields of both grain and straw. For the autumn-sown rye, winter damage seemed to be a critical determining factor. Winter damage was linked to landscape factors such as marginal production zones, indicating more challenging climatic conditions. This effect could, however, be buffered if the farmer has long experience of landrace rye cultivation. In the interviews by the rye fields in connection to the on-farm data collection, farmers often stated that their motivations to use spring rye were because the field conditions caused difficulties to overwinter crops (e.g. low soil quality, a high degree of frost damage, or flooding during winter). This meant that the spring rye fields tended to be grown under more challenging growing conditions. Nevertheless, even for this rye type, farmers with longer experience of landrace rye cultivation were able – at least to a certain degree – to achieve relatively high yields also on more marginal lands. To a higher degree than for the overwintered rye, the yields of spring rye appear to be related to a number of soil parameters. A high proportion of clay, for example, was related to low yields in the subset with only spring rye. The spring rye yields were generally considerably lower than for the other rye types.

The most important factors related to yield and general rye performance were related to farmers' management, experience and access to knowledge. Farmers' access to a network and to mentors, for example, a neighbour, friend or parent with long knowledge of landrace cultivation, was also of importance. A high degree of mentorship or being part of a network focused on landrace cereal cultivation could partly compensate for short experience. Farmers with long experience of landrace rye cultivation, or a high degree of access to knowledge through networks or mentors, tended to have a higher yield of grain and straw. In a separate model focusing on performance indicators for the weed suppression ability of the rye, a similar connection was seen between farmers' knowledge and weed cover, both early and late. In the weed performance model, the farmers' experience of organic farming in general was also of importance, and grouped together with low weed infestation. Supposedly, the farmers' experience and knowledge about the cultivation were connected to management practices. Certain management factors were related to lower yields, and with a lower degree of experience or access to knowledge for the farmers. Fertilisation (with manure or organic amendments) did not increase yield, but was instead connected to low yield and higher weed cover, suggesting that the weeds rather than the crop benefited from the fertilisation. High seed rate in the overwintered rye was related to lower and more variable yields, with higher weed cover and a higher degree of winter damage. In a subset with only spring rye, the seed rate was not of importance for yield or for weed cover. A more intense weed management, i.e. harrowing 2-3 times or row hoeing, was associated with higher yield and lower weed cover in a subset with autumn- and midsummer-sown rye. Variation in ploughing practices was not of importance for landrace rye performance, not even low-till management, where harrowing is used without previous ploughing for preparing the sowing bed.

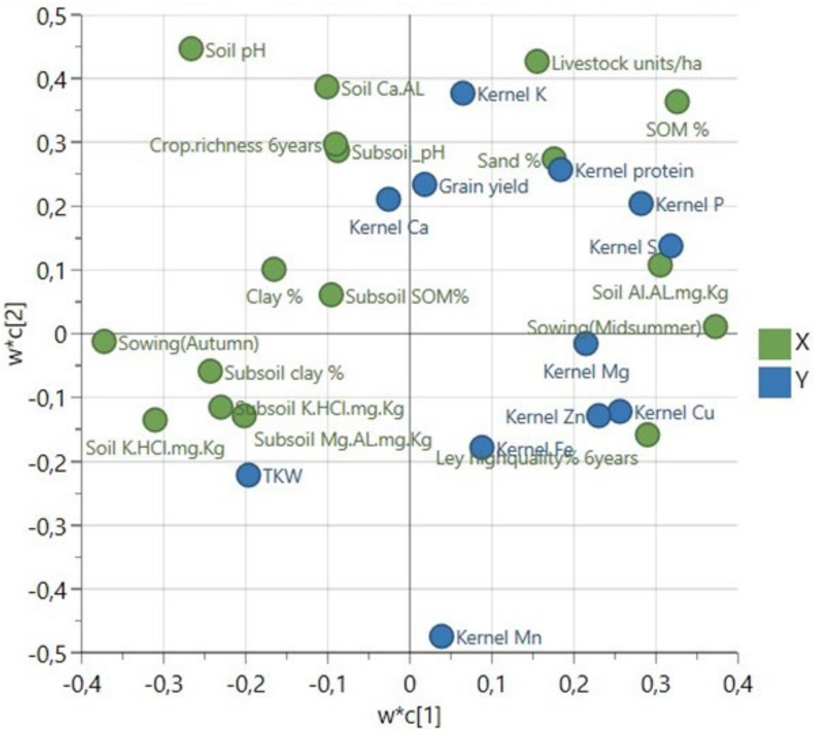

Figure 15. The relationship between quality indicators of landrace rye (Y), and management and environment variables (X), in a model with autumn- and midsummer-sown rye (n= 24), shown as PLS scores (R2x[1] = 0.394; R2x[2]= 0.139) Variables included in the model are presented in full detail in Paper III, Table B2.

Management factors also appeared to be connected with nutrient content of the landrace rye. When analysing the quality indicators in a subset with overwintered rye (Figure 15), high nutrient content (Cu, Mn, Mg, S, Zn N, S, Fe and P) grouped together with a high proportion of leys in the crop rotations, both historically and the proportion of high-quality leys over the latest 6 years, as well as with a high level of soil organic matter. Midsummer rye (Rye type 3) clustered with high nutrient concentration (Cu, Mn, Mg, S, Zn N, S, Fe and P), together with some fields of autumn-sown rye. All fields in the cluster belong to farms with a large proportion of leys in their crop rotations, often related to the fact that their main farm line of production involved cattle or sheep, and that the leys were used as feed.

When analysing all the rye types together, spring rye is grouped towards high nutrient content but with low grain yield and TKW (see Paper III, Appendix B), while midsummer rye is grouped with nutrients towards higher grain yield and kernel size. The high nutrient content in the spring rye seems to be related to a concentration of nutrients in the kernels due to low grain yields and low TKW.

4.4 How is landrace cereal cultivation affected by landrace seed exchange, management and legislation? (Paper IV)

When discussing landrace cereal production with the farmers in interviews and in other discussions at for example meetings and field walks, it was clear that the seeds were considered the key for landrace cereal cultivation. The landrace seeds can be seen as packages of potentials, opening up possibilities for farmers to fulfil the ambitions and ideals that have been presented in paper I. However, as the results of this investigation of landrace seed systems show, the seeds are also closely associated with norms and certain management practices, as well as with legislative restrictions and seed health problems – challenges that can threaten the entire landrace cereal cultivation.

4.4.1 Exchange in seed commons

Landrace cereals are unique, since they are spread outside the formal seed systems. This investigation shows that landrace seeds in Sweden were primarily exchanged through seed networks, either through the national Swedish seed swapping association Allkorn, or through regional networks. The Allkorn association started in the 1990s as a participatory plant breeding project, and consists of Swedish farmers, bakers and hobby-growers with an interest for organic cultivation of landrace cereals. The regional networks were either groups formed within Allkorn, or were centred around mills, which provide contracted farmers with seeds. The seeds in the Allkorn collections either originated from the Nordic Gene bank (NordGen), from European farmers or landrace collections, or from Swedish farmers that have persisted in using landraces. The seeds were collaboratively stored in a community seed bank, and were propagated by the involved farmers and hobby-growers themselves. The seeds could either be shared in formal distribution from the Allkorn collections, or through informal exchange between farmers (see Figure 16). This exchange system can be regarded as a seed commons, where resources – the seeds – are exchanged.

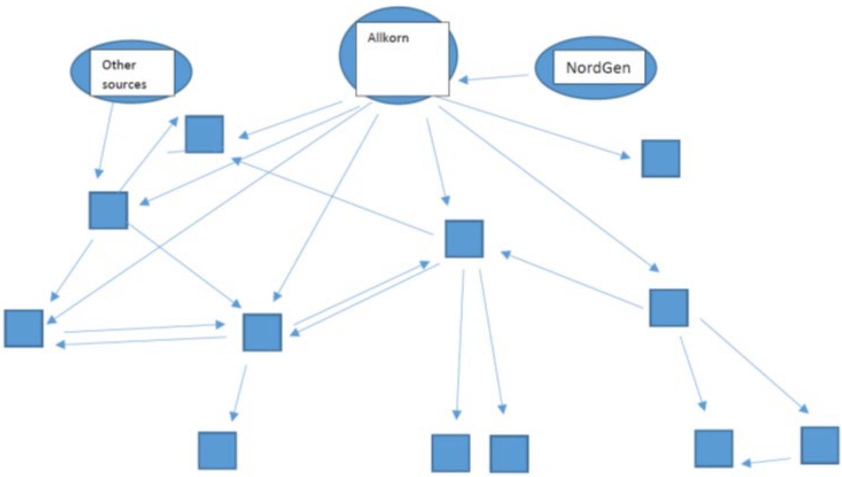

Figure 16. An illustration of the landrace seed exchange in Sweden described in paper IV. Each blue box represents a farm. Observe that some farms are only receivers, while others both receive and give seeds away to other farms more or less actively.

4.4.2 Norms and knowledge within the seed commons

When the seeds are shared within the seed commons, it is not only the actual seed that is exchanged, but also an associated collection of norms and knowledge of how the landraces should be cultivated. Farmers with long experience of landrace cereal production, and who were engaged in the seed networks, often grew several landraces and acted as a kind of seed and knowledge hub. These farmers became mentors for new farmers, and conveyed a set of normative principles for the cultivation. The results of this study show that these norms were focused on low-input organic management, free seed exchange and diversity both in the landraces and in the entire farming systems. These norms were based on the farmers' experiences of the agronomic properties of the landraces, and became a way of keeping the landraces associated with "outstandingly" organic practices and values (see paper I), with low-input levels, circular farming systems with animal manure and with diverse crop rotations. The landrace seed exchange was partly a response to the circumstance that the modern varieties provided by the ordinary formal seed system did not fulfil the needs of these organic farmers. The seed exchange was described as a way to gain control of the available seeds, and of receiving and developing varieties adapted for the local farm conditions. In addition, it is a way of controlling that the seeds are only shared to farmers that are going to cultivate them in accordance to the norms of low-input organic management. The free seed exchange envisioned by the farmers in this study was therefore a free seed exchange with other farmers who share the same values and who have similar types of farming systems, not a general free seed exchange.

4.4.3 Seed legislation

The seed legislation at the time of the study limited the amount of seeds that were exchanged. Landraces are considered to be conservation varieties under the seed legislation 2008/62/EC (Batur et al. 2021). If the landraces are not registered as conservation varieties, the only seeds that can be legally exchanged are small batches within networks. Consequently, the seed commons in this study were in a legal grey zone. The seed exchange was accepted by Swedish authorities; from their perspective it acts as an in-situ conservation of important genetic resources, and fulfils the requirements for the exceptions in the legislation– namely exchange of small amount in closed networks. Some of the most engaged farmers in Allkorn express concern that the restrictions on the amounts of seeds that can be exchanged will lead to genetic erosion of the landraces: a loss of diversity within the landraces and thereby loss of important traits, through genetic drift. Instead, they would prefer a freer seed exchange that allows for sale of larger quantities of landrace seeds between farmers. Our investigations have shown that no Swedish farmers had registered any landraces of cereal as a conservation variety at the time of the study, and that farmers considered registration problematic, since the landraces are too heterogeneous and dynamic to fulfil the requirements for a conservation variety. A large genetic diversity was perceived as a key trait of landraces by the farmers, e.g. because it contributes to the ability of landraces to adapt to local conditions. Thus, making the landraces less heterogeneous was not considered desirable. Allowing exchange of larger quantitates of heterogeneous landraces and evolutionary mixes, so called modern landraces, was instead seen as a way forward, and as a measure to enhance genetic diversity of the landraces.

4.4.4 Seed management and health:

Since the seeds exchanged within the seed commons are organically cultivated, the farmers have limited access to seed treatment. Seed borne diseases are a relatively widespread problem, for example common bunt, Tilletia tritici syn. T. caries (Figure 17) which could reduce the value of the harvest grain to nothing. The more experienced farmers state that they make sure to instruct new farmers in seed management, such as rinsing, testing and treating the seeds if possible. Seed management is thus integrated in the norms that are conveyed in the seed commons. Inadequate seed treatment and exchange of infected seeds were described as a risk for the entire landrace cereal cultivation.

Farmers' experiences of common bunt

Common bunt is a widespread problem among the farmers. The more experienced farmers strongly underline the need to practise proper rinsing and storage of the landrace seeds, combined with regular testing of the seeds at labs. If a variety is infected by pathogens, the only alternative in the farmers' experience (due to lack of organic seed treatments) is to select a number of healthy ears, and propagate the healthy genotypes by a reselection of the variety. This is a set-back for the cultivation, and it might take several years of re-selection before the farmers have enough to sow larger areas and sell the products. Certain Swedish landraces have been abandoned to a greater or lesser extent because of the high level of infection in the seeds. Some of the farmers with relatively short experience of landrace cereal production state that they have very little knowledge about seed borne diseases, for example bunt, and that they never or seldom test the seeds for other diseases.

Figure 17 Examples from the farmer's descriptions of landrace cereal management: problems with common bunt (*Tilletia tritici* syn. *T. caries*)

The options for seed treatment have long been very limited for farmers who save their own seeds, and because of this, seed treatment is not commonly used. However, recent developments have opened up for more options for organically certified treatment of small units of seeds (e.g. from private farmers and not only for larger seed companies), for example biological treatment or heat-treatment of the seeds.

5. Discussion

5.1.1 Farmers' motivations for cultivating landraces – potential of landrace cereals for organic farming

An important motivation for farmers to use landraces was shown to be related to a perception that landraces are suited to their type of farming system, either for organic management, or for more challenging environmental conditions (Paper I). Systems like organic farming which use ecological principles are often regarded as well suited to maintaining production in harsher environments (Ahmadzai et al. 2023; Csikós and Tóth 2023). Farmers specifically choose landraces since they perceive this as a way to reach ideals of "outstandingly organic" farming systems with a low degree of inputs. They specify several traits that make landraces interesting for organic or low-input systems, e.g. an ability to produce relatively high yields in conditions with low levels of available nutrients. Another common motivation for farmers was that it was at least as profitable to grow landrace cereals as modern varieties even if yields would be lower, because they could sell the products for a high price as an organic and local niche market product. According to their experiences, modern varieties have higher demands for fertilisation and other support, e.g. weed control, and are therefore more expensive to grow. Similar experiences have also been made by farmers growing landrace barley in marginal growing conditions in Scotland (Mahon et al. 2016), and emmer wheat in Turkey (Giuliani et al. 2009). In contrast to these previous studies, both the agronomic field studies and the farmer interviews in this study show that landrace cereal traits can make landrace valuable also to organic farmers located in a more favourable environment.

The farmers' interest for landraces in the present study (Paper I) can partly be seen as a consequence of the fact that the strong focus on high yields under intensive management in formal plant breeding has led to a lack of suitable plant material for organic farmers (Wolfe et al. 2008; Lammerts van Bueren et al. 2018). That the farmers' motivations are so closely linked to ideals about how landrace cereals should be managed means that these ideals also steer the management, and indeed the spread and development of the landraces. It is important for the farmers that the landraces continue to be associated with low-input organic management so that important traits are not lost, and this makes the farmers restrictive in their seed exchange, sharing seeds with farmers who share the same norms about farming (See paper IV).

The inability of landraces to take advantage of high nitrogen availability, as shown in paper II and in studies by e.g. Motzo et al. (2004), Ruiz et al. (2008) and Daaloul Bouacha et al. (2014), was a reason for their abandonment in the first place. However, this inability is only a problem if nutrients are readily available and cheap. In conditions with lower availability of nitrogen, e.g. on many organic farms, or on marginal lands where the yield potential is low, this could rather be an advantage. The crop does not produce more kernels than it can support with sufficient nitrogen to produce grains with high enough protein content to reach bread baking quality (Paper II; Foulkes et al. 2011). Thereby, the trait that was an important cause for their abandonment (Kingsbury 2009; Newton et al. 2009), becomes an influential motivation for farmers (Paper I).

Similarly to findings of the multifunctionality of landraces (Ficiciyan et al. 2018), the results in both the interview study (Paper I) and agronomic studies (Paper II and III) suggest that landraces of cereal can produce more values and services than grain yield. Examples are: high straw yield, good weed suppression and a higher quality of the products. These values can sometimes be the main motivation for farmers to cultivate landraces, and rather than focusing only on producing a high yield, farmers appreciate the multiple values. These values include additional ecosystem services such as the return of more biomaterial to the soil through a larger volume of straws, and weed regulation that makes it possible to use less intensive weed management (Paper I, II and III). The use of landraces can thereby support production of multiple functions at the farm, which can add considerably to the sustainability of farming systems (Garibaldi et al. 2017; Wezel et al. 2020).

5.1.2 How do environmental factors and management affect agronomic performance, weed suppression and grain quality of landrace spring wheat and rye?

The findings of this thesis indicate that landraces are particularly suited for low-input or organic practices; this has also been shown in studies by Serpolay et al. (2011) and Bocci et al. (2020). In both agronomic field studies that are part of this thesis (Papers II and III), a high degree of available nitrogen, either as a result of early season mineralisation (Paper II) or applied as fertiliser (Paper III), was associated with lower yield from landraces, compared to modern varieties in paper II and compared to fields with less application of nutrients in paper III. Indeed, many farmers describe it as "useless" to apply high nutrients to landrace cereals, or sometimes even to apply any at all, and that there is no need to give high fertilisation doses in order to reach high protein content in landrace wheat (Paper I). Instead, the farmers prioritized fertilising other crops than landrace cereal. The findings in paper II and III reflect the statements of farmers interviewed for paper I. Landrace spring wheat produced high protein levels also in non-fertilised plots (Paper II), and rye fields with low or no fertiliser application produced higher yields with a lower weed cover than when they had been fertilised. Fertilisation was associated with low yields, high weed cover and short experience of landrace rye cultivation of the farmer.

Certain landraces were also found to be good weed competitors, in particular the historical landraces Dala lantvete and Svedjeråg. According to farmers (Paper I), the weed suppressive ability of the landraces enables the farmers to apply less intense weed management strategies. The weed suppression ability seems to be partly related to high straw biomass and leaf area index (Paper II and III), traits that enable cereal crops to compete well with the weeds for light (Andrew et al. 2015). However, findings from farmers' experiences in paper I and of differences in weed suppression between landraces found in paper II, suggest that there might be allelopathic traits in some of the Swedish landraces included in this thesis study, both in the field studies and grown by farmers. These indications are partly contradicted by findings of low allelopathic ability in Swedish spring wheat landraces (Bertholdsson 2007), but in line with the well-known tendency for strong allelopathic traits in rye (Schulz et al. 2013).

The significance of farmer experience and knowledge of landrace cereals for the performance was an important finding in paper III, and in line with farmers' experiences (Paper I and IV). With e.g. a restrictive nutrient application (paper II and III) and careful seed management (rinsing, testing and treatment, see papers II and IV), the landraces could form an important part of organic or low-input systems (Paper I). An example of appropriate management could also mean not spending unnecessary resources on the landraces, e.g. fertilisation or weed management, but rather saving the resources for other crops (Paper III). Further, there is evidence that management, such as early sowing, can be more important than intervention with inputs, for example, in Bere, a Scottish landrace barley, *Hordeum vulgare* L. (Martin et al. 2010). However, farmers' knowledge of management methods that suit landraces might not be the only reason for long experience being important for landrace performance. Landraces are dynamic, and have been shown in on-farm studies to have a high ability for local adaption (e.g. Serpolay et al. 2011; Peratoner et al. 2015). The positive effect of the number of years that the farmer has cultivated a certain landrace in regard to yield, as seen in e.g. paper III, can also be an effect of local adaption of the landrace. In the analyses for paper III, the different mechanisms could not be distinguished from each other. Many farmers related that it takes a few years to succeed with a landrace, and in the interviews for paper I and IV, the farmers gave examples of local adaption of landraces. By using the first year of the spring wheat experiment as a propagation year (Paper II), the landraces had the opportunity for one year's adaption. However, the main reason for this propagation was the seed health problems, which caused the landraces to germinate at a considerably lower rate than the modern varieties. These experiences from our experiments also put the farmers' experiences of problems with seed quality into perspective, as well as results of previously published field experiments with landraces. The low yields experienced by some farmers in new landraces the first years (Paper I), and the poor performance of landraces in field experiments (as summarised by Newton et al. 2009), could potentially be caused by low seed quality of the landraces when first introduced. Much is yet uncertain about how seed borne diseases affect seed commons of landraces, although seed borne diseases constitute a well-known problem connected to farmers' seed exchange (Pautasso et al. 2013), and this is an important subject for future research, in order to protect the landrace seed systems.

One concrete example of how the performance of landraces depends on management, is how the proportion of leys in crop rotations is linked to high nutrient content (Paper III). Leys are known to increase yields of annual crops in the rotation (Martin et al. 2020; Nilsson et al. 2023), probably mainly due to improved nitrogen supply (Nilsson et al. 2023). However, leys can also propagate arbuscular mycorrhiza and therefore lead to more opportunities for colonization of subsequent crops. This can increase plant uptake of some minerals (Khan et al. 2022; Austen et al. 2022) and potentially have positive health implications for consumers (Ryan et al. 2004). The right management can therefore be key to explaining possible nutrition advantages in the landraces. Overall, the findings that are the basis for this thesis show that the values created by using landrace cereals, such as weed suppression and high product quality indicated by protein and mineral content, are closely interconnected with some low-input and agroecological management practices (Paper II and III). This is in line with farmers' insistence (Papers I and IV) that landraces should be used exclusively in organic management in order for them to reach their full potential. Furthermore, the association between landraces and organic or low-input management expressed by farmers in this study is in accordance with FAO's view and definition of landraces that they should be used in low-input farming systems (FAO 2019).

5.1.3 Potential of landrace cereals for cultivation in harsher environmental conditions on marginal lands

Farmers stated that landraces are not only a means of finding varieties that work well in organic or low-input systems, but also that they make it possible to grow cereals for baking quality also on more marginal growing conditions (Paper I). This is in line with observations of landrace rye performance in paper III, where environmental conditions – such as production zone and landscape factors – were less important for rye performance than management related factors, especially for midsummer-sown rye or if the farmer had long experience of landrace rye cultivation. Studies where local wheat landraces are compared with modern varieties on farms with marginal land, show how landraces tend to produce similar or higher and more stable yields than modern varieties (Serpolay et al. 2011; Dawson et al. 2013). Nevertheless, in the experiments with spring wheat (Paper II), there were few differences in performance between landraces and modern varieties in response to the two different locations. Indeed, in one of the years, all varieties performed better at the location that was representing less fertile soil. This is probably because the conditions at the less fertile site were still too good, with high degrees of soil mineral nitrogen (Table 1), for the performance of the varieties to be useful as indicators on ability of varieties to resist environmental stresses. Based on the experiences from Paper II, future research concerning comparisons of responses to environmental conditions between landraces and modern varieties should use a broader gradient of sites, and include more marginal locations.

One example of a trait that enables the landraces to perform well on marginal land is the ability to fill the grain under stressful environmental conditions (Yahiaoui et al. 2014). This trait is complex, and differs depending on the limiting factor for growth (Lopes et al. 2015), but it could potentially be related to strong early growth (Yahiaoui et al. 2014), or a high straw biomass of the landraces – observed in papers II and III – which means that more nitrogen has potential to be remobilized from the straw to the grains during grain filling (Álvaro et al. 2008). Another key to parrying environmental stresses is winter hardiness, which was an important factor for rye performance (Paper III). In several published on-farm studies with winter cereal landraces, the growing conditions were so harsh that only the locally adapted landraces survived the winter (Serpolay et al. 2011; Migliorini et al. 2016). A similar connection could be discerned in the present findings (Paper III), generating many questions about how local adaption of heterogeneous populations – such as landraces – can adapt to local growing conditions and management. These traits can potentially be of considerable interest not only in order to include marginal lands in active yet ecologically sustainable agricultural production (in line with the suggestions of e.g. Grass et al. 2021), but also for adapting crop production to withstand more extreme environmental conditions caused by climate change (see e.g. Ceccarelli and Grando 2020).

5.1.4 How is landrace cereal cultivation affected by landrace seed exchange, management and legislation?

This thesis is closely concerned with the genetics of the landraces, but since the subject and aims are related to agroecology rather than plant physiology, the effects of the genotype and its interactions have been investigated without connecting this to the actual genomics. Indeed, the genetic diversity of the landrace material used in the studies is surmised, based on phenotypical heterogeneity and former studies of similar populations, and not on actual investigations. However, this study gives rise to questions for future genomic research about the effect of genetic diversity in landraces, and interactions with environment and management factors, e.g. about local adaption of landraces (Paper III), allelopathic traits (Paper I and II) and the effect of small seed sample size for the diversity of landrace populations (Paper IV). A main result of this thesis is that the traits of landrace cereals are closely interconnected with farmers' management and the environments in which the landraces are grown. The results thus support and explain previous research (Camacho Villa et al. 2005; Desclaux et al. 2008; Casañas et al. 2017). Through the investigations in this thesis, it has been shown that under certain management or in certain environments, the landraces can provide multiple values that can be of much use for farmers (Paper I, II and III). However, under other management or environmental conditions, e.g. high nitrogen availability (such as in the experimental environment Ekhaga 2021 in paper II), the landraces are failing to produce as much as modern varieties. An implication of these results is that landraces suit organic or low-input farming, and should probably not be used in conventional or more intense organic farming systems.

The investigations of landrace seed exchange in Sweden (Paper IV) provide new insights and add to the understanding of the concept of seed commons as described by e.g. Sievers-Glotzbach et al. (2020) and Mazé et al. (2021). One key finding was that it was not only seeds that were exchanged, but also a set of norms regulating the practice in the form of knowledge about how to cultivate the landraces. The norms consisted of a set of ideals for how landrace cereals should be grown: organic and low-input, with a high degree of diversity in the crop material and in the farming system as well – e.g.

diverse crop rotations, lines of production and sale channels. These norms were shared by farmers together with the seeds, often by more experienced farmers who acted as a form of seed- and knowledge hubs or mentors. Interestingly, the degree of mentorship, access to these types of knowledge-hub farmers, was an important factor for the performance of landrace rye in the on-farm rye study (Paper III).

One concrete instance where the management is potentially affecting the landraces' genetic diversity involves the current restrictions on landrace seed management. The current regulations of landrace seed exchange restrict the farmers' seed exchange to small batches (see paper IV), which can cause genetic erosion and loss of genes (Ellstrand and Elam 1993) and actually reduce landraces' genetic diversity. Genetic drift, potentially through the small sample sizes that were saved in the gene banks, has been found to decrease the genetic diversity of Scandinavian landraces (Hagenblad et al. 2012). The present legislation can therefore pose a threat to the genetic diversity of the landraces and their associated traits. Consequently, to avoid this, the seed regulations could be opened up for exchange of larger quantities. Another factor that can affect the genetic display of the landraces is the use of evolutionary mixes (Döring et al. 2011). Evolutionary mixes have been described as a promising way forwards for organic plant breeding, in order to cope with challenges such as climate change, through dynamic responses to changing or challenging conditions, because of the large genetic diversity in the populations (Bocci et al. 2020; Ceccarelli and Grando 2020). In our material, there are indications that the historical landraces have traits that the present evolutionary landraces do not share to the same degree, such as winter hardiness in the landrace Svedjeråg compared to more recent material including evolutionary mixes of winter rye (Paper III), or weed suppression in historical landraces of spring wheat (Paper II). These findings highlight the continued need to preserve historical landraces, and to keep up the development and improvement of evolutionary mixes with special attention to traits among the included varieties, as suggested by Wuest et al. (2021).

6. Conclusions

In this thesis the performance of landrace cereals, both in terms of yield and other ecosystem services, has been studied in a transdisciplinary approach using both quantitative and qualitative methods. The findings of Paper I show that farmers who grow landraces were motivated by a perception that landraces have traits which suit certain types of management, specifically low-input organic farming, or low-input farming on marginal lands. Furthermore, farmers were motivated by the market opportunities for landrace cereal products. Therefore, high baking quality and nutrient content were important for them rather than high yields. Landraces of spring wheat outperformed modern varieties at low and medium nitrogen availabilities in the field experiment presented in Paper II, by producing similar grain yields and baking quality but in addition also providing higher straw yield and better weed suppression ability than the modern varieties. There were no differences in response to fertilisation, but in one of the environments, where initial soil mineral nitrogen was unusually high, the landraces were outyielded by the modern varieties, indicating that landraces perform best under low-nitrogen conditions. The findings from the on-farm study presented in Paper III show that management factors are crucial for landrace rye performance, and partly also of importance for the product quality in terms of mineral content. Skilful crop management can, moreover, enable landrace rye to perform well also under marginal environmental conditions. These results show that the performance of landrace cereals is dependent on knowledgeable farmers who manage and develop the landraces in a way suitable both to the landraces and to the local farm environment. Landrace seed exchange in the seed commons, which is the focus of Paper IV, was shown to be closely associated with certain norms, focused on low-input organic farming and enhancing agrobiodiversity. The landraces are formed by the norms about how to manage them, but also by legislation putting restrictions on landrace seed sharing.

Based on the findings from this thesis, it is possible to conclude that landrace cereals show interesting crop traits that can contribute to making agriculture more sustainable. Examples of such traits are weed suppression, nitrogen use efficiency at low-input conditions and yield stability, even under more challenging environmental conditions. Furthermore, this study shows how the traits of landraces are closely intertwined with the management of the farmers that use them, the knowledge, experiences and motivations of these farmers, as well as the seed regulations and market opportunities for the cultivation. A recommendation based on the findings of this thesis is that for supporting the cultivation of landraces and more heterogeneous plant materials, knowledge on management practices as well as support in seed exchange and landrace development should be made available for farmers by supporting farmer networks, and through collaborations between farmers, advisors, researchers and agricultural authorities. By continued development, and by maintaining the association with low-input and ecological management practices, landrace cereals have a potential to contribute to future sustainable crop production.

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Popular science summary

Landraces are plant varieties with an historical origin, which were abandoned as part of the agricultural development during the 20th century. However, do these varieties have traits that can be of use in today's farming and in the future? Farming is under high pressure: the changing climate and extreme weather makes crop production more challenging. To handle climate change and other environmental and societal challenges, farming needs to become more sustainable, and rely less on high inputs of for example pesticides and mineral fertilisers. There is a need to find plant varieties that can cope with tougher and more variable growing conditions, and low-input management. In this context, landraces – often adapted to harsher climates or less intensive management – can contribute. In this thesis, the potential of landrace cereals (for example landrace wheat and rye) to contribute to making farming more sustainable is investigated.

An important point of departure was to talk to farmers with experiences of actually growing landraces. The practical knowledge from these farmers has been used to design field experiments and other studies, and also to understand and discuss the findings. In the first part of this study, when interviewing farmers growing landraces in Sweden, it was found that landrace cereals are grown since they suit organic farming, especially for low-input management or if the farms had poor soil conditions – e.g. in more forested regions and not on the fertile plains of Sweden. The farmers also valued the landraces' ability to provide other advantages besides yield; for example suppressing weeds, producing a high and stable protein content and high straw yields. The latter could either be used for livestock bedding or for mulching back into the soil to improve the soil quality.

When landrace spring wheat was compared to modern varieties in a field experiment, in the second study of this thesis, the landraces produced equal

yields to modern varieties when the levels of soil nitrogen were low. However, when nitrogen levels in the soil were high, the landraces were outyielded by the modern varieties. This is in line with farmers' experiences, and shows that landrace spring wheat should primarily be used in low-input organic farming. In the experiment, the landraces produced a high yield of straw, high protein levels, and the two landraces Dala- and Ölands lantvete competed well with weeds; all of which are traits of substantial relevance for organic farmers. In another study, landrace rye was followed throughout the growing season in the farmers' own fields, a so called on-farm study. The farmers' management and knowledge about growing landraces proved to be important factors for the success of the rye cultivation, while the environmental conditions – like climatic and landscape variables – were of less importance. The midsummer sown landrace Svedjeråg "Swidden rye" was seen to be especially robust. In addition, it had a high level of nutrient content.

In the final part of the study, the seed exchange in Sweden was investigated in more detail, since this is the main source for obtaining landrace seeds. It was found that landrace seeds are shared by farmers in collectively managed seed commons, which exist outside the established seed market. An important part of these commons was to share norms and knowledge on how to grow, manage and share the seeds in an organic and low-input way. The main overall conclusion of this thesis is that landrace cereals have potential for contributing to organic or low-input farming, and can thereby be a part of making farming more sustainable and robust to future challenges.

Populärvetenskaplig sammanfattning

Lantsorter av spannmål, eller kulturspannmål som de också kallas, är växtsorter med historiskt ursprung, som slutade odlas som en del av jordbruksutvecklingen under 1900-talet – men har dessa sorter egenskaper som kan vara till nytta i dagens och framtidens jordbruk? Jordbruket idag är under stor press: klimatförändringar och det extremväder som det för med sig kommer göra växtodling mer och mer utmanande. För att hantera klimatförändringar och andra miljö- och samhällsutmaningar behöver jordbruket bli mer hållbart och mindre avhängigt av höga nivåer av insatsmedel som till exempel kemiska växtskyddsmedel och konstgödsel. Det finns ett behov av att hitta växtsorter som klarar tuffare och varierande odlingsförhållanden och mindre intensiv skötsel och i sammanhanget kan lantsorter – som ofta är anpassade till sämre odlingsförhållanden och extensiv skötsel – bidra. I denna avhandling undersöks potentialen hos lantsorter (till exempel vete och råg) att bidra till att göra jordbruket mer hållbart.

En viktig utgångspunkt var att prata med lantbrukare som hade erfarenhet av att faktiskt odla lantsorter. Dessa lantbrukares kunskaper om hur det är att odla lantsorter har använts för att utforma fältexperiment och andra studier, och även för att förstå och diskutera resultaten av studierna. I den första delen av denna avhandling, som baseras på intervjuer med lantbrukare som använder lantsorter i Sverige, visade det sig att lantbrukare använder lantsorter eftersom det fungerar bra i ekologisk odling, speciellt på gårdar som använder mer extensiva odlingsmetoder eller på gårdar med dåliga odlingsförhållanden – t.ex. i skogsbygder utanför någon av de svenska slättbygderna. Lantbrukarnas uppskattade också lantsorternas förmåga att producera fler värden utöver skörd, till exempel att ogräskonkurrens, ett högt och stabilt proteininnehåll och hög halmskörd. Halmen kunde antingen användas till strö eller djurfoder, eller för att plöjas ner och därmed främja jordhälsan.

När lantsorter av vårvete jämfördes med moderna sorter i ett fältexperiment i den andra delstudien i denna avhandling, visade lantsorterna liknande skörd som moderna sorter när halterna av markkväve var låga, men när kvävehalten i jorden var hög, gav lantsorterna sämre avkastning än moderna sorter. Detta är i linje med lantbrukarnas erfarenheter och visar att lantsorter av vårvete främst bör användas i extensiv ekologisk odling. I försöket gav lantsorterna hög skörd av halm, höga proteinhalter och de två lantsorterna Dala- och Ölands lantvete konkurrerade bra med ogräs. Allt detta är egenskaper som är viktiga för ekologiska lantbrukare. I en annan delstudie följdes olika lantsorter av råg under växtsäsongen ute på lantbrukares egna åkrar, i en så kallad gårdsstudie. Vilken typ av skötsel som lantbrukarna använde, och hur mycket kunskap eller erfarenhet av att odla lantsorter visade sig vara viktiga faktorer för att lyckas bra med rågodlingen, medan miljöförhållanden – som klimat- och landskapsfaktorer – var av mindre betydelse. Den midsommarsådda lantsorten Svedjeråg var särskilt robust och hade dessutom högt näringsinnehåll.

I den sista delen av studien studerades utsädesutbyte av lantsorter i Sverige närmare, eftersom detta är den huvudsakliga källan till utsäde av lantsorter. Det visade sig att utsäde av lantsorter delas av bönder i kollektivt förvaltade utsädesallmänningar, som finns utanför den etablerade utsädesmarknaden. En viktig del av dessa sammanslutningar var att dela normer och kunskap om hur man odlar, hanterar och delar lantsorter på ett ekologiskt och extensivt sätt. De viktigaste övergripande slutsatserna i denna avhandling är att lantsorter har potential att bidra till ekologiskt eller extensiv odling, eller odling i mindre optimala odlingsförhållanden, och därmed vara en del av att göra jordbruket mer hållbart och robust inför framtida utmaningar.

Populærvitenskapelig sammendrag (Norsk, bokmål)

Landsorter av korn, eller kulturkorn som det ofte kalles, er kornsorter med historisk opprinnelse, som nesten forsvant i løpet av jordbruksutviklingen på 1900-tallet – men har disse sortene egenskaper som kan være nyttige i dagens og fremtidens jordbruk? Jordbruket er under høyt press: klimaendringer og ekstremværet som dette fører med seg, vil gjøre plantedyrking mer og mer utfordrende. For å håndtere klimaendringer og andre miljø- og samfunnsutfordringer må jordbruket bli mer bærekraftig og mindre avhengig av høye tilførsler av for eksempel plantevernmidler og mineralgjødsel. Det er behov for å finne plantesorter som kan takle tøffere og mer varierende vekstforhold og med lavere innsatsnivåer, og i denne sammenheng kan landraser – som ofte er tilpasset tøffere klima eller mindre intensiv skjøtsel – bidra. I denne avhandlingen undersøkes potensialet til kulturkorn (f.eks. hvete og rug) til å bidra til å gjøre planteproduksjon mer bærekraftig.

Et viktig utgangspunkt for avhandlingen var å snakke med bønder som hadde erfaringer med å dyrke landsorter. Den praktiske kunnskapen fra disse bøndene har blitt brukt til å designe felteksperimenter og andre studier, og også til å forstå og diskutere funnene. I den første delstudien av denne avhandligen, som bygger på intervjuer med bønder som dyrker landsorter i Sverige, ble det funnet at bønder dyrker kulturkorn siden det fungerer godt i økologisk landbruk, spesielt når bønder brukte lavt nivå av innsatsfaktorer eller hvis gårdene deres hadde dårlige jordforhold – f.eks. i skogsbygder utenfor de fruktbare slettene i Sverige. Bøndene verdsatte også andre verdier fra kulturkornet i tillegg til kornavling, for eksempel å konkurrere med ugress, ha høyt og stabilt proteininnhold og gi høye halm-avlinger, som enten kunne brukes til husdyrstrø eller til å pløye det ned i jorda og forbedre jordkvaliteten.

Når landsorter av vårhvete ble sammenlignet med moderne sorter i et felteksperiment i den andre delstudien av denne avhandligen, hadde landsortene lik avling som moderne sorter når nivåene av jordnitrogen var lave, men når nitrogennivåene i jorda var høye, ga kultursortene lavere avling enn de moderne sortene. Disse funnenene stemmer overens med bøndenes erfaringer, og viser at landsorter av vårhvete først og fremst bør dyrkes i økologisk landbruk med lave nivåer av innsatsmidler. I forsøket ga landsortene høy avling av halm, høye proteinnivåer, og de to landsorterne Dala- og Ölands landvete konkurrerte godt mot ugress, som alle er egenskaper av høy relevans for økologiske bønder. I en annen delstudie ble landsorter av rug fulgt i vekstsesongen på bondens egne åkre, i en såkalt gårdsstudie. Bøndenes skjøtsel og kunnskap om dyrking av landsorter viste seg å være viktige faktorer for å lykkes med rugdyrkingen, mens miljøforholdene – som klima- og landskapsfaktorere – var av mindre betydning. Den midtsommersådde landsorten Svedjerug var spesielt robust, og hadde i tillegg høyt nivå av næringsstoff.

I den siste delstudien av avhandlingen ble såkornsutvekslingen i Sverige sett nærmere på, siden dette er hovedkilden til såkorn av landsorter. Det ble funnet at såkorn av landsorter deles av bønder i kollektivt forvaltede såkornsallmenninger, som eksisterer utenfor det etablerte såkornsmarkedet. En viktig del av disse allmenningene var å dele normer og kunnskap om hvordan man dyrker, forvalter og deler landsorterne på en økologisk og ekstensiv måte. Hovedkonklusjonen i denne oppgaven er at kulturkorn har potensiale til å bidra til økologisk eller ekstensiv dyrking, eller korndyrkning i mindre optimale dyrkningsforhold, og dermed være en del av å gjøre dyrking mer bærekraftig og robust overfor fremtidige utfordringer

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I have dedicated this thesis to Sune Hjerpe at Gusseröd farm, because without him there would have been no thesis. Sune has helped me so much ever since I started working at his farm at the age of 12, a young kid halfway on the wrong track and with a need to do other things than schoolwork because of illness (my parents are neighbours to his farm so it was a quite natural thing to do, especially since I love animals). He taught me so much about farming, about wildlife: birds, insects and flowers. And most importantly, about working hard and enjoying it – but also to rest every so often, rest your hand on the hay fork and admire all the good work you have been doing, looking at the cattle enjoying their food. I never did learn properly to repair tractors or build a new roof on the barn, not having a talent for practical things – everything I build is rather lopsided - so maybe it is for the best that I have become a "desk-farmer", just working with farming in theory. But Sune also taught me so many skills that have been useful in my PhD work – thinking about the farm as a system, thinking critically and most importantly – to drink coffee! Many thanks to you Sune! Many thanks also to Leila Hjerpe, who was always there when we were drinking coffee in the farm kitchen, and who introduced me to playing folk music on the fiddle, an interest which has been enriching my life ever since.

Here, the above section is added in Swedish, for the benefit of Sune and Leila:

Jag har dedikerat den här avhandlingen till Sune Hjerpe på Gusseröd gård, för utan honom hade det aldrig blivit någon avhandling. Sune har hjälpt mig så mycket, ända sedan jag började jobba på hans gård vid 12 års ålder, en unge på glid och med behov att göra nåt annat än skolan på grund av sjukdom (mina föräldrar bor grannar så det var naturligt att hjälpa till på gården, framförallt eftersom jag älskar djur). Sune lärde mig så mycket om lantbruk, om natur: om fåglar, insekter och blommor. Och kanske viktigast om att jobba hårt och trivas med det – men också att vila då och då, vila handen mot högaffeln och se på det goda arbetet du utfört, hur kossorna äter nöjt. Jag lyckades ju aldrig riktigt lära mig att koppla traktorsläp eller reparera ladtak, för jag har inte helt talang för det praktiska – jag tror allt jag nånsin byggt har blivit lite snett, trots dina ansträngningar att lära mig att mäta ordentligt Sune. Det är nog lika bra att jag blivit en skrivbordsbonde, som bara jobbar med teoretiskt lantbruk. Men Sune lärde mig också mycket som har varit till stor nytta i doktorandarbetet – att tänka på gården som ett kretslopp, att tänka kritiskt och framförallt att dricka kaffe! Tusen tack för allt Sune! Även

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Appendix

Appendix A – Interview guide, Landrace cereal cultivation
(Translated from Swedish)

Shorter structured part:

Can you tell me more about your farm? Some background information to get us started

-How long have you had the farm? What did you do before? How is the farm owned?

-Farm size in hectares? What type of land, in hectares: forest, arable land, semi-natural pasture? (Has this changed over time? Have you bought or sold land, rented land etc.?)

-Production: Type of cultivation? Livestock? Forest? Off-farm work? Other activities on the farm?

-Approximately how much profit from the different production lines? How important part is the cereal cultivation?

-How many employees/incomes from the farm?

-Do you have any certification? Organic? What type and when did you get certified?

-How long have you grown landrace cereals?

-Generation shift/the future?

Semi-structured part – themes with follow-up questions

What is your motivation with your farm?

What motivates you to run the farm the way you do? Has that changed over time?

How would you like your farm to look in the future? Dreams and visions?

Why do you grow landrace cereals?

Why are you growing landraces and not a modern variety?

Why did you start growing landrace cereals?

How does the landrace cereal cultivation fit into your business model with the farm, and vision of what your farm should look like? And in society in general?

Experiences of landrace cereal cultivation:

- Different landraces: How many landraces do you grow? How many hectares per year? Has this changed over the years? Why?
- Soil: What are your soils like? How does that affect your management?
- Soil preparation: What type of methods are you using for soil preparation? What type of machinery?
- Fertilisation: Strategy - What type? How much? Problems with lodging? Differences in response between landraces and modern varieties?
- Weeds – Strategy – what weed management? What type of weeds do you have problems with? Differences in response between landraces and modern varieties?
- Plant health – diseases? Pests? What type of strategy? Differences in response between landraces and modern varieties?
- Yield – approximate yields, differences in response between landraces and modern varieties? What determines the yield of landrace cereals?
- Other management – sowing density, crop rotation strategy etc
- Seeds – where did you get the landrace seeds from? How do you treat it? Do you exchange it with other farmers? How do you get new landraces?
- Selling the product- what channels? Prices? Consumer contact? How does this influence what landraces you grow?

I

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Farmers' motivations for landrace cereal cultivation in Sweden

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ABSTRACT

The interest in landrace cereals, i.e. genetically diverse varieties with historical origin, has increased in recent decades. While several studies exist on farmer's motivations to grow landraces in a Global South context, investigations are much less common in the Global North. Through an interview study with 32 Swedish farmers that cultivate landrace cereals on a commercial scale, farmers' motivations to grow landrace cereals were explored. The farms in the study ranged from medium sized to large. The majority were located in areas with marginal agricultural land and less fertile soil. All farms sold the landrace cereals at advantageous prices as niche products and all except one were certified organic. The farmers' motivations for growing landraces were grouped around three themes: i) sustainable farming systems; ii) suitable agronomic traits; and iii) economic incentives. The first and overarching theme was that cultivation of landrace cereals fitted well with the farmers' ideals on sustainable farming, with for example less intensive weed control and novel intercropping systems, as well as enabling production of wheat with baking quality on marginal agricultural land. Cultivation of landrace cereals was framed in contrast not only to conventional farming, but also to 'conventionalised' high input organic farming. The farmers regarded producing and marketing landrace cereals as an important foundation for more sustainable and multifunctional farming and food systems. This reflected the farmers' perception of a lack of modern varieties suited for these systems as well as the ability of landraces to buffer risks of crop failure on marginal land.

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Introduction

For more than a century, agricultural systems have been developed to produce large amounts of food at low economic costs. Over the last 60 years, average farm size has increased in high- and medium-income countries (Lowder et al. 2016), and farmers have become increasingly efficient in meeting the demand for cheap and abundant food for an increasing population (Pretty et al. 2010). This development has been mirrored in plant breeding, resulting in high-yielding varieties dependent on high input levels (Newton et al. 2009). More recently it has become politically accepted that agriculture urgently needs to change in order to meet challenges such as climate change (IPCC 2014, 2021) and loss of biodiversity (IPBES 2019; Willett et al. 2019), while at the same time taking socioeconomic perspectives into account (Garibaldi et al. 2017). To meet these multiple challenges,

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farmers have been encouraged to grow more climate resilient crops (IPCC 2014) and to diversify their cropping systems (Zimmerer 2010). In this context, landraces – heritage varieties characterised by a high genetic diversity and a lack of formal plant breeding (Camacho Villa et al. 2005) - can contribute with valuable traits. Landrace cereals generally yield less than modern cereal varieties, but they have been shown to provide acceptable yields under marginal conditions, i.e. conditions characterised by low resource availability and low yields, and under extreme weather conditions (Newton et al. 2009; Yahiaoui et al. 2014). Crop robustness will be increasingly important in the light of climate change (IPCC 2014; Lopes et al. 2015; Migliorini et al. 2016), and maintaining crop genetic diversity has been pointed out as a key to future food security (Esquinas-Alcázar 2005; Swarup et al. 2021).

During the 20th century, landraces were increasingly abandoned in the Global North, including in Sweden, as the availability of external inputs, such as mineral fertilisers and pesticides, increased. Plant breeding was able to provide farmers with genetically homogenous cereal varieties that were well adapted to high levels of input, had high yield potential (Kingsbury 2009; Newton et al. 2009) and good pathogen resistance, for example against different rust diseases such as *Puccinia triticina* and *Puccinia striiformis* (Smale 1997). In the European Union, crop varieties were standardised and the exchange of heterogeneous seeds prohibited (Batur et al. 2021).

However, the last twenty years have seen a renewed interest in the cultivation of landrace cereals in Europe (Veteläinen et al. 2009), and the EU seed regulations have opened up for restricted landrace seed exchange on a limited scale (Batur et al. 2021). Landrace cereal products have also become increasingly popular among European consumers (Mahon et al. 2016; Wendin et al. 2020; Varia et al. 2021). They can be sold at higher prices than conventional cereal products in high and middle-income countries in the Global North (Brouwer et al. 2016; Nizam and Yenal 2020). Landrace cereals have been suggested as particularly suitable for organic farming (Wolfe et al. 2008) and for farming under low-input conditions (Bellon 2004; Van Bueren ET et al. 2011; Orsini et al. 2020). In field experiments, landrace cereals have been shown to have traits that make them better adapted to harsh environments and more extensive farm management practices than modern varieties (Newton et al. 2009; Yahiaoui et al. 2014; Ficiciyan et al. 2018). Landraces generally have large root systems making them good at acquiring soil resources (Bektas et al. 2016), and long straw making them competitive against weeds (Lazzaro et al. 2019).

In Sweden, landraces were only conserved by a few farmers and in gene banks (Leino 2017). In the 1990s, some organic farmers started using the historical landraces again, in search for varieties that suited organic farming systems (Allkorn 2023). They organised a participatory plant breeding project together with a professional plant breeder, which developed into the national seed swapping association Allkorn (Larsson 2020). In order to improve and adapt landraces to local conditions, the Allkorn farmers have recently started to use so called evolutionary mixtures in addition to the historical landraces. The mixtures are produced by combining many landraces of the same species and type, e.g. spring wheat (*Triticum aestivum* L.), which have been selected for desirable traits (ibid). After a few generations, the mixtures develop into a locally adapted population that is genetically diverse and resilient to biotic and abiotic stresses caused by adverse conditions, such as weeds, pests, diseases and drought (van Bueren ET and Myers 2012; Wolfe and Ceccarelli 2019).

What motivates farmers to cultivate landraces? There are relatively few studies describing farmers' experience of growing landrace cereals in the Global North (Raggi et al. 2021a). Landrace cultivation is still relatively common in developing countries in the Global South, despite continuous initiatives to replace landraces with modern varieties (Wattnem 2016; Fischer 2016; Atlin et al. 2017). Earlier studies from, for example, China (Li et al. 2012), Ethiopia (Abay et al. 2009; Hailu 2017), Mexico (Hellin et al. 2014), El-Salvador (Olson et al. 2012) and the Himalayan Highlands (Bisht et al. 2007) have suggested that yield and profit maximisation were not what primarily motivated farmers to cultivate landraces of cereals like tetraploid wheat (*Triticum spp*.), barley (*Hordeum vulgare* L.), sorghum (*Sorghum bicolour* L.), maize (*Zea mays* L.) and rice (*Oryza sativa* L.). Rather, the farmers appeared to cultivate landraces to minimise risks associated with harsh environmental conditions, e.g. irregular rainfall in terms of amount, duration and timing, and droughts. Specific cultural features attributed to landraces, such as family traditions and cooking preferences (ibid; Xu et al. 2014; Monteros-Altamirano 2018) were also drivers for the cultivation. Moreover, it was mainly smallholder farmers using low input strategies that were inclined to grow landrace cereals (Bezançon et al. 2009; Bellon et al. 2017), partly due to a lack of alternatives and the costs of purchasing modern cultivars and associated inputs. Finally, experiences from the Global South have indicated that women were more engaged in landrace cultivation and conservation than men (Diop et al. 2018; Nchanji et al. 2021).

There are only a few examples of interview studies investigating the motivations of the farmers to use landrace cereals in a Global North context dominated by highly mechanised agriculture. Most of the present literature on landrace cereal cultivation from the Global North deals with farming under marginal conditions with relatively small farm units. Where Italian farmers managed marginal land, some tended to prefer landrace cereal and pulses instead of modern varieties, since they experienced that the landraces had a higher yield-stability than the modern varieties (Negri 2003; Varia et al. 2021; Leoni et al. 2021). Similar results were observed by landrace vegetable growers in Romania (Maxim et al. 2020) and small-scale farmers growing landrace oats (*Avena strigosa* Schreb) and Shetland cabbage (*Brassica oleracea* L .) in Scotland (Scholten 2012). Among farmers growing landrace barley Bere in Shetland and Orkney, UK, the main motivations were opportunities to sell the crop on niche markets, the cultural values of the landrace e.g. as part of traditional recipes, and that farmers perceived the crop suitable to grow in poor soils and with low inputs (Mahon et al. 2016). It has been observed that European farmers growing landraces of cereals and vegetables were elderly, and concern has been raised that landrace cultivation might not be handed down to the younger generations (Negri 2003; Veteläinen et al. 2009; Scholten 2012; Maxim et al. 2020; Raggi et al. 2021a).

The reasons why farmers grow a certain variety are complex, and may vary from the biophysical environment of the farm, the agronomic management system or the socio-economic conditions, including market opportunities (Desclaux et al. 2008). The farmers' identities and ideals may also play an important role in the choice to cultivate landraces (ibid). An interview study with eight farmers that grew landrace cereals and pulses in Sweden suggested that the motivation of farmers to grow landraces was strongly connected to their identity as organic farmers, and to their underpinning ideals of what sustainable farming should be like (Öhnfeldt 2019). How the farmers identified themselves has been shown to be key to decisions related to cultivation and other farming practices, indeed often overriding the basic economic and biophysical preconditions of the farm (Marquardt et al. 2022). The farmers' ideals related to farming have been suggested to range from 'productivist' to 'multifunctionalist' approaches to farming (Burton and Wilson 2006), where 'productivism' is often associated with bulk production of a few crops, while 'multi-functionalism' emphasises a more diversified farming approach (OECD 2001; Woods 2011; Roche and Argent 2015) that utilises, for example, regulating and supporting ecosystem services (Garland et al. 2021).

The study reported in this article explored farmers' motivations to grow landrace cereals in a highly mechanised agricultural context. In particular, four research questions were addressed:

(1) What are the characteristics of the farms where landrace cereals are grown?
(2) What are the farmers' motivations for cultivating landrace cereals?
(3) How are these motives connected to the farmers' ideals relating to the sustainability of their farming systems, and
(4) What is the role of landraces in their strategies to achieve these ideals?

Farmers' experiences of, and motivation for, growing landrace cereals in a Global North context were investigated by a qualitative interview study with farmers growing landrace cereals in Sweden.

Materials and methods

The basis for this article was an interview study with 32 Swedish farmers who cultivate landrace cereals on a commercial scale. An important entry point for finding farmers with experience of landrace cereal cultivation was through the Swedish national seed swapping association Allkorn (Allkorn 2023). In order to meet a broad range of farmers, the study was advertised at Allkorn meetings and at seminars focused on landrace cereals. Mills and bakeries that sell products from landrace cereals were contacted, as well as agricultural advisors, in order to find farmers that grew landrace cereals. Advertisements were also put in newsletters and on social media. The snowball method was then used (Noy 2008), i.e. asking the initial informants if they knew other farmers who were growing landrace cereals. Since landrace seeds are primarily spread by farmers' seed exchange, it was possible to find farmers also in the outskirts of the landrace cereal community, e.g. those who were newer to landrace cereal cultivation, or who were not active in Allkorn.

In total, 47 farmers were identified and briefly interviewed over the telephone about their experiences of landrace cereal cultivation. The study was limited to farmers who were growing landraces on a commercial scale, and who had at least two years' experience of landrace cereal cultivation, and 10 of the 47 farmers were excluded based on these criteria. Five farmers declined to be interviewed due to the COVID-19 pandemic. The remaining 32 farmers consented to be part of the study, and were interviewed using semi-structured interviews, which took one to two hours. The first part of the interview was structured with formal questions to gain detailed information on the general farm characteristics, while the rest of the interview was organised around themes (the interview guide used is shown in Supplemental Table S1). Most interviews were carried out at the farms, except three that were held by video or telephone. In order to reach an improved understanding of the farm and the farming system, farm-walks were conducted together with the farmers. These walks included visits to both the fields and essential buildings connected to the landrace cultivation, such as storage buildings, on-farm mills and farm shops. During the walk, farmers would often bring up matters that had not been mentioned in the interview, and themes from the interview were elaborated in more depth. The farm visits were documented in field notes and the interviews were recorded and later transcribed. Some of the farm interviews were carried out with several persons, for example spouses or grown-up children that also were active in the cultivation of landrace cereals. The interviewees were anonymised using letters, and in the cases where several persons were involved in the decision-making of the farm, numbers were used in combination with the letter, e.g. Farmer X2. An additional interview was also held with the plant breeder who had a key role in founding Allkorn. The interview study was further complemented by participant observation of meetings, field walks and seminars about landrace cereal cultivation arranged by, for example, Allkorn and Sweden's national centre for artisan food Eldrimner (Eldrimner 2016). Parallel with the interview study, an on-farm agronomic study of landrace rye (*Secale cereale* L.) was conducted. Many of the farmers (25 of 32) in the present interview study grew landrace rye and were thus part of both studies. This meant that these farms were visited 5–8 times during the growing season, giving many possibilities to ask additional questions. All interviews and farm visits were done by the lead author.

The material was thematised inductively (Bowen 2016) by first classifying farmers' motivations and experiences into subcategories, which were then grouped into three major themes. The quotes from the interviews that are included in this publication were translated from Swedish to English by the authors.

Results

These are varieties that suit the way I want to farm! (Farmer M).

Farm characteristics

The farms represented in the interview study differed in terms of size and line of production but shared many other characteristics (Table 1). All farms except one were certified organic following the EU 2018/848 certification standard (European Commission 2018), the majority (22) were in addition certified with the Swedish KRAV certification (KRAV 2023), and one farmer was certified biodynamic (Demeter 2022). One of the farms was described by the farmer as 'virtually organic, but not certified'. More than half of the farmers (17) kept livestock. The landrace cereals grown by the farmers included wheat (*Triticum aestivum* L.), rye (*Secale cereale* L.), spelt (*T. spelta* L.), emmer (*T. dicoccum* Schrank ex Schübl.), einkorn (*T. monococcum* L.), barley (*Hordeum vulgare* L.), and oats (*Avena sativa* L.). In total, the farmers grew 44 different landraces of cereals (hereafter referred to as landrace cereals) on field scale. The farmers were using 2–14 different landrace cereals on a regular basis in their crop rotations. The mean number of landraces used by the farmers was four, and the most common were 'Dala' and 'Öland' spring wheat, 'Fulltofta' evolutionary winter rye and 'Svedjeråg' rye. All the farms were situated south of latitude 62 in Sweden (Figure 1), where the climate is more suitable for cereal cultivation than further north. Most of the farms (27) were located in mixed agriculture-forest landscapes, and only five were situated on the plains – the most productive agricultural areas in Sweden. Many farms (16) were located on what was described by the farmers themselves as marginal land for cereal production, e.g. with relatively poor soils. The majority of the interviewed farmers were men (34 out of 40) and the age-span of the farmers ranged from 30 to 73. The average age of the farmers was 54 years. The farm sizes varied from a few hectares to about 600 ha arable land with most farms between 30 and 80 ha. All farmers sold their landrace cereal products as niche products, either directly to consumers (20 farmers) through farm shops, farmers' markets, farmers' cooperatives focused on landrace products, or REKO-rings, or through small-scale millers that specialise in landrace cereal products (17). REKO-rings are a form of informal market place for direct sale organised by producers and consumers through social media (Daving Götberg 2018). The products were mostly sold locally, i.e. in the same county, but several farmers (10) also sold landrace cereal products outside their home county on a regular basis. Products were often sold to artisan bakers located in larger cities, or to larger mills for making special landrace cereal products. All farmers except two earned their main income from farming. Two of the participating farmers described themselves as hobby farmers, since they had retired and only cultivated small quantities of landrace cereals, but still on a commercial scale.

Motivations for landrace cereal cultivation

When analysing the farmers' motivations and experiences connected to landrace cereal cultivation, three main themes emerged; motives connected with: 1) ideals of sustainable farming; 2) agronomic properties of the landraces; and 3) economic incentives and markets for landrace cereal products (Table 2). The motivations for growing landrace cereals were often expressed as a combination of these themes, with the theme connected to 'ideals of sustainable farming' being the most prominent. This could be seen as an overarching theme. In the following sections, these three themes have been presented in more detail.

Ideals of sustainable farming

Vision of more sustainable farming systems. Many farmers, especially farmers with long experience of landrace cereal cultivation (10–30 years), described their motivations for using landrace cereals as part of their ideals about sustainable farming, often in similar ways to this farmer:

Table 1. Description of the informants and the farms in the study.

Alias	Gender	Age	Years with landrace cereals	Total farm size (ha)	Area arable land (ha)	Livestock	Main production	Channels for selling and processing of landrace cereal products
A	Woman & man	61 & 63	15	110	70	No	Cereals, apples	Farm shop, REKO (informal sale organised through social media), farmers' markets, local mill
B	Man	53	18	100	85	40 suckler cows	Cereals, beef cattle	Farm shop, REKO, Farmers' cooperative
C	Man	73	10	89	60	40–50 dairy cows	Cereals, dairy cows.	Farm shop, REKO, local grocery stores, directly to bakers. Own mill and bakery
D	Man	58	25	90	80	20 suckler cows, 4 sows	Cereals, beef cattle, pigs, potatoes, honey, rapeseed oil	Farm shop, REKO, directly to local bakers. Own mill.
E	Man & woman	40 & 40	5	150	70	50–60 dairy cows	Dairy cows, cereals	Local mill
F	Man	45	16	110	30	35 ewes	Sheep, cereals, eggs, honey	Farm shop, REKO, local mill, directly to bakers
G	Man	74	10	1,6	1,6	No	Hobby farmer, bakery	Own bakery
H	Man	61	4	80	50	130 ewes	Sheep, cereals	Local mill
I	Man	55	3	110	101	22 suckler cows, 200 ewes	Sheep, beef cattle, cereals	Farm shop and local mill.
J	Man	61	10	210	210	No	Cereals	Selling through farmers' cooperative
K	Father & daughter	67 & 40	30	80	60	No	Cereals	Farm shop, directly to bakers. Own mill.
L	Father & son	65 & 30	6	110	100	95 ewes, 20 beef cattle	Sheep, beef cattle, cereals, peas, lentils	Farm shop, local mills directly to retailers.
M	Man	42	10	1000	630	180 suckler cows	Cereals, beef cattle	Farmers' cooperative. Own mill.
N	Man	71	10	600	100	500 beef cattle	Beef cattle, cereals, cray fishing.	REKO, farm shop. Own mill and bakery.
O	Man	55	3	140	140	No	Cereals and herbs	Farm shop, local mill
P	Man & woman	43 and 43	3	140	110	35 dairy cows	Dairy, cereals	Local mill
Q	Man	39	10	260	260	Organic broiler production	Cereals, rapeseed, vegetables, off-farm work.	Local mill
R	Man	55	8	39	32	40 oxen	Beef cattle, cereals	Farm shop, directly to local bakers
S	Man	60	10	140	100	No	Cereals, vegetables, herbs, tourism, sheep	Farm shop, REKO
T	Woman	59	4	27	27	No	Cereals, vegetables, field mustard	Farm shop, REKO, directly to bakers
U	Man	70	5	8	8	No	Hobby farm	Local mill
V	Man	58	5	32	32	No	Cereals	Local mill
W	Man	58	20	370	270	No	Cereals, clover seed, peas, beans	Farm shop, REKO, farmers' cooperative. Own mill
X	Man & woman	65	30	106	70	120 ewes	Sheep, cereals	Farm shop, mills in other counties, directly to local bakers
Y	Man	59	20	95	10	35 ewes	Sheep, vegetables, cereals	Farm shop, local mill, directly to local bakers
Z	Father & son	67 & 27	10	100	100	No	Potatoes, cereals, white clover seeds	Local mills.

(*Continued*)

Table 1. (Continued).

Alias	Gender	Age	Years with landrace cereals	Total farm size (ha)	Area arable land (ha)	Livestock	Main production	Channels for selling and processing of landrace cereal products
AB	Father & son	59 & 30	3	180	120	15 suckler cows	Beef cattle, cereals	Local mill.
BB	Man	52	4	580	380	400 beef cattle	Beef cattle, cereals, off-farm work	Local mill
CB	Man	63	2	80	80	No	Cereals, off-farm work	Local mill
DB	Man	62	5	228	228	No	Cereals	Local mill
EB	Man	49	3	130	130	No	Cereals	Local mill
FB	Man	70	7	25	25	No	Cereals	Local crisp bread bakery

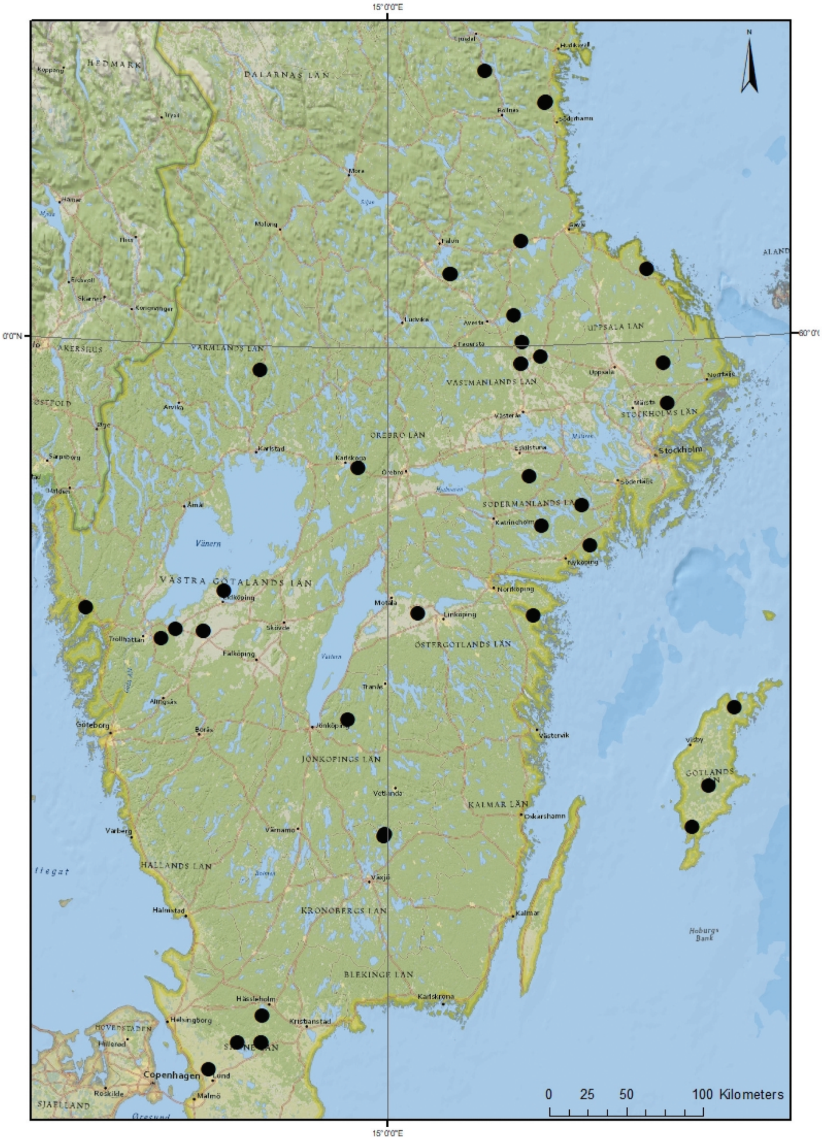

Figure 1. Approximate positions of the 32 farms in Sweden, where most of the interviews took place.

> *For me personally, one of the main drivers is to find a sustainable and resilient farming system* (Farmer W).

Most of the interviewed farmers identified themselves as wanting to be at the forefront of developing sustainable farming systems – to be 'outstandingly organic' (in Swedish: 'Spjutspets-ekologisk') was a common expression – and the cultivation of landraces was described as an important means to achieve such ambitions. All interviewed farmers stated that landrace cereal cultivation '*makes sense for organic or low-input farms*'. Many of the farmers with long experience (10–30 years) of landrace cereals had started to grow landraces when they transitioned to organic

Table 2. Three major themes for motivation and experiences of landrace cereal cultivation, with sub-categories (see text for motivations).

Ideals of sustainable farming
Vision of more sustainable farming systems
Networking
Upholding farming in marginal areas
Varieties adapted to organic practices
Conservation and development of landraces
Agronomic properties of the landraces
Low demands on nutrient availability
Prone to lodging
Low harvest index and straw production
Weed competition
Diverse crop rotations and intercropping
Tolerance to pests and diseases
Tolerance to extreme weather events
Ability to adapt to local conditions
Economic incentives and markets for landrace cereals
An increasing market for landrace products
Short value chains
A nutritious product
Exploitation of niche markets

farming in the 1990s and early 2000s. For these farmers, landrace cereals were considered as an important cash crop, and they cultivated landraces as a way to achieve more sustainable cropping systems. In this group of farmers, it was for example common to experiment with innovative intercropping strategies involving landraces, as described below in section 'Agronomic properties of the landraces'.

When the farmers presented their motivations and reasons for growing landrace cereals, they used several arguments that were connected to an alternative vision for how agriculture and the entire food system should look in the future. They described visions of farming systems with diverse crop rotations using genetically diverse landraces. A common feature for the farmers was an accepting attitude towards weeds. Having a diverse ecosystem on the farm was regarded as more important than having a perfectly weed-free field:

I sort of have nothing against weeds, acceptance is more my line (Farmer L).

The ideal farming system was depicted as circular and independent of agribusiness. Within this line of reasoning, farmers expressed ambitions to promote and act within a local food system with direct sale, with what was described by the farmers as healthy and nutritious landrace products. Farmers also often emphasised the importance of being '*a free farmer*', i.e. independent of large multinational companies. The farmers talked about growing landrace cereals as a means of reducing dependence on external inputs and developing a more circular system for nutrient supply. Such statements were often contrasted to more intensively managed organic farms, where large yields were stated to be achieved with the help of high levels of organically permitted external inputs such as pelleted meat and bone meal and chicken manure. Landrace cereal cultivation was thus mainly associated with organic and low-input agricultural systems, and the cultivation of landraces in conventional systems was described by the farmers as fundamentally wrong and in contrast to their ideals of what landrace cereal cultivation should be like.

> *I know that there used to be a farmer outside [a bigger town], he was completely conventional, sold it as landrace spelt wheat, that's just not right!* (Farmer Z1).

Networks. All farmers mentioned that growing landraces gave them networks with others who '*think along the same lines*' about sustainable farming, as one farmer stated when asked about why they started to cultivate landraces. These networks were often facilitated through Allkorn events or through regional networks for seed swapping, and by means of marketing landrace cereal products through alternative food networks. Most importantly, the farmers described the networks as a way of meeting other farmers from all over the country who have a focus on sustainability, and who cultivate organically as conscientiously as possible, something that might not always be the case in their own local farming communities.

Upholding farming in marginal areas. The farmers that were new to landrace cereal cultivation, with only about 2–3 years of experience, did not always share the vision of being at the forefront of organic farming to the same extent as the farmers who had been growing landrace cereals for a longer period of time. Some of these newcomers emphasised landrace cereal production as a way to maintain cereal production in marginal agricultural areas and to maintain farming traditions. They typically described themselves as '*ordinary organic farmers*'. The agronomic traits of the landraces combined with the increased market interest and price premia made it possible for the farmers to grow cereals on marginal lands, e.g. in areas with much forest and less fertile soils, where the arable land would otherwise be turned into forest plantations or leys. One farmer, whose farm was in a region with a large proportion of forest area, and who had recently started to grow landrace rye and spring wheat, stated the following when asked about why he started to grow landraces:

> *Well, it is certainly much more fun to be able to grow cereals here than keeping the land in ley (. . .) and keep the land in the area cultivated and in use.* (Farmer FB).

Varieties adapted to organic practices. Closely connected with the farmer's ideals of growing landraces as part of an organic and sustainable cultivation system, were arguments about the need to develop varieties adapted to organic farming practices. A common narrative from the farmers was that seed production and supply of seeds have become global assets in the hands of a few powerful multinational companies and actors, and that growing landrace cereals is a way to take back the right to cultivate one's own seeds. One direct effect of centralised plant breeding for the farmers is the lack of locally adapted varieties, and a lack of varieties adapted to organic farming conditions. The farmers explained that they propagate their own landraces, since regional and national plant breeding centres either have shut down or are focused on conventional and intensive cultivation.

> *These varieties had been mothballed for a long time, but when organic cultivation was increasing and we tried to find varieties that suited better in organic cultivation, they [landraces] became interesting again!* (Farmer X1).

Landrace propagation is in the above quote presented as a consequence of the lack of plant breeding for low-input organic systems. In a similar vein another farmer argued '*We have to take matters into our own hands and do it ourselves*'. Several farmers expressed a desire that landraces should be freely distributed and in the hands of the farmers or local organic plant breeders. The majority of the farmers (21) were engaged in participatory plant breeding through the Allkorn community gene bank (*Bruksgenbanken* in Swedish), exchanging seeds and propagating landraces together.

Conservation and development of landraces. Farmers described their perspectives on growing landrace cereals as different from the official views of the Swedish public authorities, such as gene banks and actors from governmental boards, which they claimed had a too strong conservation-oriented perspective. The farmers often described the motives of these public authority actors as focused on conserving landraces for cultural heritage, a security for the future, and as a resource to supply breeding material suited for high input conventional farming. In contrast, the farmers described themselves as active users and developers of their own landrace plant material. The farmers were not mainly interested in conserving the landraces '*just for the sake of conserving them*' (Farmer M) or '*conserving for the sake of conserving*' (Farmer B), as two farmers stated when asked why they cultivate landrace cereals. The farmers described the goal of their landrace conservation as to enable the use of the landraces in organic or low-input farming. The agronomic properties were an important motivation for growing landraces. One farmer who has grown landraces for a long time and who has propagated several landraces stated the following:

> *Conservation? No, I leave that to the state. If anyone wants me to do any conservation work, they would have to pay me. We just want to use them [landrace cereals] because they have properties that I need to farm my land in an organic way.* (Farmer A1).

A farmer who has long experience of growing many different landrace cereals and who has been involved with propagating landraces stated:

> *We are not so idealistic that we just grow them [landrace cereals] only for the sake of growing them, we want to get a living from it!* (Farmer Z2).

Agronomic properties of the landraces: experiences of agronomic traits and management

Landraces were argued by the farmers to be suitable for organic farming systems and in agreement with their ideals about sustainable farming systems, because of their agronomic traits, which were described as lacking in modern varieties. The farmers often emphasised that they were unsure whether their experiences of agronomic properties were connected only to the actual traits of the landraces, or if it was also related to how these traits interacted with how they managed their crops and the local environmental conditions on the farm. In either case, the combined effect of variety, management and environment suited their farming systems. A farmer with long experience of landrace cereal cultivation stated the following when asked about his motivations for growing landraces:

> *The most important reason for me is that the modern varieties are not adapted to the way that I want to farm, the way I want to grow crops. (. . .) I think that plant breeding has drifted away from my needs, from what I want from the crop. And that is the most important reason for me – that these [landraces] are really good for me!* (Farmer M).

Furthermore, landraces were also described as having agronomic properties particularly suitable for organic farming on marginal lands, e.g. with less fertile soil. More than half of the farms were located outside the major cereal production areas, in regions where large areas of agricultural land have been replanted with forest. They typically described their soils as not being optimal for cereal production, for example like this:

> *We don't have the land with the best growing conditions, so the landraces suit well. They are not so demanding, but still give stable yields.* (Farmer L).

The agronomic traits associated with landrace cereal cultivation were thematised under eight subcategories (Table 2), which have been further elaborated in detail below.

Low demands on nutrient availability. All farmers in the study stated that landrace cereals require less nitrogen than modern varieties, or rather that the landraces cannot take advantage of high doses of nitrogen as well as modern varieties. Most of the farmers generally applied less fertilisers to landrace cereals than to modern varieties. This enabled them to save on fertiliser costs compared to more modern conventional varieties and was especially valuable for farmers who do not have access to manure from livestock, and therefore are dependent on bought fertilisers. In the farmers' experience, using landraces is a way of growing a crop with sufficient protein levels for baking, but with less input of fertilisers. One farmer with over 20 years' experience of growing landrace wheat stated:

> *We always have a shortage of fertilisers in organic farming, and if you then can get bread wheat quality at 80–120 kg nitrogen [per hectare] it is certainly interesting, especially if you can sell it at higher prices.* (Farmer M).

Prone to lodging. The farmers described lodging as a problem when growing landraces but argued that it can be handled through appropriate management. One farmer related:

> *If we fertilise too much, well, they just lodge then – they always do that in the end, but if we fertilise less they lodge later in the season, and then it is alright, because then we can harvest and get a good yield anyway.* (Farmer L).

Many farmers described how landraces tend to bend and form 'vaults' rather than lodging flat with the straw breaking close to the soil surface, as modern varieties do. Since lodging is relatively common, many farmers have developed techniques for harvesting lodged landrace crops, for example, adapting combine settings.

Low harvest index and straw production. Most farmers had experienced lower grain yields from landrace cereals than from modern varieties. The farmers often attributed this to morphological traits of the landraces, e.g. longer straw and smaller ears and kernels of the landraces. The smaller size of the kernels was argued to be problematic, since small kernels can make the milling process difficult. Regarding the longer straw of landraces, the majority of the farmers regarded this as an advantage:

> *A wheat with longer straw is easier to raise protein levels on, in my experience. When a longer straw starts to ripen it has more to send up to the kernels.* (Farmer M).

I much rather want a longer and strong straw with a smaller ear than these short worthless ones with large ears. (Farmer D).

The experience of the farmers was that well-established landrace cereals produce more straw than modern shorter varieties. The farmers whose main income came from livestock production stated that it is critical for them to have straw for bedding and fodder. Buying straw in an area with few cereal producers can be both expensive and a logistical problem. Growing landrace cereals that give high straw yield is therefore seen as advantageous, and was by some farmers described as the main motivation for growing landrace cereals:

> *The reason that I grow this [landrace cereals]) is the straw, straw is difficult to get here and expensive . . . there are crazy amounts of straw [from landrace cereals]! If I were to grow more, I would maybe even be able to be self-sufficient on straw!* (Farmer I).

Farmers without livestock also regarded the high straw-production as positive, even though it was not a direct economic benefit to them unlike the livestock producers. The long straw can be used for mulching and fits in with the ideal described by the farmers of not taking too much from the soil and taking care of the system in a circular way. A farmer that specialises in cereal production stated:

> *We want the straw back in the ground, we want to give back as much material as possible, so we mulch down the straw, making it circular. But for us it is not a direct economic advantage to get a higher straw yield, because we don't have livestock*. (Farmer K2).

Three of the farmers in the study also used the straw in alternative ways, for example selling to artists working with handicraft, or for thatching, where the length and strength of the landrace straw is considered as an advantage.

> *The goal for us is to get straw for thatching (. . .) Rye straw is the best (. . .) it must be strong and long, preferably 1,5–1,6 metres*. (Farmer D).

Weed competition. All farmers mentioned that landrace cereals compete better against weeds than modern varieties. Farmers generally attributed this to the longer straw of the landraces that shades out the weeds. To illustrate the competitive advantage of landrace cereals compared to modern varieties one farmer paraphrased his neighbour:

> *The neighbours say about our spelt fields that 'You are out spraying the fields during night-time, you don't fool us, no one can have so weed free organic fields!' (*Farmer Z1).

Along the same line, a couple running a dairy farm in a region dominated by forest described why they chose to grow the landrace 'Dala' spring wheat and not modern spring wheat:

> *No, it would not be an option to grow modern spring wheat, we have tried that and it is too . . . weak. It hasn't got enough competitiveness against the weeds*. (Farmer P1).

Some farmers used landrace cereals as a '*weed cleaning crop'*, because of their high ability to compete for sunlight, water and nutrients. The most commonly used crop for weed cleaning was landrace rye, but sometimes landraces of spring wheat and other species were also mentioned as weed cleaning crops. Some farmers also ascribed allelopathic abilities to the landraces:

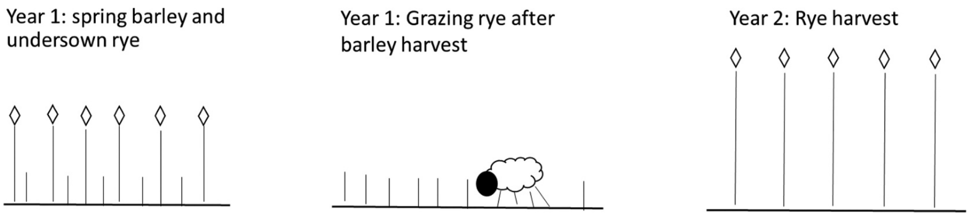

Figure 2. An example of an intercropping system with the 'Svedjeråg' rye landrace (described further in text).

> *I took over a few fields on the other side of the road that had lots of thistles, and after a few years I broke the ley and sowed Dala spring wheat – and the thistles didn't have a chance! There were a few wretches, but they kept a low profile – proper ashamed of themselves. I guess that it is like with rye, that it is something about the roots* [*of the landraces*] *that senses the weeds and make sure that the weeds don't make any mischief.* (Farmer C).

Many of the farmers experienced that the competitiveness of the landraces made it possible for them to have less intensive weeding strategies, enabling fewer mechanical weed treatments, such as weed harrowing, row hoeing or stubble cultivation between crops, than with modern varieties.

Diverse crop rotations and intercropping with landraces. A common experience was that landrace cereals provide farmers with more crop alternatives, enabling more diversified crop rotations. Having access to several landrace alternatives has encouraged farmers to experiment, both with longer and more complex crop rotations, and with intercropping. Intercropping landrace rye ('Svedjeråg') with undersown clover or ryegrass (*Lolium* spp) is a good example of an alternative management practice that is becoming popular (Figure 2). The landrace rye is commonly sown by the end of June together with the undersown crop, thus allowing an early season fallow to control weeds, but it can also be sown earlier or later – the sowing date is flexible. The rye grains are then harvested the year after sowing. According to the farmers, the rye should be grazed or cut several times during the first autumn to facilitate winter survival. The farmers that keep animals recounted that this late autumn grazing provides valuable late season livestock feed. When the rye is harvested in year 2, the forage crops remain as a well-established grass-clover ley. Some farmers have also tested the relay intercropping of 'Svedjeråg' rye with a spring sown crop, e.g. barley, spring wheat, peas (*Pisum sativum* L.) or faba bean (*Vicia faba* L.). The two crops are sown in spring and the companion crop is harvested in year 1, while the rye is harvested in year 2. These tests, inspired by traditional ways of growing 'Svedjeråg' rye, have created interest among other farmers, especially since it means '*two crops but with only one ploughing*' (Farmer D). Several of the farmers that are more specialised landrace cereal producers have also grown pulses for direct human consumption in intercropping systems, where different landraces of pulses are grown together with landrace cereals, e.g. lentils (*Lens culinari*s Medik.) with spring emmer. The landrace cereals were described as providing a higher yield than modern varieties in their intercropping system, being able to 'hold their own ground' against the pulses. However, some farmers reported that the long thin straw sometimes causes problems when intercropping with climbing species, e.g. lentils, and increases the risk for lodging of the cereal.

Tolerance to pests and diseases. The majority of the farmers in the study described landrace cereals as generally more tolerant to pests and diseases, something that the farmers attributed to the genetic diversity of the landraces. For example, one farmer with long experience of landrace cereal cultivation explained how pest and disease control worked in a landrace field:

> *Well, if you take a modern field, then it is all homogeneous. And if you then take a field with landrace cereal – they are different all of them, every grain is different, they are different individuals all of them. And if there is an intruder, some pest, aphids or whatever, then the plants cooperate, it becomes harder for the pests to find (. . .) all the kernels, and before that happened the ladybirds and others have already had time to get there, and that is how the balance works . . .* (Farmer X2).

In this quote, the farmer attributed the genetic diversity of the landraces as a way to delay pest invasions, which in combination with natural enemies in the field acts as a safeguard against serious damage. This was often contrasted against a field with modern varieties.

Sometimes other traits were described as making landrace cereals in general more tolerant to diseases. Several farmers mentioned how the long distance between the flag leaf and the ear in the landraces makes landrace cereals more tolerant to leaf spot diseases spread by spores, since the spores are less likely to reach the ear. Farmers often contrasted the tolerance of landraces towards pathogens to the more uniform modern varieties:

> *These new varieties that are developed are like clones, they all have the same genetic set up and they all have the same protection against diseases – and the same weakness.* (Farmer Z1).

Although the landraces were described as generally tolerant to pests and diseases in theory, the farmers still struggled with keeping their crops healthy. The main disease issue cited by the farmers in relation to landraces were connected to seed and soil borne diseases. Some landraces of wheat were described as impossible to grow, since they are subject to so much common bunt or dwarf bunt (*Tilletia* spp.). Farmers with long experience of landrace cereal production were worried about the spread of common bunt and other seed-borne diseases through seed exchange and pointed out seed health and seed cleaning as major challenges for landrace cereal cultivation.

Tolerance to extreme weather events. A common experience among the farmers was that landrace cereals were noted to be more tolerant to extreme weather than modern varieties. Landraces were described as hardier, and better at maintaining yield under variable conditions, than modern varieties. The farmers attributed this to traits such as deep roots, high tillering ability and most of all to the genetic diversity within the landrace. Farmers also brought up the issue of landraces being more tolerant to droughts. A common narrative was that the landraces gave normal or next to normal yields even under dry conditions, while modern cereal varieties tend to fail, as illustrated by the quotes below.

> *In 2018 yields were a bit lower – it rained almost nothing after we sowed that year, it was like a desert. Many [other farmers] didn't get a yield at all, but we had a decent yield – but it [the crop] germinated less [fewer plants emerged due to dry conditions during establishment], of course.* (Farmer BD).

> *No one got any yields to speak of 2018, and then I got 3,5 tonnes* [*landrace rye*] *without fertilising! Perfect! It is probably because – taller variety, deeper roots that can reach the water.* (Farmer I).

> *The thing is that it* [*landrace cereals*] *is possible to grow . . . we have seen that, during the last three dry years, that we still get a yield of cereal.* (Farmer X2)

> *It was very dry, and then we saw a difference between the landrace cereals and the other varieties (. . .) It [the modern varieties] grew dreadfully bad because of the drought. The landraces were relatively good.* (Farmer E1).

Local adaption and genetic diversity. The farmers commonly described genetic diversity within the landraces as an important positive trait. Many suggested that the genetic diversity enables the landraces to adapt to local conditions, which was regarded as advantageous. As a way to enhance genetic diversity, many farmers have started using evolutionary mixtures. The most widespread evolutionary mixture was autumn and spring sown rye, but in some cases, farmers have developed their own mixtures of spring wheat, emmer wheat or oats. Farmers stated that it takes three to four years for a local adaptation effect to be noticeable in the mixes. A period of three years was considered as an informal limit in the Allkorn association for when an evolutionary mix can be considered as locally adapted and can be renamed after the farm. Genetic diversity is, however, associated with challenges. The present regulations for seed exchange make it mandatory to register landraces as conservation varieties if farmers want to sell their seeds on a commercial scale. To register landraces as a conservation variety requires among other things that the varieties are uniform, which excludes most landraces from being registered. Several of the farmers regarded the new EU regulations (EU 2021/1189) that will open up for sale of organic heterogeneous material (European Commission 2021) as a positive development.

Economic incentives and markets for landrace cereals

Farmers' motivations to grow landrace cereals were also related to economic incentives. Although the agronomic properties enabled the farmers to increase the sustainability of their farming systems in line with their ideals, economic incentives and the market opportunities were described as prerequisites for farmers to start growing landrace cereals or scaling up the production.

An increasing market for landrace cereal products. The farmers in the study reported an increasing demand for landrace cereal products and many of the farmers that had recently started growing landrace cereals explained how they were motivated by the demand from consumers. Experienced growers of landrace cereal cultivation described how the interest from consumers had increased gradually over the last 20 years and how they themselves had taken an active role in creating a demand for landrace cereals among consumers and bakers, by informing them about the qualities of landrace cereals. Consumer interest in landrace cereals seemed to have begun with the cultivation of spelt:

It was that [the spelt] that started it all. And then came a sudden boom for 'Ölandsvete'. (Farmer M).

The spring wheat landrace 'Ölandsvete' was described as the starting point for the landrace cereal trend among consumers, a trend that has been increasing since around 2005:

Suddenly we started to receive a totally different kind of feedback from the customers in the farm shop. That's when the 'Ölandsvete' hype really got started . . . the customers were mad for it . . . and since the mid '00s it's just gone upwards! (Farmer K).

Short value chains. More than half of the farmers reported that they sold landrace products directly to consumers (Table 1), either as whole kernels, flour, flakes or as processed food such as bread, cakes, granola, or as vegetarian meat substitutes. The motivations for direct sale were described as economic, but also as a pride in producing a unique and premium product. Many farmers narrated how they used different marketing techniques to increase the demand for their landrace products. Selling landrace cereal products directly to consumers or to small-scale mills thus constituted an important business model for the farmers. Many farmers specialised in crop production mainly sold their landrace products directly to consumers. The specialised cereal producers had in many cases invested in drying and storage facilities at the farm, while farmers specialised in livestock production were more inclined to sell their produce directly to small agrifood businesses such as local mills. The farmers described selling to larger retailers or cooperatives as futile. Selling landrace cereal produce directly to consumers through short food chains was described as important for the farmers, and a way of motivating consumers to pay premium prices for landrace products. A couple with long experience of selling their products directly to consumers stated:

We have seen in the supermarkets that there is no point in trying to sell it [landrace cereal products] there, not unless the staff is very knowledgeable (. . .) there is an ongoing battle in the supermarkets about the space (. . .) if it just stands on the shelf and does not sell enough you are soon out (. . .) and there is no point in selling through Lantmännen (large farmer's cooperative) either. (Farmer X1).

Another farmer described:

Well, you need to sell it [*landrace cereal products*] *directly to the customers to get paid enough . . . so that's why we invested in the mill in the first place.* (Farmer C)

A nutritious product. Landrace cereals were often depicted by the farmers as being nutrient dense, in contrast to modern varieties:

These [landraces] are filled with healthy stuff, not like those conventional varieties! (Farmer B).

Most farmers, especially farmers with relatively long experience of growing landrace cereals, were convinced that landrace cereal products are healthier and have a better and richer taste than modern varieties. In the experience of many of the farmers, the landrace cereals are also well suited for artisan sourdough baking, and for traditional recipes. Several farmers stated that consumers had reported health benefits from consuming their landrace cereal products. Most of these experiences are related to consumption of emmer, einkorn or spelt wheat. Other related narratives among the farmers were that products made from landrace cereals makes you '*feel more full*' (Farmer X2) and that the products are '*more nutritious, containing more micro-nutrients*' (Farmer W). This belief was often expressed in stories that mentioned a historical decline in nutrient content in modern cereals:

> *Until the 70s the modern cereals were completely OK with regard to minerals, but nowadays you need to eat the double amount of modern wheat to get enough minerals (...) we really ought to get paid for nutrition content, if you get full at half the amount [from landrace cereal products], then you don't need so high yields. (*Farmer X2).

Many farmers said that they felt that they have a lack of knowledge about what causes the positive health experiences that their customers had told them about. They often expressed a wish that this should be investigated further in research, since scientific findings on nutritional benefits would be an advantage in communications with customers and strengthen the position of landrace cereal producers.

Exploitation of niche markets. Marketing landrace cereals as a unique niche product was important for many farmers, and some have built their entire business by portraying landrace cereal production as associated with healthy products, authenticity and being at the forefront of organic farming, i.e. communicating their ideals related to farming and food production. This positioning of landrace cereals as a unique product becomes prominent in the way some of the farmers reasoned about the size and value of their yields. Producing for a niche market makes large yields less important:

> *I don't want to maximise the yield (...) I don't need 8 t, 2 t can be enough. It is important to keep track of the market, and not dump the prices, not like those big growers ... [mentions a large organic farm]. We must keep the prices up, and make sure to tell the customers what they are paying for*. (Farmer S).

Especially the more specialised landrace cereal producers ascribed quality traits to the landraces. They argued that the landraces were healthier, as opposed to 'mass produced' cereals. In their opinion, landrace products should be sold more or less directly to the consumers as a niche product, in contrast to bulk cereal production. Farmers often positioned their products in opposition to conventional farming. They criticised conventional farming as being associated with low prices, unethical and unhealthy products, and focused on producing:

> *... as many tonnes of carbohydrates as possible (...) we want to produce high quality tasty products instead.* (Farmer W).

However, the rising demand for landrace cereals has meant that more farmers have become interested in trying out landraces. Especially the farmers that were newer to landrace cereal cultivation (2–3 years-experience) stated that they do not have time or equipment to process the cereal on the farm and sell directly to customers, nor do they have the interest to propagate new landraces from small seed samples. Instead, being able to buy larger quantities of seeds, and to sell the grains to larger companies, for example to large crisp bread bakeries, was described as a desirable scenario by some of these farmers.

Discussion

What characterises farms that cultivate landrace cereals in the highly mechanised agricultural context of Sweden? The farms in the study were mainly located in what the farmers themselves described as areas marginal for cereal production, similar to other studies of landrace cultivation in Europe (Negri 2003; Scholten 2012; Peratoner et al. 2015; Maxim et al. 2020). However, the farmers were primarily not smallholders, which is frequently the case in the literature from the Global South (Altieri and Merrick 1987; Bellon et al. 2017) and also in some instances from the Global North

(Scholten 2012; Mahon et al. 2016; Leoni et al. 2021). They were, with some exceptions, farmers with medium to relatively large sized farms, and all the farms except one were organic without this being a selection criterion. Unlike other studies from a Global North context (Negri 2003; Maxim et al. 2020; Raggi et al. 2021b), findings of this study suggested that landrace cultivation in Sweden is not primarily carried out by elderly farmers, but by farmers in all stages of their farming career (Table 2). The mean age was five years lower than the Swedish average age for farmers (Swedish board of Agriculture 2021), indicating a resurgence of a new generation of farmers who are interested in cultivating landrace cereals. The gender distribution, with a majority of male farmers, followed the pattern of Swedish cereal cultivation in general (Andersson 2014). Similar to Veteläinen et al. (2009), it was mainly organic farmers that use landrace cereals in Sweden. These farmers were not newcomers to farming as in e.g. Leoni et al. (2021), but represented a wide range of commercial organic farmers.

The farmers' motivations for cultivating landraces were shown to be closely connected to certain ideals of what sustainable farming is or should be. These ideals could be seen as the underlying and overarching motivation to grow landrace cereals. A common feature among the farmers was a vision of developing sustainable farming systems and identifying themselves as being – or at least wanting to be – at the forefront of organic farming. The farmers wanted to produce sustainable, nutritious food while at the same time provide other ecosystem services than just provisioning, ideals that have been described as typical for multifunctional farmers (see Burton and Wilson 2006). In order to attain this ideal, the farmers utilise landrace cereals in designing their farming systems, a phenomena that has been previously described in a meta-study of multifunctionality of landraces by Ficiciyan et al. (2018). The agronomic properties of the landraces were an important motivation for the farmers, forming the basis of the farmer's sustainability claims with regard to landrace cultivation. The farmers ascribed certain traits to the landrace cereals and explained how these agronomic properties provided many different and important ecosystem services to the farms. Examples of these were regulating services such as controlling weeds by competition for resources, and cultural services less commonly discussed in the literature, like flour for sourdough baking and long straw for crafts and thatching. Several of the farmers' experiences of agronomic traits of landrace cereals were in line with other experimental results, such as weed suppression (Murphy et al. 2008; Lazzaro et al. 2017), larger root biomass and water retaining ability (Bektas et al. 2016), as well as yield characteristics (Murphy et al. 2008; Konvalina et al. 2010; Diederichsen et al. 2012), while other experiences are yet to be investigated. Landrace cereal cultivation was considered as a way for farmers to develop varieties with agronomic properties suited for their way of farming. Producing varieties adapted for organic systems has long been overlooked in formal plant breeding (Wolfe et al. 2008; van Bueren ET and Myers 2012; Osman et al. 2016). In this light, the farmers in this study regarded landrace cereal cultivation as an alternative, a way for them to take control of the plant breeding and develop locally adapted landrace plants that suited their farming systems.

An important economic motivation was the opportunity for farmers to sell their cereal products through local niche markets for landrace cereal products, where landraces could be sold at advantageous prices. The farmers in the study described the market for landrace cereals as increasing, and several of them had developed business models based on landrace production, similar to what has been observed by farmers keeping native breeds of cattle (Soini et al. 2012; Ovaska and Soini 2017).

Interestingly, when farmers described their motivations for growing landrace cereals, the ideal of developing 'outstandingly organic' and multifunctional farming systems was not just contrasted against conventional agriculture, but also against the so-called 'conventionalised organic farming' (Darnhofer et al. 2009). In such descriptions of the conventionalised versus non-conventionalised organic farming, the properties of the landraces were presented by the farmers as being a more sustainable alternative than the modern varieties that are available for organic farmers. Landrace cereal cultivation was described as more in line with the IFOAM principles, i.e. the principles of Health, Ecology, Fairness and Care (De Wit and Verhoog 2007; IFOAM 2008). In contrast, the farmers positioned organic cereal production with a high reliance on bought nutrients, as conventionalised organic farming (see Darnhofer et al. 2009). Landrace cereal cultivation can in this light be regarded as a counter practice against both conventional or conventionalised farming practises (see Coolsaet 2016). The results of this study indicated that farmers wished to restrict the cultivation of landraces to low-input organic farmers, partly in order to protect their niche market.

These results contributed with perspectives on what motivates farmers in a northern European context to use landrace cereals. The crop characteristics and management practices described by the farmers can be of particular importance when developing plant material and farming systems to meet challenges such as climate change, biodiversity loss, loss of arable land, and reduced availability of effective pesticides. The study showed how different agronomic properties of landrace cereals enabled multifunctional farming practices such as novel intercropping systems, and less intensive weed management, which enabled farmers to cultivate cereals on marginal land. The agronomic properties in combination with increasing market opportunities for landrace cereal products, means that landrace cereal production can potentially generate livelihood opportunities in rural areas with marginal agricultural land, where cereals for human consumption would otherwise not be grown. In addition, utilising marginal land for food production by using crops adapted to these challenging growing conditions can considerably contribute to increased global food security.

Conclusions

This study showed how landrace cereal cultivation in a developed country like Sweden was closely associated with organic farming, and that characteristics for farms using landraces ranged from large to medium sized, and from specialised cereal producers to mixed and livestock-based farms. The farmers' motivation to grow landrace cereals was mainly based on the need for suitable varieties for multifunctional organic farming systems, which was closely interlinked with the farmers' ideals of sustainable farming. Landraces were described by the farmers as having agronomic traits that suit these systems well, although the bulk yields were generally somewhat lower than for modern varieties. The products were sold on an emerging niche market, which provided an important economic motivation. The interest in cultivating landraces can be regarded as a consequence of the lack of modern varieties adapted for low-input organic farming. The experiences of the Swedish farmers in this study illustrated how landrace crops – long believed to be outdated and obsolete – can in fact play an important role in an agroecological approach towards development of more sustainable farming and food systems.

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Landrace cereals – historical varieties with high genetic diversity – have almost completely been replaced by high yielding but high input dependent cultivars. However, the need for increased crop robustness in farming systems means a reevaluation of landraces. Through a transdisciplinary perspective, involving farmers' experiences in field experiments, the results of this thesis indicate that landraces can be a valuable resource in multifunctional farming systems and for farming on marginal lands. This can contribute to increased food security and sustainability of food production.

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