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– analysis of a long-term experiment in Northern Sweden

Växtföljdssystem med vallar – analys av ett långliggande försök i norra Sverige

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Abstract

Climate change affects agriculture all over the world and in the Northern hemisphere the change towards warmer temperatures is more rapid than other parts on the planet. As this progresses the need to produce food in a sustainable way and stabilize or increase yields is essential. In Sweden, as well as the rest of the world, the trend in the 20th centaury has been to produce large quantities of food in an intensified large-scale cropping system where a short crop rotation or monoculture has been the norm. One of the fears in agricultural research during the 1950s was what effect these cropping systems would have on soil properties and yield over time. In order to evaluate these effects, a number of long-term field experiments (LTEs) were established during the 1950-1960s. LTEs gives important information about what is beneficial for the soil and crops over time and in that way, what is beneficial for our food production. For a sustainable food production, it is crucial to know what an agricultural system should include to be resilient and sustainable over time.

In this thesis an LTE in northern Sweden, established in the 1950s with 4 different cropping systems and different 6-year crop rotations, was analysed for the effects on barley and ley yield. The results suggest that having an animal-based cropping system with longer ley-years, 5 years, reduces the depletion of soil organic carbon and produce a significantly higher yield trend for barley yield over time compared to cropping systems with 0–2 years of ley in the rotation. The results also suggest that cropping systems with shorter ley-years, 2-3 years, result in significantly higher first year ley yield trends over time, compared to a cropping system with 5 years of ley.

Keywords: yield, yield stability, crop rotation, cropping system, ley, barley, long-term experiments

Sammanfattning

Klimatförändringarna påverkar jordbruket över hela världen och på det norra halvklotet går uppvärmningen snabbare än på andra delar av jorden. Allteftersom detta fortgår blir det allt tydligare att vi måste finna lösningar för att producera mat på ett hållbart sätt och samtidigt stabilisera och öka skördarna. I Sverige och andra delar av världen, har trenden genom 1900-talet varit att producera storskaligt och intensivt med korta växtföljder eller monokulturer. För att kunna undersöka olika växtföljdssystems effekter på markförhållanden och skörd, anlades flertalet långliggande försök under 1950–1960-talet. Långliggande försök ger ovärderlig information om effekter på markförhållanden och grödor över tid, vilket i sin tur ger information om hur vi skapar en hållbar livsmedelsproduktion. I den här uppsatsen har ett långliggande försök, som etablerades på 1950-talet, som utvärderar olika växtföljders effekter på skörd för korn och vall analyserats. De fyra växtföljdssystemen hade olika långa vallår i en sexårsrotation. Resultaten antyder att ett husdjursbaserat växtföljdssystem med längre liggande vallar på 5 år har en positiv effekt på det organiska markkolet i matjorden och har en skördeökande effekt på korn över tid i jämförelse med växtföljdssystem med få eller inga djur och vall på 0–2 år. När det kommer till skörd för vall visar resultaten signifikant att växtföljdssystem med kortare vallar, på 2 år, har en signifikant skördeökande effekt på första vallåret i jämförelse med växtföljdssystem med vallar på 5 år.

Nyckelord: skörd, skördestabilitet, växtföljd, växtföljdssystem, vall, korn, långliggande försök

Kunskap om odling över tid

Världen förändras och vi måste förändras med den. Att odla med olika grödor som byter av varandra har under århundraden visat sig ha positiva effekter på skördarna och när man går ifrån denna odling ökar riskerna för att marken eroderar och att skördarna minskar. Att producera mat på ett hållbart sätt har aldrig varit viktigare än nu med klimatförändringar som skapar nya utmaningar för odlandet och matförsörjningen globalt. Vad är då ett hållbart odlande? Hur svarar vi på frågor som hur väl jorden håller kvar vattnet när det blir torka? Kommer störtregnet skölja bort matjorden eller hinner jorden suga åt sig vattnet och behålla struktur och näring? Hur påverkar olika former av gödsel marken och i sin tur skörden? Vad händer med kolet som ligger i marken när vi börjar odla? Försvinner kolet eller kan det byggas upp över tid? Och har platsen man odlar på någon inverkan på odlingen? Svaren på dessa frågor kan vi få genom att utvärdera odlingssystem över flera decennier i något som kallas långliggande försök. Över tid får vi kunskap om hur de olika odlingssystemen påverkar jordens förhållanden som i sin tur påverkar skördarna och matproduktionen.

I den här uppsatsen har jag försökt ge en överblick över odling i Norrland och odlingsforskningen som pågått och pågår där idag. För det var först på 1950-talet som en statlig forskningsanstalt anlades i Norrland med fokus på odlingssystem och växtföljder för att utvärdera effekter på jord och skördar över tid.

Kolet, som ger liv åt vår värld, försvinner i snabb takt upp i atmosfären tillsammans med andra växthusgaser som bidrar till klimatförändringarna genom våra antropogena aktiviteter. När vi börjar odla ny mark försvinner ca 20–50% av markkolet efter ca 50 år. Markkolet har en positiv effekt på skördarna för de flesta grödor vi odlar. Om kolet minskar i marken över tid minskar generellt också skördarna. Finns det då någonting som vi kan göra för att kolminskningen ska gå långsammare eller kan vi till och med öka kolinlagringen i jorden samtidigt som vi behåller eller till och med ökar skördarna? I ett långliggande försök i Norrland som startade på 1950-talet har vi några av svaren. Försöket, som anlades i de fyra nordligaste länen Jämtland, Västernorrland, Västerbotten och Norrbotten, utvärderades fyra olika odlingssystem utifrån deras olika växtföljder. Två av systemen var baserade på mjölk/köttproduktion där 5 och 3 års vall odlades till hö och silage och ingick i en sexårig växtföljd och en stor andel av gödseln kom från djuren. De andra två systemen fokuserade mer på avsalugrödor som spannmål och rotfrukter och odlade 2 år eller 0 år vall, hade mindre eller ingen stallgödsel. Alla systemen kompletterades med mineralgödsel. Det visade sig att skördarna på korn ökade över tid i systemen med 5 och 3 års vall i växtföljden. I Västernorrland ökade det organiska markkolet då man hade 5 år vall medan det långsamt minskade i alla andra växtföljder i proportion med mindre andel vall och det var likadant på alla försöksplatser. Även om kornskördarna ökade när det fanns mer vall i växtföljden så var det växtföljden med 2 års vall som gav den högsta skördeökning över tid när man jämförde första årets vallskörd mellan 5, 3 och 2 års vallar.

Det jag kommit fram till i min uppsats utifrån detta långliggande försök är att om vi vill producera mat till både människor och djur i Norrland är det bra att odla i ett djurbaserat odlingssystem med vall i växtföljden. Det ökar skördarna på spannmål, kortare vallar ger bättre skörd för vallen och det kan hålla kolet kvar i marken.

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Abbreviations

LTE	Long-term field experiment/Long-term experiment
SLU	Swedish University of Agricultural Sciences
SOC	Soil organic carbon
SON	Soil organic nitrogen
DM	Dry matter

Aim of the study

The aim of this study was to explore the published and unpublished data on yield in a long-term experiment with different crop rotations in central and northern Norrland, Sweden.

1. Introduction

1.1. The most important crops in Sweden

1.1.1. Ley

In 2019, ley covered 43% of all arable land in Sweden and in the four most northern counties Jämtland, Västernorrland, Västerbotten and Norrbotten ley covered as much as 83%, 78%, 70% and 76% respectively (JBV 2020). So, its easy to say that ley is the most important crop for farmers in the North and the same trend goes for the rest of the country. But although the percentage of land used for growing ley has been rather constant, there has been an overall decline in production of ley since

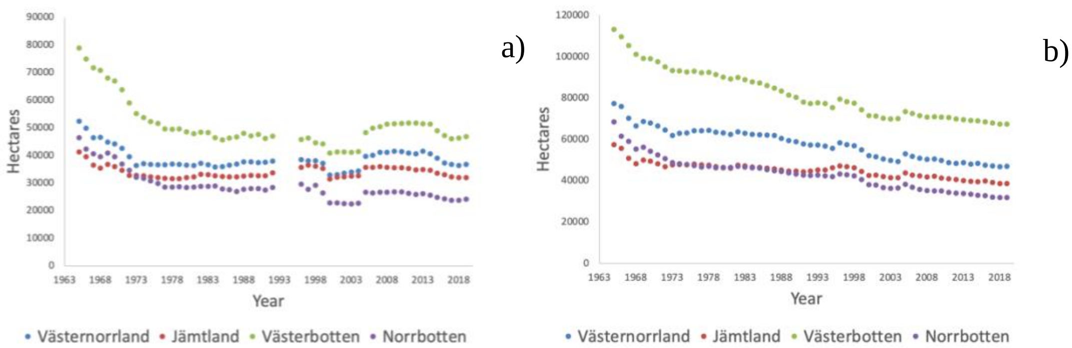


Figure 1. *Agricultural land used for a) ley production and b) total arable land between 1965-2019 for four counties in northern Sweden. For ley, no data is available for the years 1993-1995.*

the 1960s which follows the same decline in total arable land (Figure 1, JBV 2020). The use of ley is to produce fodder in the form of grazing, silage and hay for animals, mainly dairy cows and cattle, and it is also an important component in long-term rotations. Ley is a diverse crop and is composed of grasses and legumes, usually grown in a mix. There are a variety of grass species and the most common for northern Sweden are Timothy (*Phleum pratense L.*) and Meadow Fescue (*Festuca pratensis Huds.*). Legumes such as red clover (*Trifolium pratense L.*) and white clover (*Trifolium repens L.*) gives protein to the fodder and farmers may also add Bird's-foot trefoil (*Lotus corniculatus L.*) to the ley mix (Ericson 2018). Ley is a perennial crop that is cut one or two times during the season in an extensive system and two to three times in an intensive system. In the North of Sweden ley is grown between three to eight years before it is resown or sown into an annual grain, most commonly barley (Hagsand & Landström 1984; Ericson 1992). Since ley is a perennial crop, it grows during all the growing season which include spring, summer and autumn. It also gives nutrients to the soil. Legumes fixate nitrogen from the air through a symbiosis with the soil bacteria rhizobia (Wang et al. 2018; Martin et al. 2020). This symbiosis does not only give nutrients to the legume whilst it is growing but also leaves nitrogen in the soil when the plant aboveground and root biomass decomposes. When the plant residue is broken down it leads to mineralisation and the nutrients can then be taken up by the growing crops (Nkurunziza et al. 2017). Ley has an over-all positive effect on soil properties such as increasing micro and macro fauna (Jarvis et al. 2017; Wang et al. 2018), high production of root biomass leading to high carbon input (Martin et al. 2020), lower bulk density and slower decrease in soil organic carbon and nitrogen (Ericson 1992; Bolinder et al. 2010).

1.1.2. Barley

Spring barley is the third most important crop in Swedish agriculture and in the North, it is the second most important. It covers around 280000 hectares which is 11% of the total agricultural land farmed in Sweden today. Spring barley production has dropped quite substantially since 1965 when it covered 44% of Sweden's arable land (JBV 2020). In the North today, spring barley covers 9% of agricultural land, while in in 1961 it covered 22% (Figure 2). Today the crop is grown mainly as animal feed and for the malt industry, but that was not always the case: before the twenty-first century barley was almost solely grown as human food for making bread, porridge and beer (JBV 2015).

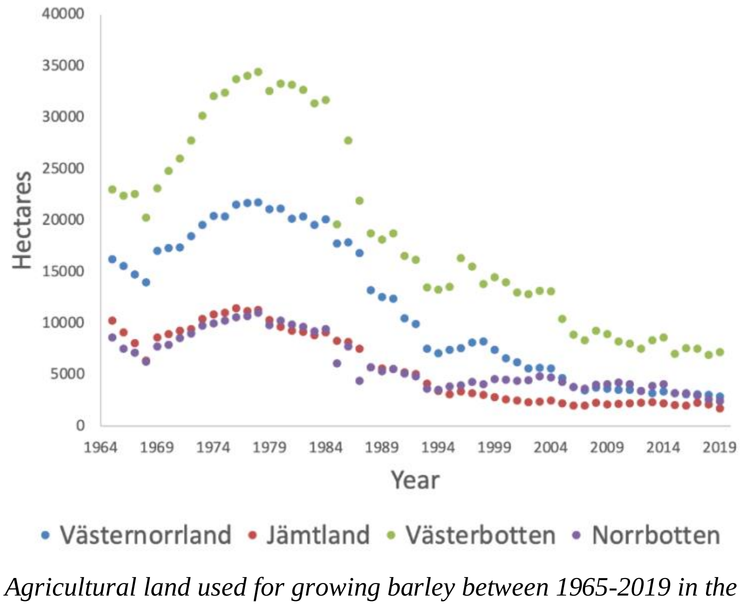


Figure 2. *Agricultural land used for growing barley between 1965-2019 in the North Swedish counties of Västernorrland, Jämtland, Västerbotten and Norrbotten.*

Barley comes in two varieties, two and six rows. The six-row barley is more favoured in the North due to its ability to grow in more acidic soils, which are sometimes more common in the north (JBV 2015). The six-row barley also matures faster than the two-row barley. This is especially important for the north where the growing season is short.

1.2. Cropping systems and crop rotation

What defines a cropping system? A system in which a crop or several crops are produced is defined by several factors. The way the soil is disturbed before and during the growing period where it can be ploughed, harrowed or managed using minimal tillage. Fertilizer strategies affect the system. Depending on if the farmer has animals and access to manure, the system can either use manure or mineral fertilizers in the system or a combination of the two to get the right nutrients for the crops. Previous cropping systems and crop rotation also affect the current system (Angus et al. 2014; Fogelfors 2015). A cropping system is also dependant on socio-economic factors. How the economy and finances are for the individual farmer and what access the farmer has to machinery, technologies and what previous experience the farmer has also affect the choices made in a cropping system as well as shifting demands from consumers (Nkurunziza et al. 2020).
Crop rotation is defined as a series of different species of crops that is grown in a sequence in the same field over time compared to monoculture where the same species are grown season after season in the same field (Fogelfors 2015). The benefits of crop rotation are many, such as higher yield for non-related species. A rotation of crop species lead to broken cycles for weeds and pathogens which leads to less use of herbicides and pesticides which in turn leads to less risks of resistance (Angus et al. 2014).

1.3. Yield and yield stability

Yield and yield stability are critical effects on how a cropping system, or a variety of a crop, performs and depending on the recipient, yield can give different information. Yield tells a breeder how a variety of a specific crop compares to other varieties at a specific site or when that variety is grown under the same conditions at multiple sites. It gives the researcher a measurement that can be evaluated in a research project such as a field experiment. Yield is dependent on many factors such as annual precipitation and temperature (climate), what soil type the field is cultivated upon, nutrient input, fertilizer strategy and timing for harvest, previous land use and cropping system (Yesmin et al. 2014; Nkurunziza et al. 2020). Depending on what species is of interest and what the recipient is going to use the

harvested crop for, the yield parameters can differ. In the evaluation of yield for barley the main yield parameters are harvested grain and straw dry matter per hectare and for ley it is the total dry matter per hectare. Another important yield factor for ley is botanical composition, where the proportions of grass, legumes and weeds gives information on nutritional value for the fodder (Damar et al. 2019).
Yield stability is defined as a cropping system that produces relatively the same amount of yield produce year after year. It can be measured as the variability in yield of one crop from one year to another (Macholdt et al. 2020).
Cropping systems become more vulnerable due to climate change – this in turn affects yield and yield stability (Macholdt et al. 2020). Studies in long-term experiments (LTEs) give important data on yield over time that can be analysed for yield stability through e.g., analysis of covariance (Damar et al. 2019) and using mixed models (Macholdt et al. 2020). Some of the studies done on yield stability in LTEs give evidence that cropping systems with diversified crop rotations have a positive effect on yield stability (St-Martin et al. 2017).

1.4. Long-term field experiments and Northern research

Long-term field experiments

Long-term field experiments (LTEs) give invaluable information on how a cropping system and all its variables affect soil and crop yield over time (Johnston & Poulton 2018). During the mid-1800s several LTEs were established in the Rothamsted estate in England. This is also where many of our modern statistical tools such as regression and analysis of variance were developed by R.A. Fisher (Johnston & Poulton 2018). Long-term experiments all over the world give information on agricultural management, cropping systems, ecology, environment and climate (Granström 1988; Johnston 1997; Marini et al. 2020). Already in the 19th centaury the Government in Sweden started to understand the importance of improving farming to stabilize and increase yields. This was due to an increasing population and several famines that took a toll on the country (Fogelfors 2015; KSLA 2020). But it was not until 1936 in Lanna, Southern Sweden, that the first LTE evaluating the interactive effect of liming (Ca) and phosphorus (P), was established. Since the 1950s and 1960s there have been many LTEs established all over the country with the aim to evaluate everything from nutrient inputs, organic versus inorganic fertilizers, soil properties, environmental effects, agricultural management to crop rotations and cropping systems (SLU 2020).

Research in Northern Sweden

In the North the first field stations were Röbäcksdalen (Västerbotten county) established in 1938 and Öjebyn (Norrbotten county) established in 1946. Crop rotation has been known to have an effect on yield and in 1954, one year after the Institution for Northern Agricultural Research was established at Röbäcksdalen, a dissertation on northern crop production by L. Agerberg stated the positive effects that previous crops had on yield and especially the effect from leys (Granström 1988). The LTE analysed in this thesis was established just after the new Field-trial section for Northern Crop production was launched in 1954, followed by the Field-trial section for questions on crop rotation in 1962 (Granström 1988). At the same time the Green revolution was conquering the world. New ways for farming with mineral fertilizers, herbicides, pesticides and new machinery made it possible to specialize farming, separating crop production and animal husbandry. These new ways raised questions on systemic effects that could affect crop yield and soil properties. By looking at data from LTEs that focus on crop rotation, important information has been revealed about the benefits of cropping systems with animal husbandry and crop rotations including ley. Benefits such as higher carbon and nitrogen stocks, less compaction and lower bulk density (Bolinder et al. 2010; Palmborg 2019) and benefits of manure on yield (Damar et al. 2019) have been identified.

If the effect of crop rotation on yield and soil properties was a hot topic in the 1950s and 1960s, the focus had shifted towards soil health in the 1980s (Granström 1988). However, today the focus in agriculture and Government has shifted once again. New aspects of food production and food sovereignty made Sweden think more about its own sensitivity and vulnerability as a food importing country. With climate change and a more unstable world every region in Sweden needs to be better prepared. In 2017, Sweden took on a national food strategy which stated that Sweden should become more self sufficiently reliable on food through increasing the food production in the whole country (Regeringen 2017). So, the pendulum swings back again to having an interest in yield and what our crops can provide.

1.5. Long-term experiment with different crop rotations in central and northern Norrland

1.5.1. Experimental design

The long-term experiment (LTE) with different crop rotations in central and northern Norrland, the Swedish north, was established in the 1950s to evaluate different crop rotations and their effect on soil and yield in the mid and most northern parts of Northern Sweden. The original design for the experiment was developed by the agronomists Erik Hagsand, Lennart Lomakka and district field managers Sven Ohlsson and Hans Skoog in March 1957 in Umeå, Västerbotten

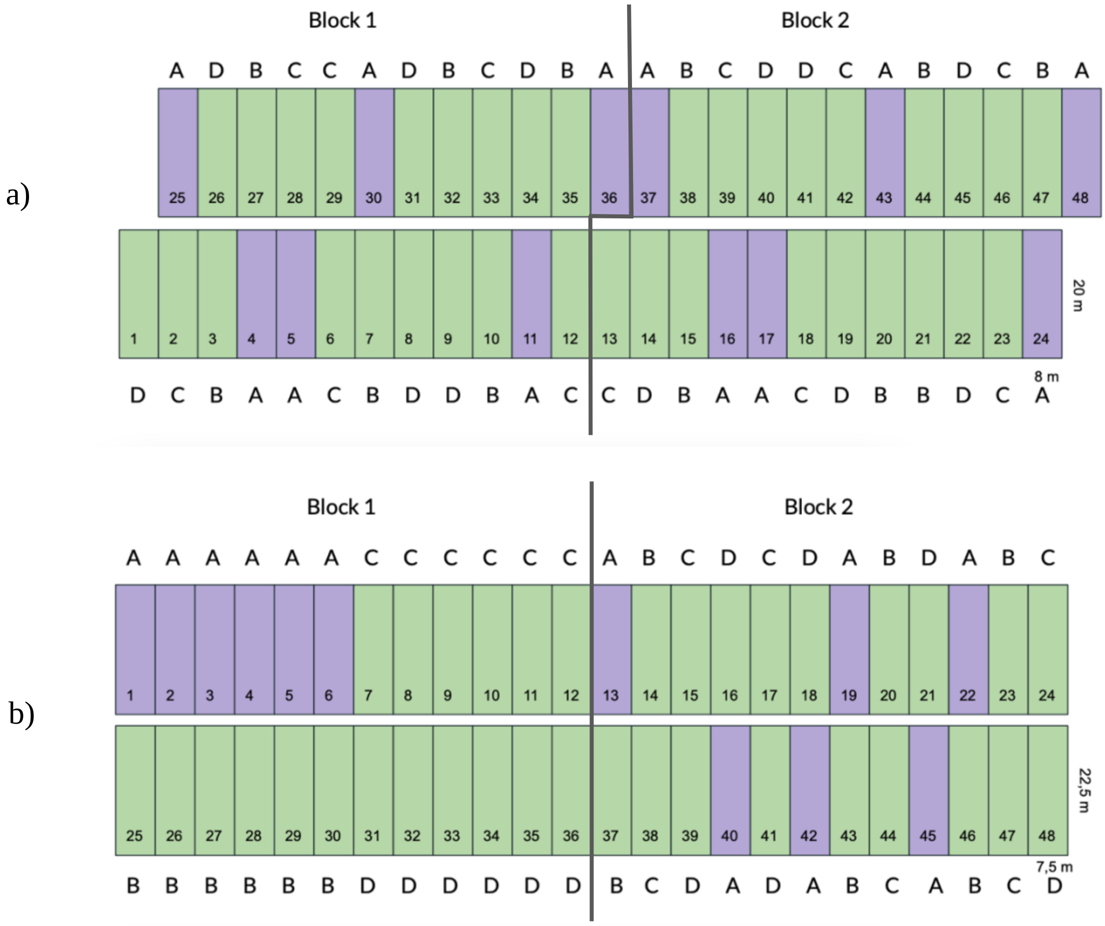


Figure 3. Experimental design in the field at a) Offer and b) Röbäcksdalen, showing the blocks, cropping systems A, B, C and D, plots and plot-size. Cropping system A is in a different colour to visualize the plot-design for the different locations. At Offer, plots 1-24 and 25-48 are not aligned in the field, as visualized in the figure.

(Hagsand et al. 1961). The sites selected were situated at Ås, in Jämtland county established 1955, Offer in Västernorrland county established 1956, Öjebyn in Norrbotten county established 1957 and Röbäcksdalen in Västerbotten county established 1958. The experimental site at Öjebyn was terminated in 1967 due to selling parts of the fields where the experiment was located, leaving three sites (Hagsand et al. 1961). The design at the field sites at the different locations all had a different plot-design (Appendix 1, Figure 3). Four cropping systems (systems) A, B, C and D, each with a six-year rotation and two replicates, were established to represent different types of farms in Northern Sweden. Systems A and B were animal-based and C and D were crop-based farms (Table 1). The crops at all locations were spring barley (*Hordeum vulgare L.*), winter rye (*Secale cereal L.*), potato (*Solanum tuberosum L.*), spring peas (*Pisum sativum L.*), spring oats (*Avena sativa L.*), spring fodder rape (*Brassica napus L.*), carrot (*Daucus carota L.*), swedes (*Brassica napus L. ssp. rapifera*) and ley. The ley composition was red clover (*Trifolium pratense L.*), timothy (*Phleum pratense L.*) and meadow fescue

(*Festuca pratensis Huds.*). The crop varieties were determined by the best fit for the region and were exchanged if a new variety with better qualities entered the market. All the systems started with barley under-sown with ley, which was the crop that the original plan intended to use for evaluating yield between all systems.

Table 1. Crop rotations for the different cropping systems (systems) A, B, C & D. In parentheses are the revised crops after 1987 [a].

	Animal based		Crop based	
Year	A	B	C	D
1	Barley undersown with ley	Barley undersown with ley	Barley undersown with ley	Barley undersown with ley
2	Ley 1	Ley 1	Ley 1	Ley as green manure
3	Ley 2	Ley 2	Ley 2	Winter rye (Barley 1)
4	Ley 3	Ley 3	Winter rye (Barley)	Peas (Potatoes 1)
5	Ley 4	Oat/pea (Barley)	Potatoes	Potatoes (Barley 2)
6	Ley 5	Forage rape (Rape+Barley+Pea)	Oat/pea (Rape+Barley+Pea)	Carrot/Swede (Potatoes 2)

[a] Hagsand et al. (1961, 1987)

Systems A and B were to constitute animal-based farms where A focused on ley for fodder, with five years of ley. System B focused on fodder with a higher value, ley for three years, one-year oat/pea-mix and one-year forage rape. Systems C and D were to constitute crop-based farms with less or no animals and more annual crop production. The crop rotation in system C was barley undersown, ley year 1, ley year 2 with one cut harvested and the second ploughed down, one year of winter rye, oat/pea mix and potatoes. System D was a cropping system without animals and had intensified annual crops with barley undersown with ley and only one year of ley as green manure (ploughed down in spring), followed by winter rye, pea, potatoes and carrots or swedes (Hagsand et al. 1961). Systems A, B and C had different amounts of manure and system D had no manure. All systems were fertilized with different amounts of mineral fertilizer (Table 2). In 1963 all sites sowed all the plots for the different rotations and data collection started. In 1967, carrots were exchanged for swedes in system D at Offer, after a rapid decline in yield for carrots at the site. Röbäcksdalen and Ås continued with carrots until 1979 before it was exchanged for swede in 1980. The original plan for the LTE was to terminate the experiment in 1986 after four rotations. In the spring of 1987, the experiment had been going on for 30 years and was revised by Erik Hagsand, Sven Andersson and Lars Ericson (Hagsand et al. 1987). The experiment was to continue but to reduce costs for future up-keep the LTE was downsized from 48 plots to 24, resulting in no replicates. Some of the plots were still sown in 1987 and 1988 with barley to measure the after effect from the crop rotation. Annual crops such as winter rye, pea, mixed oat/pea and swede were exchanged for barley, potatoes and mixed rape/pea/barley. The new crop rotation made it possible to analyse more crops between the systems such as barley after the break of different years of ley. Ley for system D was added so that all systems had both barley and the first ley year in common. From then on the focus for the experiment was the effect that the crop rotation had on soil properties (Hagsand et al. 1987). In 1994 the experiment was downsized to just one location, Offer. Today, the experiment is still running. It is administrated by the Department of Agricultural Research for Northern Sweden, SLU Umeå, and managed by Lantmännen AB at the plant breeding station at Lännäs.

1.5.2. Fertilizer strategy

Systems A and B were to constitute animal farms providing a crop rotation with fodder for dairy cows and cattle. This system therefore produces manure that would be used as fertilizer together with complementary mineral fertilizers. Both A and B added 60 tonnes of manure during the six-year rotation, which would have been the equivalent to 1 ½ cows/hectare. Cropping systems C and D were to focus more on annual crop production, with less or no manure for fertilizing the fields. System C was added with 40 tonnes/rotation and D had no manure in the strategy (Hagsand et al. 1961). All systems were fertilized with nitrogen (N), phosphorus (P), potassium (K) and boron (Table 2), which complemented the application of the different amounts of manure in the different systems and the different crops in the crop rotations. Since the locations had different soil pH levels, Röbäcksdalen and Öjebyn were limed before the experiment started to even out the differences in soil properties. If there was a need to lime soils again it was done after a rotation was completed. After 1987 the fertilizer strategy was revised. The amount of manure added stayed the same but the mineral fertilization was altered, particularly for N and K (Hagsand et al. 1987). The fertilizer strategy for the experiment per six-year rotation is summarized in Table 2 and the extended strategy can be read in detail in Appendix 3.

Table 2. Fertilizer strategy per six-year rotation [a]. The output of nutrients through harvest has not been taken into account. In parentheses is the revised fertilizer strategy after 1987 [b].

Cropping system	Manure (tonnes/ha)	N (kg/ha)	P (kg/ha)	K (kg/ha)	Boron (kg/ha)
A	60	225 (670)	95 (100)	220 (415)	2
B	60	210 (490)	100 (96)	220 (330)	2
C	40	165 (410)	115 (119)	400 (400)	2
D	0	230 (380)	145 (142)	560 (330)	2

[a] Hagsand et al. (1961)
[b] Hagsand et al. (1987)

1.5.3. Location, climate and soil properties

Map

Offer, Ås and Röbäcksdalen are all located within latitude 63 in northern Sweden. To understand how far north the locations are, the polar circle (latitude 66), is added as a reference (Figure 4).

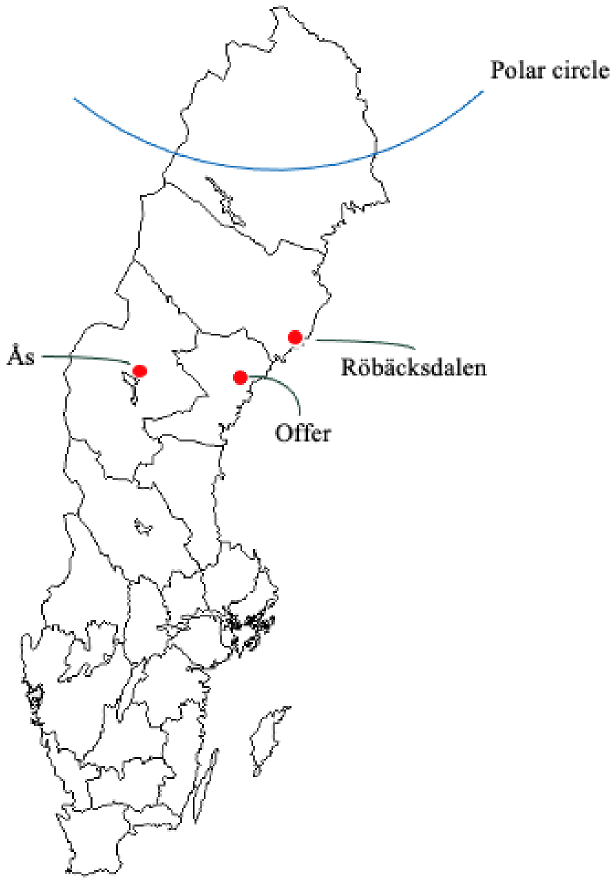


Figure 4. *Map of the experimental sites. Lines mark county boundaries.*

Location and climate

The location at Offer is in a hilly landscape close to one of Sweden's largest rivers in the county of Västernorrland. It counts as the costal region, but it is on the edge of inland climate. The soil is silty clay loam, remnants of the retracting ice sheet and sea from the latest ice age. The historical agricultural use in the area probably included forage, leys and annual grains. The average mean annual precipitation and temperature are 567 mm and 3.4 °C (Table 3).

Ås is a village close to the big lakes of the inland and mountainous county Jämtland. The climate is fast changing and can be harsh due to the fact that it lies just on the other side of the Scandic mountain ridge that harbours the North Sea outside of Norway. Around the big lake Storsjön, where Ås is located, the soil is a gravelly loam which also contain a high content of limestone. The agricultural use of the experimental site is unknown, but it was probably used as forage. The average mean annual precipitation and temperature are 490 mm and 3.6 °C (Table 3).

Röbäcksdalen lies in the costal area of county Västerbotten, not far from the Baltic Sea. The experimental site is a flat plain that used to be sea bottom and has risen over time with the isostatic land uplift. The field site was tile drained just a few years before the experiment started which meant it was newly cultivated land. The average mean annual precipitation and temperature are 566 mm and 4.8 °C (Table 3).

In Northern Sweden the annual temperature has risen from 1960s to the 21st century and annual means can be seen in Table 3 for all locations.

Table 3. Location and climate factors.

Location	Start & end of experiment	County	Latitude Longitude [d]	Precipitation [d] (mm)	Mean Temp. °C (year)	
Offer	1956-ongoing	Västernorrland	63°14N 17°75E	567	+ 2.8 [a]	+ 3.4 [b]
Ås	1955-1994	Jämtland	63°25N 14°56E	490	+ 2.9 [a]	+ 3.6 [b]
Röbäcksdalen	1958-1994	Västerbotten	63°81N 20°24E	566	+ 3.1 [a]	+ 4.8 [b]

[a] Ericson (1992)
[b] Bolinder et al. (2010) average mean temperature from 1961-2000.
[d] Zhou (et al. 2020)

Soil properties

The main publications on the LTE have been on soil physical and biological properties. After 1994 the experiment was reduced to one location, Offer, so all the data collected after 1994 has been from the Offer site. Results state that the soil organic carbon (SOC) and soil organic nitrogen (SON) decreased gradually at Offer, Ås and Röbäcksdalen in the systems A>B>C>D, meaning that at all locations system A had the highest SOC and SON content over time and system D had the lowest (Ericson 1992; Bolinder et al. 2010) (Table 4). An increase in SOC and SON over time was evident in system A at Offer (Bolinder et al. 2010) (Table 4). Bulk density increased in the following ratio A<B<C<D, and porosity decreased in the opposite ratio, meaning the soil became denser and more compacted in system D compared to systems C, B and A (Bolinder et al. 2010; Jarvis et al. 2017). The number of earthworm species and earthworm biomass also increased significantly in system A compared to C and D at Offer. System D had significantly lower earthworm biomass and species number compared to all the other systems (Jarvis et al. 2017). These findings conclude that the long-term effects of animal-based

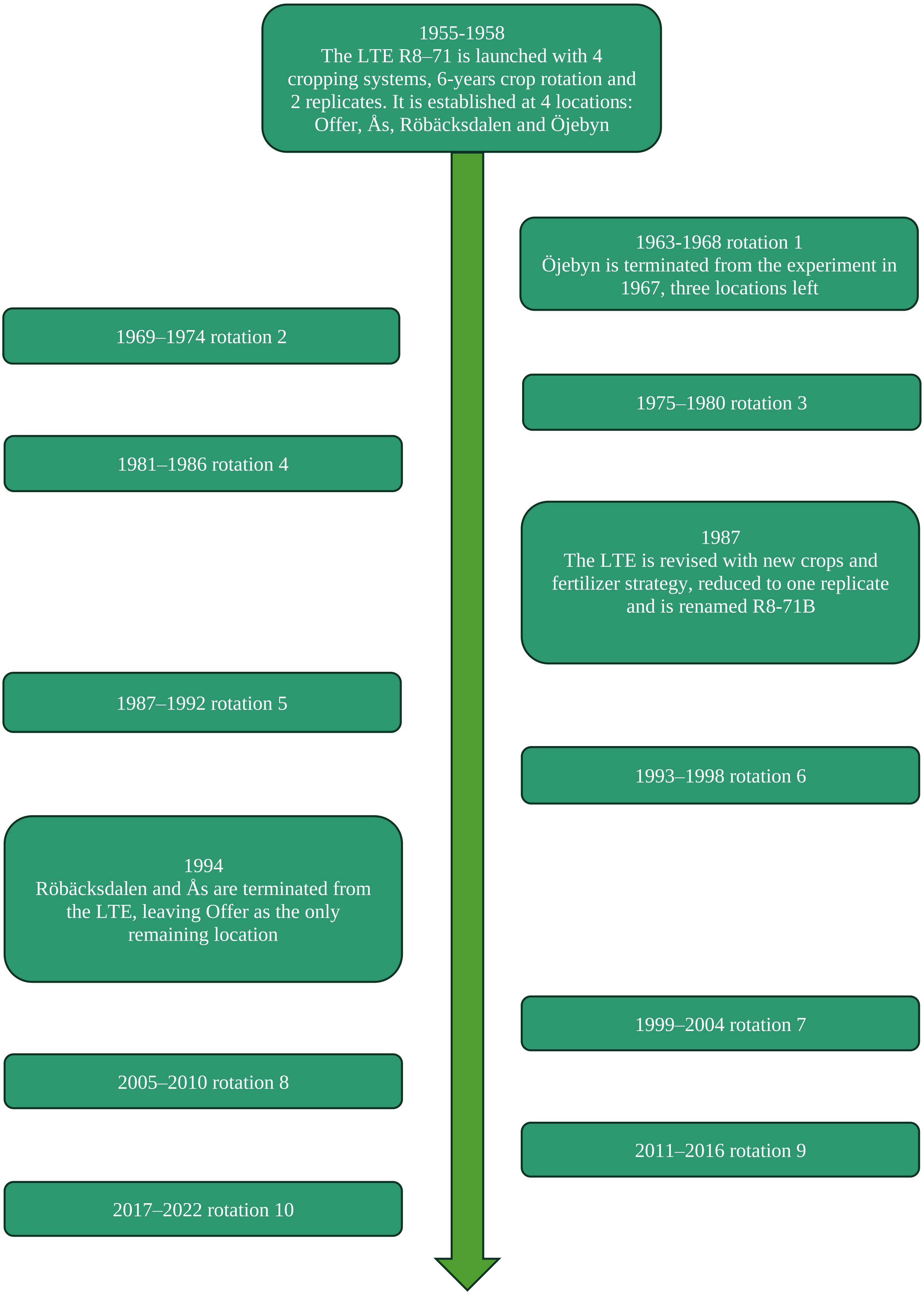
cropping systems with increasing ley years in the north have a significantly positive effect on topsoil SOC and SON, decreasing bulk density, increasing porosity and increase the populations of earthworms (Ericson 1992; Bolinder et al. 2010; Jarvis et al. 2017; Zhou et al. 2020).

Table 4. Soil properties. Pre-experiment soil carbon (C) and nitrogen (N) content at all locations and C and N content in all systems at Offer, 2008 [d].

Location	Soil texture [a]	Clay content [a] (%)	pH [b]	C (%) [a, c]	N (%) [b, c]
Röbäcksdalen	clayey silt loam	10-15	6	4.84	0.25
Ås	gravelly loam	20	6.4	3.85	0.33
Offer	silty clay loam	20-25	6	2.80	0.26
Offer				C (%) [d]	N (%) [d]
A				3.02 ± 0.55	0.28 ± 0.05
B				2.75 ± 0.24	0.26 ± 0.02
C				2.42 ± 0.31	0.23 ± 0.03
D				2.27 ± 0.17	0.21 ± 0.02

[a] Ericson (1992)
[b] Bolinder et al. (2010)
[c] Pre-experiment content
[d] Offer carbon and nitrogen content in 2008, topsoil 0–12 cm, from Bolinder et al. (2010)

1.5.5. Timeline



2. Materials and methods

2.1. Finding and controlling the data

Data from the long-term experiment was collected from the database at the Swedish University of Agricultural Sciences (SLU) and provided by the Department of Agricultural Research for Northern Sweden (NJV 2021). The initial analysis was done in Microsoft Excel to find trends that were relevant for the aim of the study and useful for analysing statistically.

Before any statistical analysis was made the data was thoroughly examined to make sure that all the data were in the right order and that all the crops and years were accounted for. To understand what to look for in a data set that is new to someone and to find eventual faults or missing data, it is important to understand the experimental design behind the data. So, the first task was to get an overview of the experiment. The process of first finding which years had missing data and then finding out what crops those years should have contained was done systematically to understand how the design was put into numbers. At all three location Offer, Ås and Röbäcksdalen there were four cropping systems (systems). Every system had a six-year rotation and there were two replicates. This generated, 4 x 6 x 2 = 48 plots per year and location. Here, the logical assumption is that there should be 48 data inputs every year for each location. However, in the dataset from SLU the most common amount of data input every year was 46. After some investigation it turned out that ley 1 for system D was not put in the database because it was ploughed down as green manure, so no measurements or analysis were done for that crop. This was also stated in the original design by Hagsand et al. (1961). The conclusion was that the input of data was reduced from the supposed 48, to 46. However, it was implicated that there was data for ley 1 in system D. Further investigation led to the revision in 1987 (Hagsand et al. 1987) where it was stated that the first cut in ley 1 should be analysed in all four systems. No data for ley 1 in system D has been found between 1963-1986. However, in the SLU database, after 1987 there is a ley for system D.

It is not so easy to see straight away what was missing from the dataset when the number of inputs were below 46. Before it was clear that barley undersown with ley, ley 1 and ley 2 were the only crops of interest for statistical analysis, the search through the data was essentially done through trying out different combinations and funnelling the columns of data by selecting a location, year and crop. There were 13 crops in the original design (Table 1). Twelve of those crops were grown every year. It was unclear why there were 13 crops and how they were grown. It turned out that carrot was grown at Offer between the start of the experiment until it was exchanged for swedes in 1967. At Ås and Röbäcksdalen carrots were grown until 1980, before it was exchanged for swedes. An example of finding data that was missing was the year of 2012 for barley undersown with ley at Offer. After some research and checking of the original excel sheet that the field-staff had compiled, there was a note saying that the barley together with most other crops had "rained away" and that the only harvest that year was for the leys. These kinds of discoveries made the puzzle become more and more whole where gaps and questions rose during the search through the data. In the end, after 1987 until today there were two years missing, 2012 and 2017, for barley undersown with ley.

After the initial controlling of the data in excel, it was clear that of the three sites Offer was the one that had most of its data put into the database between 1963 to 1986. No further investigation was made to why the other sites were missing more data. Barley, ley year 1 and ley year 2 were the crops that were used for statistical analysis. This is because they were the only crops that were consistent over time for all locations between 1963-1986 and at Offer after 1987. These crops had more or less the same fertilizing strategy which made the effect of the crop rotation in the different systems evident in the analysis on yield.

Since there have not been many publications from the LTE on yield, it was a bit of detective work to find out what data was missing or simply had not yet been put into the database. As the data was being controlled, continuous readings of published papers and experimental design was done simultaneously, comparing bits and pieces and adding them together to get a better picture of the experiment and understanding the data.

2.2. Statistical analysis

The statistical analysis was done in SAS 9.4 (*SAS Institute Inc.* 2013). Crops of interest were barley undersown with ley for systems A-D and ley year 1 and 2 for systems A, B and C. To find out if there were any effects of systems, years or plots, several models were tested to see which had the most explanatory power (Table 5). PROC MIXED for linear mixed models in SAS was used where year was a random variable and system a fixed variable. Analysing the models consisted of first looking for homogeneity of variance and normal distribution in the Conditional Residuals panel and then finding the lowest number of Akaike Information Criterion (AIC) for the best model fit. To find significance between the different systems yield slopes, which states if any of the systems had differences in the change in yield over time, the modelled estimates statements were analysed. The same analysis was used when finding significance between the contrasts A+B as animal-based farms and C+D as crop-based farms.

All models tested and the AIC-values are summarized in Table 5. Scripts/Code are provided in Appendix 2.

Table 5. Models tested in SAS 9.4 for barley and ley with AIC-values. For barley all systems were tested. In ley 1& 2 system A, B and C were tested. For ley 1 total yields were tested and for ley 2 1st harvest was tested.

					AIC values		
	Model	**Random**	**Repeated**	**Repeated**	**Offer**	**Ås**	**Röbäcksdalen**
Barley							
1	System, x, System*x	Year, Plot			2794.5	2812.7 **a**	2701.8 **a**
2	System, x, System*x	Year	Year/subject=plot	ar(1)	*	*	*
3	System, x, System*x	Year	/subject=plot	sp(pow) (x)	2794.6	2814.7	2703.2
4	System, x, System*x	Year			2792.6	2812.7	2701.8
5	System, x, System*x	Year, Plot	/group = system		2794.9	*	2702.6
6	System, x, System*x	Year/group=system, plot			2787.6 **a**	2868.7	2760.1
7	System, System*x	Year/group=system, plot			2787.6	2868.7	2756.6
8	System, x, System*x	Year/group=system			2789.0	2866.8	2758.1
Ley 1							
1	System, x, System*x	Year, Plot			2278.8	2111.0 **a**	2280.1
2	System, x, System*x	Year	Year/subject=plot	ar(1)	*	*	*
3	System, x, System*x	Year	/subject=plot	sp(pow) (x)	2277.2	2113.0	2281.2
4	System, x, System*x	Year			2276.8 **a**	2111.0	2279.2
5	System, x, System*x	Year, Plot	/group = system		2277.2	2113.0	2277.6 **a**
6	System, x, System*x	Year/group=system, plot			2346.8	2186.6	2331.8
7	System, System*x	Year/group=system, plot			2346.8	2186.6	2331.8
8	System, x, System*x	Year/group=system			2346.8	2185.8	2332.6
Ley 2							
1	System, x, System*x	Year, Plot			2254.4	2209.4 **a**	2222.8
2	System, x, System*x	Year	Year/subject=plot	ar(1)	*	*	*
3	System, x, System*x	Year	/subject=plot	sp(pow) (x)	2256.4	2211.4	2223.8
4	System, x, System*x	Year			2254.4	2209.4	2222.4 **a**
5	System, x, System*x	Year, Plot	/group = system		2288.0	*	2225.1
6	System, x, System*x	Year/group=system, plot			2240.9 **a**	2235.9	2235.9
7	System, System*x	Year/group=system, plot			2240.9	2235.9	2235.9
8	System, x, System*x	Year/group=system			2240.9	2235.5	2234.9

a Represents the best model with the lowest AIC.
* Convergence criteria met but final Hessian is not positive definite.

3. Results

3.1. Interpreting the tables and results

The results are for the analysed period of 1963-1986, which was the first part of data collection for the experiment. To interpret the result tables, explanations are provided below.

Tables 6, 8 and 10 give results for Type 3 Tests of Fixed Effects. *System(intercept)* refers to a test of differences between regression line y-intercepts. According to the null hypothesis, the systems have the same intercept, that is, the yield, y, was the same in 1963 where x = 0. Thus, *System(intercept)* determines whether any of the systems had different initial yields. *Slope* states an overall yield trend over time for the whole experiment at the location, using a single regression line for the whole data set. According to the null hypothesis, the average slope is zero. *Slope*System* provides results for the slope-by-system interaction, comparing all system-specific regression lines to each other. The null hypothesis is that the systems have the same slope. Thus, *Slope*System* determines whether any system slopes are different.

Tables 7, 9 and 11 provide results for yield when comparing systems and systems as contrasts over time. Slope ±SE are stated for the systems and are followed by letters stating significant differences. Example: if system B is followed by the same letter as system A: (A^a, B^a) then they are not significantly different. If system B is followed by two letters: (A^a, $B^{a,b}$) it is not significantly different to A, because A and B share the same letter.

The difference of initial yield (System(intercept)) seen in tables 6, 8 and 10 could be related to the initial start up-period of the experiment and might not be an experimental effect. Since initial yield was not part of the initial research questions the results for initial yield between systems are not discussed in the result section but is mentioned in the discussion.

3.2. Barley

3.2.1. Barley yields

Type 3 Tests of Fixed Effects

For Offer, there were significant trends in yield over time (Slope) and in systems over time (Slope*System). For Ås, there were significant differences in initial yield (System(intercept)) and in systems over time. For Röbäcksdalen, there were significant differences between initial yield and trends in yield over time (table 6).

Table 6. Type 3 Tests of Fixed Effects for barley yield. Numerator Degrees of freedom, Denominator Degrees of freedom, F-value and P-value at significance level 5%.

Location	**Effect**	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Offer	System (intercept)	3	47.4	0.32	0.808
	Slope	1	82.6	5.28	0.024
	Slope*System	3	46.4	3.44	0.024
Ås	System (intercept)	3	162	17.82	<0.001
	Slope	1	22	0.35	0.560
	Slope*System	3	162	10.58	<0.001
Röbäcksdalen	System (intercept)	3	152	3.65	0.014
	Slope	1	22.1	5.86	0.024
	Slope*System	3	152	1.20	0.311

Yield

For Offer, there were significant difference between yield over time – system A had a more positive slope trajectory over time compared to C and D. For Ås, system A had a significantly more positive slope trajectory over time compared to B, C and D, and system B had a significantly more positive slope trajectory compared to D. For Röbäcksdalen there was no significant difference between systems slopes (Table 7, Figure 4).

Contrasts

For Offer and Ås there were significant difference between the contrasts, A+B as animal-based farms and C+D as crop-based farms. Röbäcksdalen had no significant difference between the contrasts (Table 7).

Table 7. Results for barley yield, kg ha^{-1} DM, comparing systems slopes over time. Systems followed by the same letter are not significantly different at significance level 5%.

	Location		
System	**Offer**	**Ås**	**Röbäcksdalen**
A	60.2 (±20.4) a	22.1 (±20.0) a	-23.6 (±17.2) a
B	39.7 (±19.9) ab	-7.3 (±20.0) b	-38.7 (±17.2) a
C	-8.7 (±14.9) b	-27.4 (±20.0) bc	-47.1 (±17.2) a
D	-7.2 (±17.5) b	-32.1 (±20.0) cd	-39.2 (±17.2) a
Contrasts			
(A+B) – (C+D)	57.9 (±18.3) p = 0.002	37.1 (±7.6) p = <0.001	12.0 (±8.9) p = 0.228

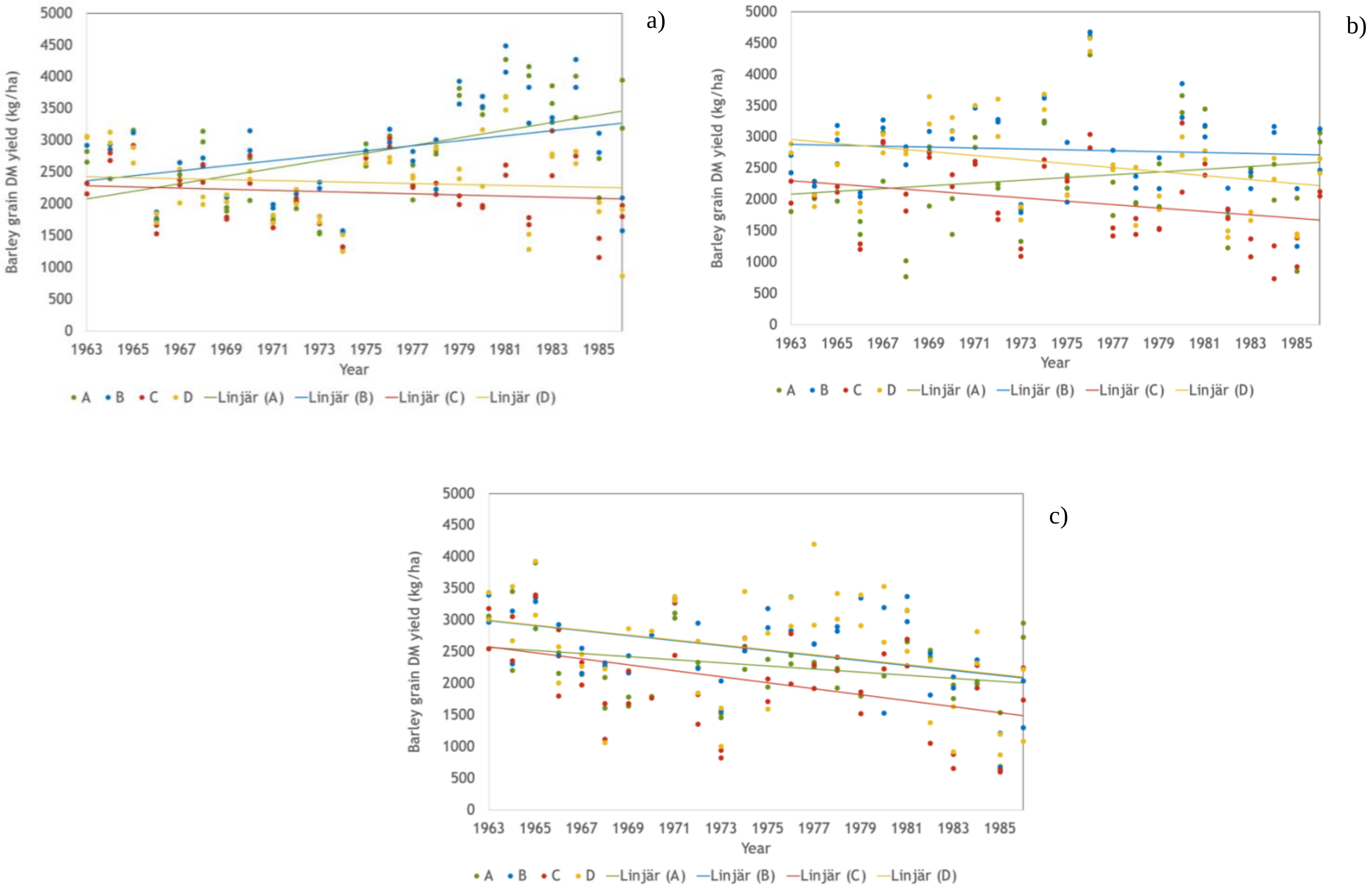


Figure 5. *Barley yield – measured data points and simple linear regression lines for a) Offer, b) Ås and c) Röbäcksdalen.*

3.2.2. Barley yield between 1987–2019

The experiment was reduced to only one replicate in 1987 and one location in 1994. All data for barley undersown with ley between 1987 and 2019 has been acquired during the work on the thesis. But due to lack of time no attempts of analysing the data for yield trends have been made.

3.3. Ley

3.3.1. Ley 1

Type 3 Tests of Fixed Effects

For first year leys at Offer, there were significant difference between systems slopes over time (Slope*System). For Ås, there were significant difference between initial yield (System(intercept)), trends in yield over time (Slope) and between systems slopes over time. For Röbäcksdalen, there were significant trends in yield over time (Table 8).

Table 8. Type 3 Tests of Fixed Effects for ley 1. Numerator Degrees of freedom, Denominator Degrees of freedom, F-value and P-value at significance level 5%.

Location	Effect	Num DF	Den DF	F Value	Pr > F
Offer	System (intercept)	2	116	0.86	0.425
	Slope	1	22	1.80	0.193
	Slope*System	2	116	3.40	0.037
Ås	System (intercept)	2	107	6.17	0.003
	Slope	1	21.8	6.65	0.017
	Slope*System	2	107	7.07	0.001
Röbäcksdalen	System (intercept)	2	69.1	2.91	0.061
	Slope	1	21.7	5.70	0.026
	Slope*System	2	62.5	0.43	0.654

Yield

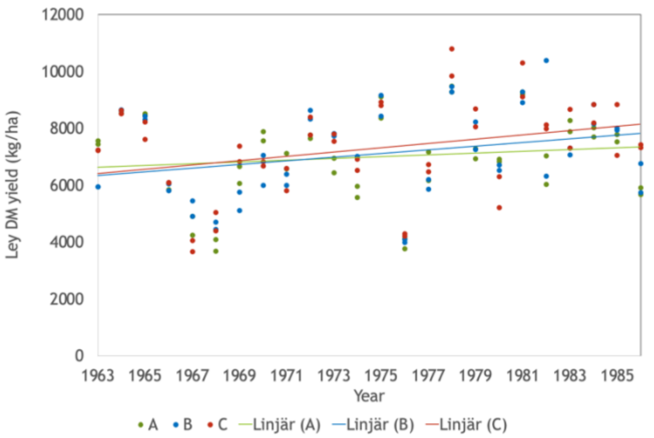
For Offer there were significant difference in system A compared to C. For Ås, there were significant difference in system A compared to system B and to system C (Table 9, Figure 5).

Contrasts

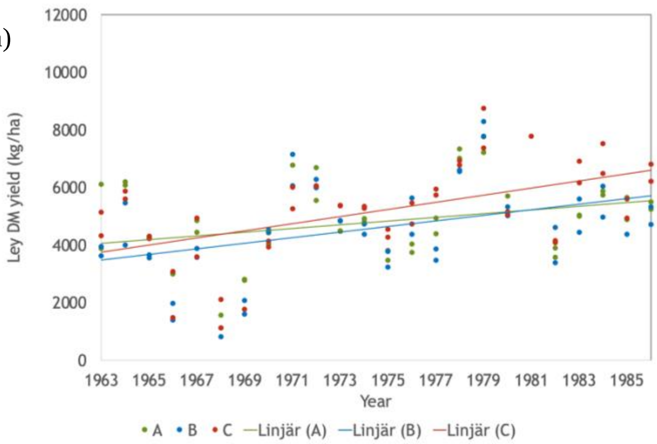
For Offer there was significant difference between the contrasts A compared to B+C. For Ås there were significant difference when comparing both contrasts A+B to C and A to B+C. For Röbäcksdalen there were no significant contrasts (Table 9).

Table 9. Results for ley 1 total season yield, kg ha⁻¹ DM, comparing systems slopes over time. Systems followed by the same letter are not significantly different at significance level 5%.

	Location		
System	**Offer**	**Ås**	**Röbäcksdalen**
A	31.0 (±43.8) a	71.4 (±41.9) a	88.4 (±42.1) a
B	64.3 (±43.8) ab	110.7 (±42.1) b	90.8 (±46.6) a
C	76.0 (±43.8) b	133.4 (±41.8) bc	112.2 (±44.0) a
Contrasts			
(A+B) – (C)	-28.3 (±15.5) p=0.07	-42.4 (±14.6) p=0.004	-22.6 (±25.8) p=0.384
(A) – (B+C)	-39.1 (±15.5) p=0.01	-50.7 (±14.5) p=0.001	-13.2 (±23.3) p=0.573



a)



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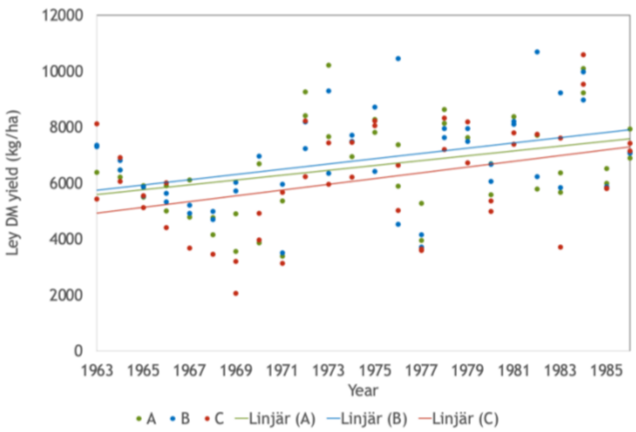

c)

Figure 6. *Ley 1 total season yield – measured data points and simple linear regression lines for a) Offer, b) Ås and c) Röbäcksdalen.*

3.3.2. Ley 2

Type 3 Tests of Fixed Effects

For the first harvest of second year leys at Offer, Ås and Röbäcksdalen there were significant differences between initial yield (System(intercept)) and for Röbäcksdalen there were significant difference for trends in yield over time (Slope) (Table 10).

Table 10. Type 3 Tests of Fixed Effects for ley 2 1st harvest. Numerator Degrees of freedom, Denominator Degrees of freedom, F-value and P-value at significance level 5%.

Location	**Effect**	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Offer	System (intercept)	2	41.7	19.55	<0.001
	Slope	1	58	2.79	0.100
	Slope*System	2	41.7	1.69	0.198
Ås	System (intercept)	2	114	29.53	<0.001
	Slope	1	22.1	3.46	0.076
	Slope*System	2	114	0.46	0.692
Röbäcksdalen	System (intercept)	2	109	11.50	<0.001
	Slope	1	21.8	6.88	0.016
	Slope*System	2	108	0.12	0.887

Yield and contrasts

For Offer, Ås and Röbäcksdalen there were no significant differences between systems or contrasts for ley 2 (Table 11, Figure 6).

Table 11. Results on ley 2 1st harvest yield, kg ha^{-1} DM, comparing systems slopes over time. Systems followed by the same letter are not significantly different at significance level 5%.

	Location		
System	**Offer**	**Ås**	**Röbäcksdalen**
A	11.8 (±23.8) a	44.9 (±28.5) a	51.2 (±28.3) a
B	-43.9 (±30.9) a	45.6 (±29.0) a	59.3 (±27.9) a
C	-59.2 (±38.4) a	59.3 (±29.0) a	65.8 (±28.2) a
Contrasts			
(A+B) – (C)	43.2 (±43.0) p=0.323	-14.1 (±14.6) p=0.338	-10.5 (±25.6) p=0.682
(A) – (B+C)	63.4 (±34.2) p=0.07	-7.5 (±14.6) p=0.608	-11.3 (±25.8) p=0.661

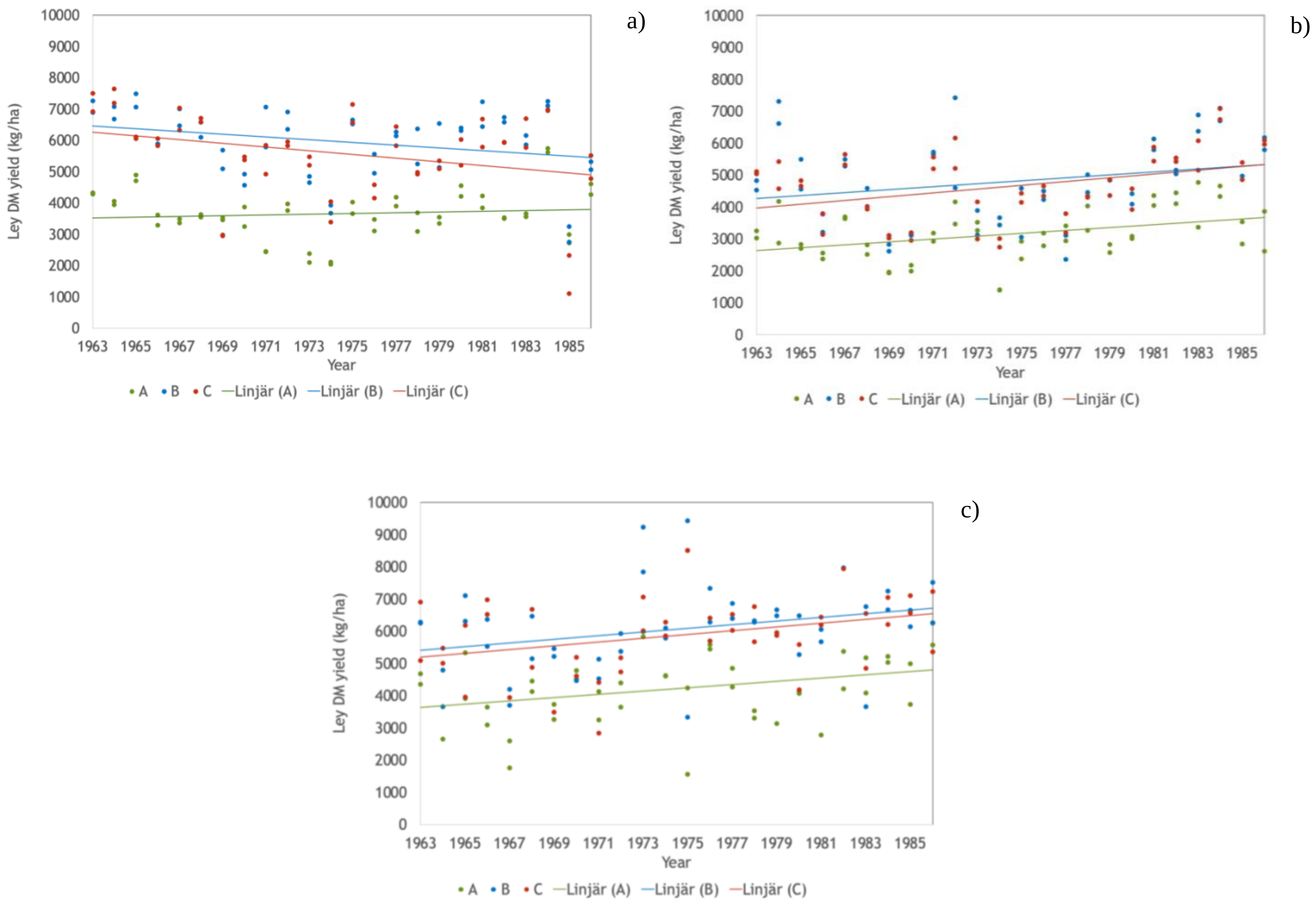

Figure 7. *Ley year 2 yield 1st cut – measured data points and simple linear regression lines for a) Offer, b) Ås and c) Röbäcksdalen.*

4. Discussion

Soil properties and locations

From a paper by Olson (2012), it is stated that forest and grassland that is cultivated or drained usually loses 20 to 50% of the top soil (15-25 cm) soil organic carbon (SOC) within 40 to 50 years. Using the information from Bolinder et al. (2010) the biggest loss of topsoil SOC between the start of the experiment and 1986 in system D was 19%, 33% and 49% for the locations Offer, Ås and Röbäcksdalen, respectively. This could be correlated to the previous use of the land that the experiment was laid upon. Offer is thought to have had more rotational crops with some grains (Hagsand et al. 1961) and it is therefore likely that that is why the SOC was lower at Offer at the initial start of the experiment compared to the other locations. In the same reasoning it is therefore also likely that the decrease of SOC was lower in Offer compared to Ås and Röbäcksdalen, because it had already decreased for some time. The previous agricultural use of the experimental site in Ås is unknown but was probably cultivated pasture which could explain that the decrease was something between Offer and Röbäcksdalen. At Röbäcksdalen the field was tile drained a few years before the experiment was launched. Drainage oxidates the soil, creating opportunities for the carbon to be utilized by microorganisms and creating more respiration which speeded up the release of carbon from the soil (Bolinder et al. 2010). As Olson (2012) stated a newly cultivated or drained grassland can lose as much as 50% of the SOC in 40-50 years. If we look at the published data, this happened in Röbäcksdalen within 30 years for system D (Ericson 1992; Bolinder et al. 2010). So, it is important to know the history of the cultivated land before any assumptions are made on carbon sequestration or decrease in carbon outlets from the soil in relation to cropping systems. An experimental location such as Offer where the carbon content which had probably already started to deplete due to a long history of cultivation, can indicate an increase and even sequestering effect on carbon for system A. Although there was no sequestration at any of the other locations or systems, it is evident from the results that with increasing leys in the rotation of an animal-based cropping system with addition of carbon rich manure, the SOC is depleted in a slower rate over time in these systems. If the experiment had been kept at Röbäcksdalen, a flattening of the yield trend would probably have been seen over time as the SOC reached an equilibrium between the output of carbon through the activity in the soil and the input through biomass by the ley and manure in system A and B (Bolinder et al. 2010; FAO 2019).

Fertilizer strategy

When it came to the fertilizer strategy, the design of the experiment was partly based on comparing different agricultural farms with more or less animals in the system. This produced different amounts of manure where system A and B added 60 tonnes ha^{-1}/rotation, C added 40 tonnes ha^{-1}/rotation and system D had no manure added. In the design it is not possible to separate the effects from manure on carbon stocks or yield. However, it is likely that the manure had a positive effect on both SOC (Bolinder et al. 2010) and yield (Damar et al. 2019). Adding manure adds carbon to the soil together with nutrients to the system. In turn, from publications on the experiment on soil properties (Ericson 1992; Bolinder et al. 2010; Jarvis et al. 2017) carbon has a positive effect on yield for barley. So, by adding extra carbon to the system through manure, it in turn has an effect on yield for barley.

Another big difference in nutrient input in relation to ley yield was potassium (K), which was added as potassium chloride. System C had 400 kg ha^{-1}/rotation of K compared to system A and B which had 220 kg ha^{-1}/rotation. The positive effects of potassium on leys might not have been known when the experiment was established, and after the revision of the experiment in 1987 much more K was added to systems A and B. System C had a significantly higher yield trend over time compared to system A at both Offer and Ås and C had also a higher yield trend compared to system B at Ås. System C and B had more similar designs when it came to the leys – C having 2 years of ley and B having 3 years, compared to A which had 5. And although they had almost the same amount of manure C had a significantly higher yield than B at Ås. The high amount of potassium put into system C can be one explanation for why the system had a more positive yield increase over time compared to system A and B (Schuch et al. 2013). Although, the biggest yield effect for the leys in system C compared to A and B was probably the break from pathogens and perennial weeds through the crop rotation (Hagsand & Landström 1984).

Barley yields

The results at Offer for barley yield showed significant results for yield trajectories over time: system A had a significant increase in yield over time (60.2 ±20.4 kg DM ha^{-1}) compared to the decrease in system C (-8.7 ±14.9 kg DM ha^{-1}) and system D (-7.2 ±17.5 kg DM ha^{-1}). System B did not have a significant change in yield over time compared to the other systems but had a positive yield trajectory of (39.7 ±19.9 kg DM ha^{-1}). Looking at the starting point for the experimental site at Offer, it had probably been cultivated in a rotation with pasture, ley and grain production. This might have had an effect on the SOC at the start of the experiment. The Offer location had the lowest starting point for SOC (2.8 %), compared to Ås and Röbäcksdalen (3.85 % and 4.84 %) (Ericson 1992). As already discussed in the previous section, SOC has been affected by the different locations and systems over time in this LTE and is increased with animal-based ley cropping systems such as systems A and B (Ericson 1992; Bolinder et al. 2010; Jarvis et al. 2017). The SOC increase or decrease is a main effect of the crops in the rotation and the inputs and outputs in the different cropping systems, amongst other things. When looking at the animal-based crop rotation and the effects the ley has on soil, such as adding large amounts of root biomass in the soil, root exudates that has a positive effect on soil micro (bacteria and fungi) and macro (earthworms) fauna (Jarvis et al. 2017) and the positive effect of manure (Bolinder et al. 2010; Damar et al. 2019), it is no wonder that the SOC increased over time for system A, 5 years ley, and B, 3 years ley, at Offer and for system A at Ås. And if the systems increased SOC, soil porosity and decreased soil bulk density, which all provide a good basis for crops to develop a deep and branched root system that has easier access to water and nutrients, it is no wonder that the yield in barley increased for systems A and B over time at Offer. At Ås the results for system A, had a significant increase in yield per year over time (22.1±20.0 kg DM ha^{-1}) compared to the decrease in system C (-27.4 ±20.0 kg DM ha^{-1}), and D (-32.1 ±20.0 kg DM ha^{-1}). System B (-7.3 ±20.0 kg DM ha^{-1}), had a significantly different yield trajectory compared to D. As discussed for the results at Offer, system A had many years to improve soil properties. But why did this not have the same effect in yield trend for system B? If the initial SOC has a major effect on yield trends over time in these systems, this might be one of the reasons. From what I conclude, with soils such as at Ås with a carbon content of 3.85 % and a land use that probably was pasture prior to the experiment, a ley of 3 years in a 6-year crop rotation and inputs through fertilizer strategy such as for system B, was not able to sustain the barley yield over time. However, these conclusions have been based on the experimental design and the publications on soil properties from the experiment. Other factors might have had an effect on the barley yield and on the ley yield discussed below. There is much more to explore, and further research is essential to make the right conclusions on what has had the biggest impact on yield over time. This will be further discussed under *Future opportunities*.

For Röbäcksdalen there were no significant differences in yield trends over time between the systems A, B, C or D. Once again, the publications from Ericson (1992) and Bolinder et al. (2010) conclude that the SOC decreased at Röbäcksdalen for all systems. Even though no statistical analysis on yield for each individual system has been made, the same decline in SOC was seen at all systems for barley yield. Although all systems had a decline in yield, system C had the steepest declining yield trajectory (-47.1 ±17.2 kg DM ha^{-1}) compared to all systems at Röbäcksdalen. This trend was seen at Offer as well. When looking at the published SOC content for the different systems at Röbäcksdalen and Offer, the highest initial SOC was found in the plots for system C, although it is not stated if there were any statistical difference (Ericson 1992; Bolinder et al. 2010). The split-plot design should prevent this from happening by evening out the differences over the experimental field. When looking at the field cards, the design for the plots of the systems were different for each location. For instance, the design at Röbäcksdalen for block 1 and for both blocks at Ås, does not seem to be randomized (Figure 3, Appendix 1), as is common practise in field experiments (Fältforsk 2019). It could mean system C got the highest SOC plots in the field because of the design at Röbäcksdalen. This is also discussed by Bolinder et al. (2010) regarding the soil organic nitrogen (SON) in system A and C, which had the same trend as the SOC, that might have been affected by the unevenness at the sites. So, the steeper decline at Röbäcksdalen could maybe be explained by the differences in initial SOC within the plots. However, at Offer the difference in initial SOC was not as great as in Röbäcksdalen and other factors might also have affected the yield decline. Further research is needed to understand why system C had the steepest decline in yield at Offer and Röbäcksdalen.

Barley yield after 1987

Although trends could be seen in the required data for barley between 1987–2019, the lack of time made it infeasible to complete the analysis. Since the data only has one replicate, finding statistical differences in the results will be more difficult. Having replicates makes the evaluated data more reliable. Effects on yield such as annual temperature and precipitation, management practise and inputs can have effects on the evaluated yield that is not a direct effect of the system, and therefore one replicate for one year can give misleading effects on the analysis between systems. However, trends that are seen over more than 30 years are not likely to be greatly influenced by a few years of effects that are unrelated to the systems. Therefore, analysis should be able to be made in the future.

Ley

When it came to the ley yields, ley 1 was analysed for the whole yield of the season. Ley 2 was analysed for the first cut of the season, due to the fact that system C only had one cut analysed for ley 2. By doing the analysis this way, the systems A, B and C could be analysed and compared for yield trends over time.

At Offer, the general trend for all systems was an increase in yield over time for ley 1. The results for system C had a significantly steeper trajectory in yield over time (76.0 ±43.8 kg DM ha^{-1}), compared to system A (31.0 ±43.8 kg DM ha^{-1}). System B (64.3 ±43.8 kg DM ha^{-1}), had a steeper trajectory over time compared to A, but there was no significant difference between the systems. At Ås the same trend was seen with an increase in yield for all systems and the results for both system C (133.4 ±41.8 kg DM ha^{-1}) and B (110.7 ±42.1 kg DM ha^{-1}), had a significantly higher yield trajectory over time compared to system A (71.4 ±41.9 kg DM ha^{-1}).

Systems A, B and C had 5, 3 and 2 years of ley respectively. The total amount of manure added in the 6-year rotations was 60, 60 and 40 tonnes ha^{-1}, for A, B and C. The larger amount of manure in system A and B did not give an advantage in yield over time compared to C. The positive effects that system A and B had on soil properties compared to C did not have the same effect as for barley yield. So how did system C yield significantly higher than system A at Offer and Ås, and where system B yielded significantly higher than A at Ås? The most probable cause is that the shorter ley in system C gave a break from pathogens and perennial weeds that often infest leys after a few years. A common problem in leys is that the red clover gets pathogens that weakens the plants. The clover starts to become more scarce, and together with an outwintering effect from e.g. snow-mould and ice-burn, the negative effect on yield becomes evident where the red clover can disappear completely after about 3 years (Hagsand & Landström 1984). Although there has been no analysis on the botanical composition of the leys or of pathogen occurrence between the systems in this LTE, the short ley-years in system C and B and the break from pathogens and weeds could be an explanation for the higher yield increase. This is also discussed by Hagsand & Landström (1984) in a publication on different ley years in the Swedish north. Another factor that could have affected the yield difference in C is the mineral fertilizer strategy. In the strategy it is stated that system A, B and C got 220, 220 and 400 kg ha^{-1} of potassium (K) respectively per rotation. In an article by Schuch et al. (2013) where grass-leys were analysed on the basis of above and below ground biomass in an LTE in Germany, the results stated that a higher fertilization strategy with K gave a higher yield in leys, however, the increase in above ground biomass/yield did not affect the below ground biomass, meaning that an addition of K on leys does not have a positive effect on SOC. So, a higher input in K on the ley does give a higher yield, but it is also important to take into account the negative effect a too high K input in the fodder can have on cows when developing a fertilizer strategy. However, the large addition of K in system C compared to system A could have had an effect on the yield trend for system C.

For ley 2 the results stated no significance between systems for yield change over time. At Röbäcksdalen there was however a significant effect in the change in yield in the whole data set over time. This meant that although there was no difference between systems, the over-all yield-trend over time was significantly positive. At Röbäcksdalen, the yield for ley 2 increased significantly over time. Why this is the case is out of the scope of this thesis and has not been analysed in any publications for this LTE. Other factors that could have had an effect on yield is the climate and especially the rise in temperature over the growing season (Eckersten et al. 2008) together with the improvement in cultivars over time (Woodfield 1999).

There are many factors that affect yield in leys. From the results from this LTE with a 6-year crop rotation, the analysis on ley 1 suggest that intensive shorter leys, 2-3 years in an animal-based cropping system, have a significantly positive effect on ley yields over time compared to animal-based cropping systems with extensive leys of 5 years.

Contrasts

In the experimental design the aim was to make cropping systems A and B resemble animal-based farms. The system would produce large amounts of ley for the cows or cattle and the manure would be used to fertilize the fields together with additional mineral fertilizers. The opposite would be for system C and D where less or no ley would be produced and less or no manure spread on the fields. This design went hand in hand with the results on barley yield over time comparing A+B and C+D as farm types, which were significantly different at Offer and Ås. However, when looking at the leys the results were not as one sided. The ley might not have been intended to be compared on the basis of yield between treatments in the original experimental design, at least no such information has been reviled in the scope of this thesis. This could be one of the reasons the analysis of the contrasts comparing systems A+B, animal-based farms, to system C, crop-based farm, was not as evident as in the analysis for contrasts on barley yield. Because the results for ley 1 had an opposite trend between the systems compared to barley, another comparison of the contrasts, A to B+C, was added to the analysis. The results for the contrasts at Offer stated that A was significantly different to the contrast B+C. At Ås, both contrasts A+B - C and A - B+C were significantly different. What can we conclude from this? When looking at the design with the crop rotation, in a way, system B and C were more alike. System A could be considered a monoculture with the 5 years of ley and the risks of developing diseases over time is greater with longer ley-years. So, when looking at the systems A, B and C for leys, systems B and C are more similar with respect to the fact that they both have shorter ley years. This could explain the different results between contrast for barley and ley year 1.

Things that might have affected the results

Something that might have had an effect in the analysis on yield for ley 1 and ley 2 were a few outliers in the data. Not all outliers were checked due to lack of time to check paper records. Unusually high or low results on yield should always be checked to make sure that they do not skew the modelled analysis. The outliers can be seen in the graphs for ley 1 and ley 2 (Figure 5 & 6). Most outliers were found in Röbäcksdalen for ley 1 between 1980-1983. For further research the outliers should be checked before analysis is made.

The design of the different locations is something that might have had an effect, as discussed in the section on barley yield at Röbäcksdalen. For future research any eventual spatial effects that the designs might have had on the systems, should be investigated.

Future opportunities

It would have been interesting to see the effects of the cropping systems at Ås and Röbäcksdalen, if they had been kept in the LTE. To see if the new fertilizer strategy and crop rotations would have affected the yield over time any differently compared to the first 30 years. The reasons to why Ås and Röbäcksdalen were terminated from the experiment has not been investigated further. However, between 1991–1994, Sweden, together with many other countries, was suffering from a financial crisis that affected state finances (Englund 2015). The LTEs are funded by the State and a reasonable assumption is that the locations were terminated due to lack of funding. This is an example of how vulnerable LTEs are to changes in society. We can not always know all the effects and answers to research questions LTEs might give us in the future, but if this LTE had been kept on as planned at all locations it could have given research much more data for understanding how different systems affect soil properties and yield at different locations in Northern Sweden.

The location at Offer is however still running and effects on soil properties have been analysed and published and given us tools for present and future agriculture in the north. The data for yield has however not been analysed between 1987 until today. Although the data between 1963–1986 has been analysed in this thesis and was published by Ericson for barley in 1992, there is much more to explore and analyse in terms of yield. We do not know what the future might hold for research in this age of climate change and the need to produce more food and feed in a sustainable way. Although there was a revision in 1987 many of the original aspects of the experimental design is still the same and it still gives opportunities to analyse the more than 30 years of additional data for Offer.

My own thoughts regarding this LTE are that it should be kept running until possible benefits are thoroughly investigated. It is clear that the LTE has not been used with its full potential. When it comes to publications on yield, there has only been one (Ericson 1992). This might have been because of lack of funding or lack of interest in the research community for analysing yield, or simply because the potentials of the data in the LTE have not and are still not known to the same community. I believe that it is of great importance to keep the LTEs that are still running in the North of Sweden, but I also agree with Johnston & Poulton (2018) in that an LTE must serve a purpose and should be altered if it does no longer serve a purpose. LTEs cost a lot of money, but they also provide research with a lot of information that can be used for publications and practical information about how to farm sustainably.

Zhou et al. (2020) suggested opportunities for further research that I will repeat here and add to. In the end of the section, I will also suggest changes to the experiment.

- Exploring the effects of yield: Botanical composition has effect on yield and quality in leys and has so far not been analysed in this LTE. Another effect on yield is the genetic varieties. In the experiment the variety used at the different locations was determined depending on local conditions and access to new and better performing varieties could have had effect on the yield trend.

- Symbiotic diversity of microfauna: The symbiotic bacteria and fungi in the different systems could be analysed with DNA/RNA in soil samples collected at the ongoing experiment at the Offer site.
- Statistical analysis of yield: In this thesis yield trends on barley and leys have been analysed on the basis of change in yield over time when comparing the cropping systems. There are many ways of conducting statistical analysis and there are many variables in this LTE, and I am sure the data set hold more analysis and interesting results for future publications.
- Crop simulation models: The extensive amount of data can be used to simulate models for crop production in colder climates.
- Carbon models: The effects that the systems have on soil organic carbon can be used to develop models or be used on existing models both for the three locations between 1963–1986 and for Offer between 1987 until today.
- Life cycle analysis (LCA): Today we have a lot of knowledge of the impacts that inputs and outputs in an agricultural system have on e.g., environment, economy and climate factors. The data from the experiment, both between 1963–1986 and 1987 to today, include information on fertilizer strategy and agricultural management that could potentially be used to assess whether any of the systems differ in a LCA in relation to e.g., climate impact.
- Climate factors relating to yield and yield in extreme weather: We live in the time of climate change where the temperatures and precipitation has already started to affect agriculture all over the world, Northern Sweden is no exception. The ability to use an ongoing long-term experiment that has been going on since 1956 is a great opportunity for analysing yield in relation to increasing temperatures and how different cropping systems are affected by extreme weather and if any of them could be considered resilient.

The following changes are suggestions for the continuation of the experiment:

1. Small changes: Alterations to the fertilizer strategy and maybe some of the crops. The fertilizer strategy should be looked over in terms of new recommendations for nutrients in the systems and another suggestion is to change the manure into a liquid slurry, which is more common in today's agriculture. The pea/barley/rape-mix is not commonly used and could be changed for oats, rape or maybe some other crop that would be a good choice for northern crop rotation. With small changes the experiment can continue to be analysed with the original research questions together with future ones, and the alterations would be a way to adapt the experiment to modern agricultural practises.

2. Large changes: Transition to organic agriculture. If the LTE would be revised and altered in a larger scale a transition to organic farming would be a relevant change. With an increase in consumers demanding more organic and locally produced foods, many conventional farmers transition to organic, both for financial reasons as well as philosophical. If the experiment would be redone this way, it could be used to see long-term effects when changing to organic and how this affects the soil and yield and analyse if it is sustainable over time. It could also be a way to include the Swedish Food Strategy and see if we can farm organically and include crops for commercial interest in the rotation. This alteration to the experiment would include a change in fertilizer strategy for all the systems. For the crop rotation the barley undersown with ley, ley 1, ley 2 and barley after ley could be kept for comparable analysis over time. In systems B, C and D the annual crops could be exchanged for crops that could be more relevant in organic rotations or that would be relevant for the Swedish Food Strategy.
3. Large changes: Evaluate the long-term effect of previous agricultural land use. The results from the experiment have given evidence that the four different cropping systems (CS) have changed the soil properties and expected yield. One way to make use of this is to change the experimental design from the original four CS to one. This would create four replicates and makes it possible to analyse how long it takes before a new equilibrium is reached in terms of soil properties and yield where different agricultural CS have been in use over a long period of time. The alterations would include a new fertilizer strategy to meet today's recommendations. System B would be the system to be kept in the experiment because it is more representative of a typical current CS.

Conclusions

My own thought on the soil properties and carbon stocks in relation to global goals to stabilize and increase yields in a sustainable way, is that it is crucial to do this on land that is already cultivated. Breaking new soil for agriculture has a very negative impact on the climate by increasing CO_2 emissions. Carbon sequestration is one aspect that is hot on the agenda to combat climate change and is correlated with an increase in soil quality. LTEs have given knowledge on what kinds of cropping system might decrease the reduction of soil organic carbon or even sequester it; leys in crop rotation are one way. The aim of this thesis was to analyse yield for barley and ley in an LTE that has been active in northern Sweden since the 1950s. My conclusion from the work is that if we want to produce food and feed for people and animals in the North, it is a good idea to do that using an animal-based cropping system, with leys in the crop rotation. These systems increase grain yield for barley over time, shorter leys produce better ley yields and it can keep the carbon in the ground.

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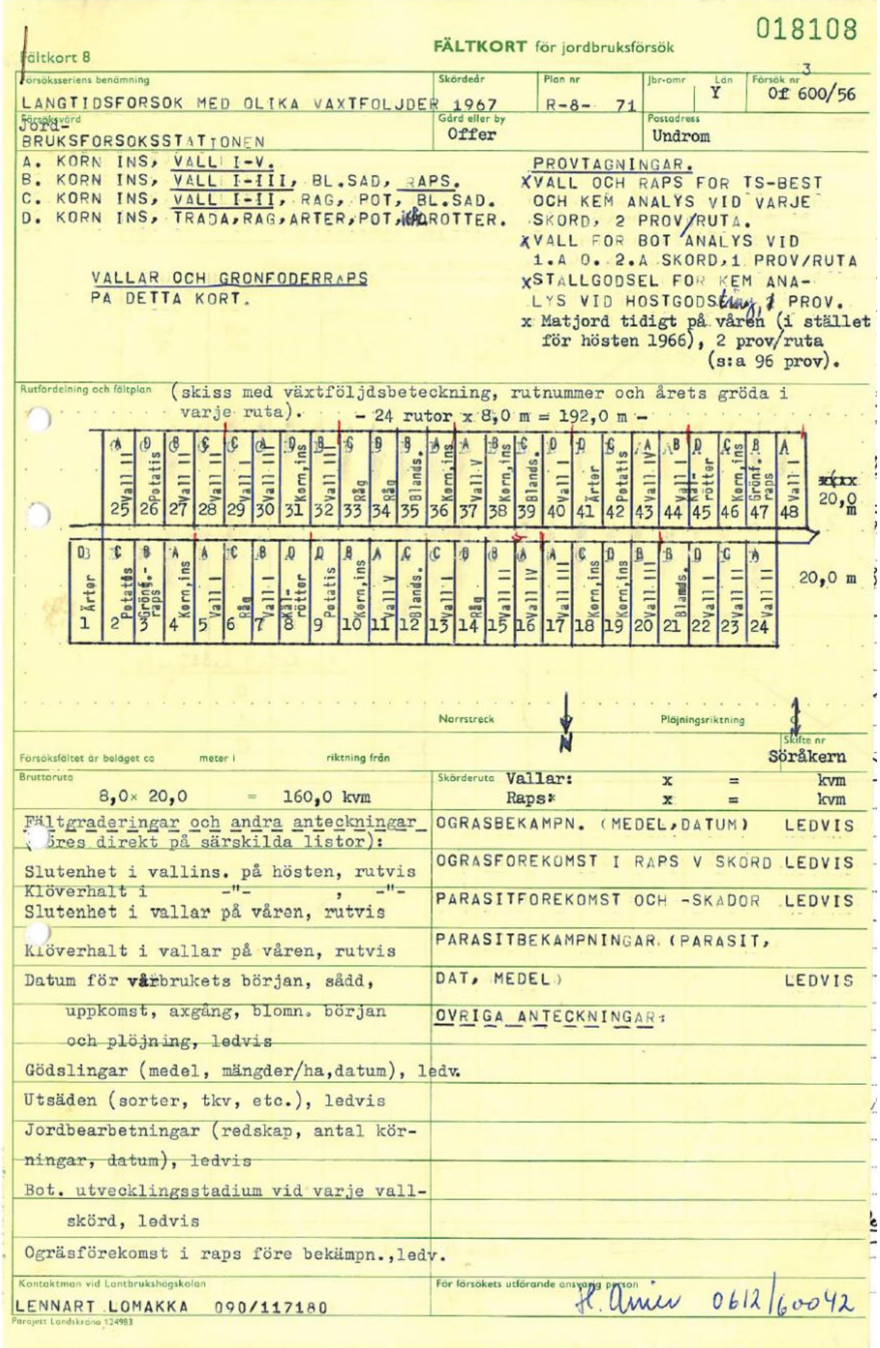
Acknowledgements

I would like to thank the field staff at Röbäcksdalen field station for collection of data and other information regarding the experiment and I would also like to thank Lars Gradin at Lantmännen for help with the Offer site. Last but not least I would like to thank my supervisor David Parsons for the support and guidance throughout the work on this thesis.

Appendix 1 – Field cards

Field card at Offer in 1967



Fältkort 8 — **FÄLTKORT** för jordbruksförsök — 018108

Försöksseriens benämning	Skördeår	Plan nr	Jbr-omr	Län	Försök nr
LANGTIDSFORSOK MED OLIKA VAXTFOLJDER	1967	R-8- 71		Y	Of 600/56 3

Försöksvärd	Gård eller by	Postadress
Jord-BRUKSFORSOKSSTATIONEN	Offer	Undrom

A. KORN INS, VALL I-V.
B. KORN INS, VALL I-III, BL.SAD, RAPS.
C. KORN INS, VALL I-II, RAG, POT, BL.SAD.
D. KORN INS, TRADA, RAG, ARTER, POT, KÅLROTTER.

VALLAR OCH GRONFODERRAPS
PA DETTA KORT.

PROVTAGNINGAR.
x VALL OCH RAPS FOR TS-BEST OCH KEM ANALYS VID VARJE SKORD, 2 PROV/RUTA.
x VALL FOR BOT ANALYS VID 1.A O. 2.A SKORD, 1 PROV/RUTA
x STALLGODSEL FOR KEM ANALYS VID HOSTGODSLING, 1 PROV.
x Matjord tidigt på våren (i stället för hösten 1966), 2 prov/ruta (s:a 96 prov).

Rutfördelning och fältplan (skiss med växtföljdsbeteckning, rutnummer och årets gröda i varje ruta). – 24 rutor x 8,0 m = 192,0 m –

Ruta	25	26	27	28	29	30	31	32	33	34	35	36
Växtföljd	A	D	B	C	C	A	D	B	C	D	B	D
Gröda	Vall II	Potatis	Vall II	Vall II	Vall I	Vall III	Korn, ins	Vall III	Råg	Råg	Blands.	Korn, ins

Ruta	37	38	39	40	41	42	43	44	45	46	47	48
Växtföljd	A	B	C	D	D	C	A	B	D	C	B	A
Gröda	Vall V	Korn, ins	Blands.	Vall I	Ärter	Potatis	Vall IV	Vall I	Kål-rötter	Korn, ins	Grönf. raps	Vall I

20,0 m

Ruta	1	2	3	4	5	6	7	8	9	10	11	12
Växtföljd	D	C	B	A	A	C	B	D	D	B	A	C
Gröda	Ärter	Potatis	Grönf.-raps	Korn, ins	Vall I	Råg	Vall I	Kål-rötter	Potatis	Korn, ins	Vall V	Blands.

Ruta	13	14	15	16	17	18	19	20	21	22	23	24
Växtföljd	C	D	B	A	A	C	D	B	B	D	C	A
Gröda	Vall I	Råg	Vall II	Vall IV	Vall III	Korn, ins	Korn, ins	Vall III	Blands.	Vall I	Vall II	Vall II

20,0 m

Norrstreck N — Plöjningsriktning — Skifte nr: Söråkern

Försöksfältet är beläget ca meter i riktning från

Bruttoruta	Skörderuta
8,0 × 20,0 = 160,0 kvm	Vallar: x = kvm Raps: x = kvm
Fältgraderingar och andra anteckningar (föres direkt på särskilda listor):	OGRASBEKAMPN. (MEDEL, DATUM) LEDVIS
Slutenhet i vallins. på hösten, rutvis	OGRASFOREKOMST I RAPS V SKORD LEDVIS
Klöverhalt i -"- , -"- Slutenhet i vallar på våren, rutvis	PARASITFOREKOMST OCH -SKADOR LEDVIS
Klöverhalt i vallar på våren, rutvis	PARASITBEKAMPNINGAR (PARASIT,
Datum för vårbrukets början, sådd,	DAT, MEDEL) LEDVIS
uppkomst, axgång, blomn. början	OVRIGA ANTECKNINGAR:
och plöjning, ledvis	
Gödslingar (medel, mängder/ha, datum), ledv.	
Utsäden (sorter, tkv, etc.), ledvis	
Jordbearbetningar (redskap, antal kör-	
ningar, datum), ledvis	
Bot. utvecklingsstadium vid varje vall-	
skörd, ledvis	
Ogräsförekomst i raps före bekämpn., ledv.	
Kontaktman vid Lantbrukshögskolan: LENNART LOMAKKA 090/117180	För försökets utförande ansvarig person: H. Amer 0612/60042

Parajett Landskrona 124983

Field card at Ås in 1967

Fältkort 8 **FÄLTKORT** för jordbruksförsök 018117

Försöksseriens benämning	Skördeår	Plan nr	Jbr-omr	Län	Försök nr
LANGTIDSFORSOK MED OLIKA VAXTFOLJDER	1967	R-8- 71		xX Z	2 Å 18/55

Försöksvärd	Gård eller by	Postadress
Jord-BRUKSFORSOKSSTATIONEN		Ås

A. KORN INS, VALL I-V.
B. KORN INS, VALL I-III, BL.SAD, RAPS
C. KORN INS, VALL I-II, RAG, POT, BL.SAD.
D. KORN INS, TRADA, RAG, ARTER, POT, MOROTTER.

SADESGRODOR PA DETTA KORT.

PROVTAGNINGAR.
X KARNA FOR TS-BEST, SADES-ANALYS OCH KEM ANALYS VID SKORDENS VAGNING, 1 PROV/RUTA.
X HALM FOR TS-BEST OCH KEM ANALYS VID SKORDENS VAGNING, 1 PROV/RUTA.
X STALLGODSEL (SE VALLKORTET).

Rutfördelning och fältplan (skiss med växtföljdsbeteckn., rutnummer och årets gröda i varje ruta).

5,0

A V I 1	A V II 2	A V III 3	A V IV 4	A V V 5	A K ins 6	C V I 25	C V II 26	C H-råg 27	C Pot. 28	C Bl.säd 29	C K ins 30
B V I 7	B V II 8	B V III 9	B Bl.säd 10	B Raps 11	B K ins 12	D Träda 31	D H-råg 32	D Ärter 33	D Pot. 34	D Morröt- 35	D K ins 36
C V I 13	C V II 14	C H-råg 15	C Pot. 16	C Bl-säd 17	C K ins 18	A V I 37	A V II 38	A V III 39	A V IV 40	A V V 41	A K ins 42
D Träda 19	D H-råg 20	D Ärter 21	D Pot. 22	D Mor. 23	D K ins 24	B V I 43	B V II 44	B V III 45	B Bl-säd 46	B Raps 47	B K ins 48

21,0 5,0 1/58 4,0 5,0

Norrstreck ----→ N Plöjningsriktning Stifte nr P VI

Försöksfältet är beläget ca meter i riktning från

Bruttoruta 21,0 x 9,0 = 189,0 kvm

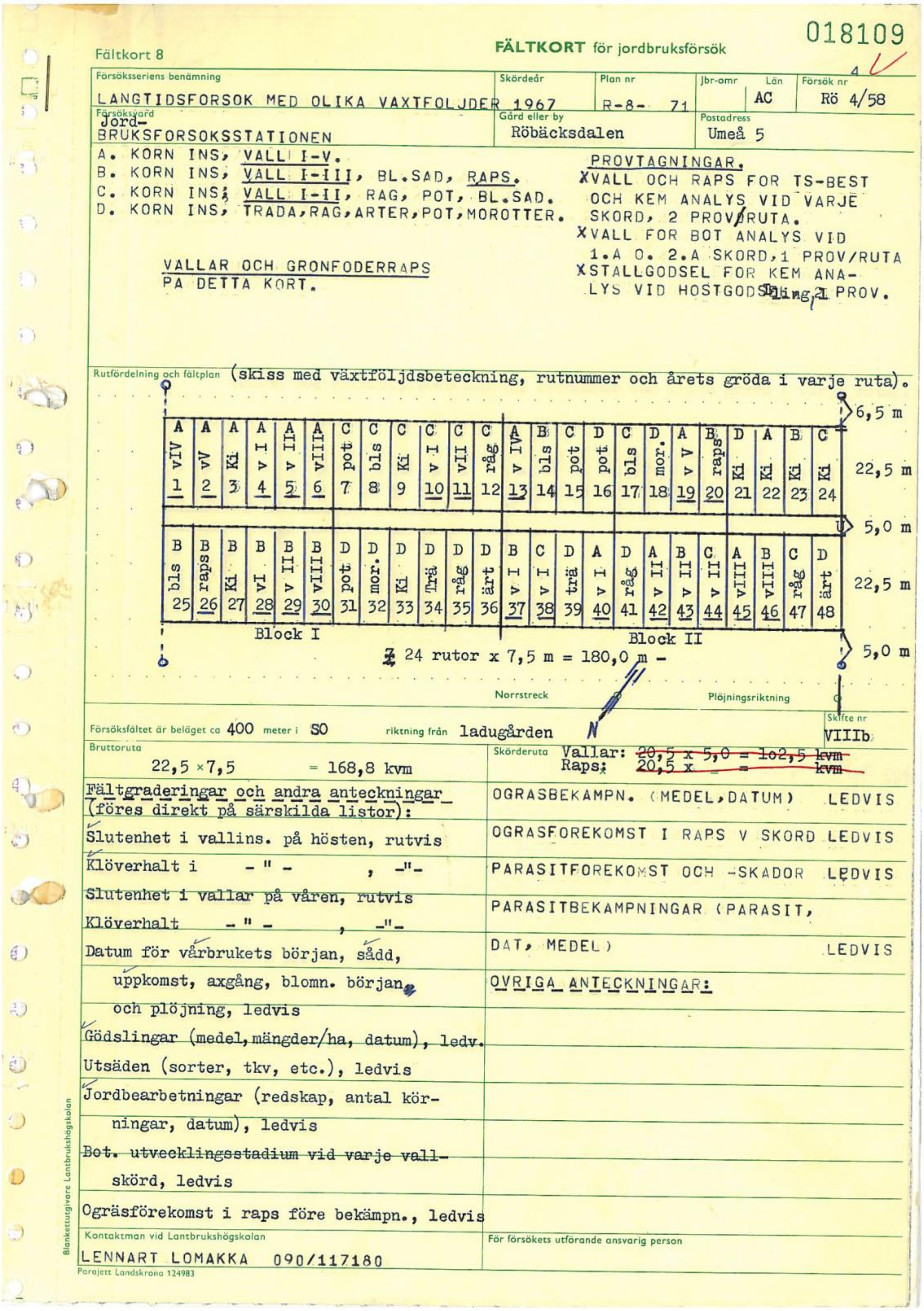
Skörderuta x = kvm

Fältgraderingar och andra anteckningar (föres direkt på särskilda listor):	PARASITFOREKOMST OCH -SKADOR LEDVIS
Slutenhet i höstråg på hösten, rutvis	PARASITBEKAMPNINGAR (PARASIT,
Vitalitet -"- , ledvis	DAT, MEDEL) LEDVIS
~~Slutenhet i höstråg på våren, rutvis~~	LIGGSAD VID SKORD RUTVIS
~~Datum för vårbrukets början, sådd, upp-~~ komst, axgång, blomn. början, mognad och plöjning, ledvis	ÖVRIGA ANTECKNINGAR:
Gödslingar (medel, mängder/ha, dat.), ledv.	
~~Utsäden (sorter, tkv, etc.), ledvis~~	
Jordbearbetningar (redksap, antal körningar, datum), ledvis	
Ogräsförekomst före bekämpning, ledvis	
~~Ogräsbekämpningar (medel, datum), ledvis~~	
Ogräsförekomst vid sköd, ledvis	

Kontaktman vid Lantbrukshögskolan	För försökets utförande ansvarig person
LENNART LOMAKKA 090/117180	Ebbe Svensson

Blankettutgivare Lantbrukshögskolan
Parajett Landskrona 124983

Field card at Röbäcksdalen in 1967



Fältkort 8

FÄLTKORT för jordbruksförsök

018109

Försöksseriens benämning	Skördeår	Plan nr	Jbr-omr	Län	Försök nr
LANGTIDSFORSOK MED OLIKA VAXTFOLJDER	1967	R-8- 71		AC	4 Rö 4/58

Försöksvärd	Gård eller by	Postadress
Jord-BRUKSFORSOKSSTATIONEN	Röbäcksdalen	Umeå 5

A. KORN INS, VALL I-V.
B. KORN INS, VALL I-III, BL.SAD, RAPS.
C. KORN INS, VALL I-II, RAG, POT, BL.SAD.
D. KORN INS, TRADA,RAG,ARTER,POT,MOROTTER.

VALLAR OCH GRONFODERRAPS
PA DETTA KORT.

PROVTAGNINGAR.
X VALL OCH RAPS FOR TS-BEST OCH KEM ANALYS VID VARJE SKORD, 2 PROV/RUTA.
X VALL FOR BOT ANALYS VID 1.A O. 2.A SKORD, 1 PROV/RUTA
X STALLGODSEL FOR KEM ANALYS VID HOSTGODSling, 1 PROV.

Rutfördelning och fältplan (skiss med växtföljdsbeteckning, rutnummer och årets gröda i varje ruta).

6,5 m

A vIV 1	A vV 2	A Ki 3	A v I 4	A v III 5	A vIII 6	C pot 7	C bls 8	C Ki 9	C v I 10	C vII 11	C råg 12	A v IV 13	B bls 14	C pot 15	D pot 16	C bls 17	D mor. 18	A v V 19	B raps 20	D Ki 21	A Ki 22	B Ki 23	C Ki 24	22,5 m
																								5,0 m
B bls 25	B raps 26	B Ki 27	B vI 28	B v III 29	B vIII 30	D pot 31	D mor. 32	D Ki 33	D Trä 34	D råg 35	D ärt 36	B v I 37	C v I 38	D trä 39	A v I 40	D råg 41	A v III 42	B v III 43	C v III 44	A vIII 45	B vIII 46	C råg 47	D ärt 48	22,5 m

Block I Block II

24 rutor x 7,5 m = 180,0 m -

5,0 m

Norrstreck N Plöjningsriktning

Försöksfältet är beläget ca 400 meter i SO riktning från ladugården

Skifte nr VIIIb

Bruttoruta 22,5 x 7,5 = 168,8 kvm

Skörderuta Vallar: ~~20,5 x 5,0 = 102,5 kvm~~
Raps: ~~20,5 x _ = kvm~~

Fältgraderingar och andra anteckningar (föres direkt på särskilda listor):	OGRASBEKAMPN. (MEDEL, DATUM) LEDVIS
Slutenhet i vallins. på hösten, rutvis	OGRASFOREKOMST I RAPS V SKORD LEDVIS
Klöverhalt i - " - , -"-	PARASITFOREKOMST OCH -SKADOR LEDVIS
~~Slutenhet i vallar på våren, rutvis~~	PARASITBEKAMPNINGAR (PARASIT,
Klöverhalt - " - , -"-	DAT, MEDEL) LEDVIS
Datum för vårbrukets början, sådd,	ÖVRIGA ANTECKNINGAR:
uppkomst, axgång, blomn. början,	
och plöjning, ledvis	
Gödslingar (medel, mängder/ha, datum), ledv.	
Utsäden (sorter, tkv, etc.), ledvis	
Jordbearbetningar (redskap, antal körningar, datum), ledvis	
~~Bot. utvecklingsstadium vid varje vallskörd~~, ledvis	
Ogräsförekomst i raps före bekämpn., ledvis	

Blankettutgivare Lantbrukshögskolan

Kontaktman vid Lantbrukshögskolan	För försökets utförande ansvarig person
LENNART LOMAKKA 090/117180	

Parajett Landskrona 124983

Appendix 2 – SAS code

SAS 9.4 code for statistical analysis models on barley and ley for the locations Offer, Ås and Röbäcksdalen. First is the code for Type 3 Test for Fixed Effect. Second are the estimates between systems.

*Offer barley;

```
proc mixed data = BarleyOffer plots = residualpanel ;
              class Year System Plot ;
              model TY = System x System*x / ddfm = kr solution ;
              random Year / group = System ;
              random Plot ;
run ;

proc mixed data = BarleyOffer plots = residualpanel ;
              class Year System Plot ;
              model TY = System System*x /noint ddfm = kr solution ;
              random Year / group = System ;
              random Plot ;
              estimate "Slope A - B" System*x 1 -1  0  0 ;
              estimate "Slope A - C" System*x 1  0 -1  0 ;
              estimate "Slope A - D" System*x 1  0  0 -1 ;
              estimate "Slope B - C" System*x 0  1 -1  0 ;
              estimate "Slope B - D" System*x 0  1  0 -1 ;
              estimate "Slope C - D" System*x 0  0  1 -1 ;
              estimate "Slope A+B - C+D" System*x 0.5  0.5  -0.5 -0.5 ;
run ;
```

*Offer ley 1 and ley 2;

```
*Offer Ley 1;
proc mixed data = Ley1Offer plots = residualpanel ;
              class Year System Plot ;
              model TY = System x System*x / ddfm = kr solution;
              random Year ;
run ; * AIC = 2276.8, BEST ;
proc mixed data = Ley1Offer plots = residualpanel ;
              class Year System Plot ;
              model TY = System System*x / noint ddfm = kr solution;
              random Year ;
              estimate "Slope A - B" System*x 1 -1  0  ;
              estimate "Slope A - C" System*x 1  0 -1  ;
              estimate "Slope B - C" System*x 0  1 -1  ;
              estimate "Slope A+B - C" System*x 0.5  0.5  -1 ;
              estimate "Slope A - B+C" System*x 1  -0.5  -0.5 ;
run ;
*Offer Ley 2;
proc mixed data = Ley2Offer plots = residualpanel ;
              class Year System Plot ;
              model Y1 = System x System*x / ddfm = kr solution ;
              random Year / group = System ;
              random Plot ;
run ; * AIC= 2240.9, best;
proc mixed data = Ley2Offer plots = residualpanel ;
              class Year System Plot ;
              model Y1 = System System*x / noint ddfm = kr solution ;
              random Year / group = System ;
              random Plot ;
              estimate "Slope A - B" System*x 1 -1  0  ;
              estimate "Slope A - C" System*x 1  0 -1  ;
```

```
                estimate "Slope B - C" System*x 0  1 -1  ;
                estimate "Slope A+B - C" System*x 0.5  0.5  -1 ;
                estimate "Slope A - B+C" System*x 1  -0.5  -0.5 ;
run ;
```

*Ås barley;

```
proc mixed data = BarleyAs ;
                class Year System Plot ;
                model TY = System x System*x / ddfm = kr ;
                random Year Plot ;
run ;
proc mixed data = BarleyAs ;
                class Year System Plot ;
                model TY = System System*x /noint ddfm = kr solution;
                random Year Plot ;
                estimate "Slope A - B" System*x 1 -1  0  0 ;
                estimate "Slope A - C" System*x 1  0 -1  0 ;
                estimate "Slope A - D" System*x 1  0  0 -1 ;
                estimate "Slope B - C" System*x 0  1 -1  0 ;
                estimate "Slope B - D" System*x 0  1  0 -1 ;
                estimate "Slope C - D" System*x 0  0  1 -1 ;
                estimate "Slope A+B - C+D" System*x 0.5  0.5  -0.5 -0.5 ;
run ;
```

*Ås ley 1 and ley 2;

```
*Ås Ley 2;
*M1;
proc mixed data = Ley2As plots = residualpanel;
                class Year System Plot ;
                model Y1 = System x System*x / ddfm = kr solution;
                random Year Plot ;
run ; * AIC = 2209.4 , BEST ;
*M1;
proc mixed data = Ley2As plots = residualpanel;
                class Year System Plot ;
                model Y1 = System System*x / noint ddfm = kr solution;
                random Year Plot ;
                estimate "Slope A - B" System*x 1 -1  0  ;
                estimate "Slope A - C" System*x 1  0 -1  ;
                estimate "Slope B - C" System*x 0  1 -1  ;
                estimate "Slope A+B - C" System*x 0.5  0.5  -1 ;
                estimate "Slope A - B+C" System*x 1  -0.5  -0.5 ;
run ;
```

*Röbäcksdalen barley;

```
proc mixed data = BarleyRobacksdalen ;
                class Year System Plot ;
                model TY = System x System*x / ddfm = kr ;
                random Year Plot ;
                repeated / group = System ;
                run;
proc mixed data = BarleyRobacksdalen ;
                class Year System Plot ;
                model TY = System  System*x / noint ddfm = kr solution;
                random Year Plot ;
                repeated / group = System ;
                estimate "Slope A - B" System*x 1 -1  0  0 ;
                estimate "Slope A - C" System*x 1  0 -1  0 ;
                estimate "Slope A - D" System*x 1  0  0 -1 ;
                estimate "Slope B - C" System*x 0  1 -1  0 ;
                estimate "Slope B - D" System*x 0  1  0 -1 ;
                estimate "Slope C - D" System*x 0  0  1 -1 ;
                estimate "Slope A+B - C+D" System*x 0.5  0.5  -0.5 -0.5 ;
                run;
```

* Röbäcksdalen ley 1 and ley 2;

```
*Ley 1;
proc mixed data = Ley1Robacksdalen plots = residualpanel ;
                class Year System Plot ;
                model TY = System x System*x / ddfm = kr solution;
                random Year Plot ;
                repeated / group = System ;
run ;
```

```
proc mixed data = Ley1Robacksdalen plots = residualpanel ;
             class Year System Plot ;
             model TY = System System*x / noint ddfm = kr solution;
             random Year Plot ;
             repeated / group = System ;
             estimate "Slope A - B" System*x 1 -1  0  ;
             estimate "Slope A - C" System*x 1  0 -1  ;
             estimate "Slope B - C" System*x 0  1 -1  ;
             estimate "Slope A+B - C" System*x 0.5  0.5  -1 ;
             estimate "Slope A - B+C" System*x 1  -0.5  -0.5 ;
run ;

*Ley 2;
proc mixed data = Ley2Robacksdalen plots = residualpanel ;
             class Year System Plot ;
             model Y1 = System x System*x / ddfm = kr solution;
             random Year ;
             run ;
proc mixed data = Ley2Robacksdalen plots = residualpanel ;
             class Year System Plot ;
             model Y1 = System System*x / noint ddfm = kr solution;
             random Year ;
             estimate "Slope A - B" System*x 1 -1  0  ;
             estimate "Slope A - C" System*x 1  0 -1  ;
             estimate "Slope B - C" System*x 0  1 -1  ;
             estimate "Slope A+B - C" System*x 0.5  0.5  -1 ;
             estimate "Slope A - B+C" System*x 1  -0.5  -0.5 ;
run ;
```

Appendix 3 – Fertilizer strategy

Between the start of the experiment and 1986 the phosphorus (P) was added as Thomas-phosphate at Offer, Röbäcksdalen and Öjebyn. At Ås, Superphosphate. Potassium (K) was added as potassium chloride for the barley and ley. The amount of N put on ley 1 and ley 2 depended on clover content (high, poor or no clover); ley 1 with 0/30/60 kg N/ha and ley 2 with 30/60 kg N/ha. In the original PM one can read how much nitrogen (N), P and K was taken out through harvest (Hagsand et al. 1961, 1987). Data and additional information can be provided by the Department of Agricultural Research for Northern Sweden (NJV 2021).

Cropping system	Year	Crop	Manure [A] (tonnes/ha)	N [S] (kg/ha)	P [S] (kg/ha)	K [S] (kg/ha)	Boron [S] (kg/ha)
A	1	Barley undersown with ley	30 (0)	0 (40)	35 (15)	60 (40)	2
	2	Ley 1	0	30 (90)	0 (17)	0 (75)	0
	3	Ley 2	0	30 (90)	15 (17)	60 (75)	0
	4	Ley 3	0 (20)	60 (150)	15 (17)	60 (75)	0
	5	Ley 4	30 (20)	45 (150)	15 (17)	0 (75)	0
	6	Ley 5	0 (20)	60 (150)	15 (17)	40 (75)	0
		Sum rotation	60	225 (670)	95 (100)	220 (415)	2
B	1	Barley undersown with ley	0	15 (40)	35 (15)	80 (40)	2
	2	Ley 1	0	30 (90)	0 (17)	0 (75)	0
	3	Ley 2	0	30 (90)	15 (17)	60 (75)	0
	4	Ley 3	30 (20)	45 (150)	15 (17)	0 (75)	0
	5	Oat/Pea (Barley)	0	15 (70)	15 (15)	40 (15)	0
	6	Forage rape (Rape/Barley/Pea)	30 (40)	75 (50)	20 (15)	40 (50)	0
		Sum rotation	60	210 (490)	100 (96)	220 (330)	2
C	1	Barley undersown with ley	0	15 (40)	35 (15)	120 (40)	2
	2	Ley 1	0	30 (90)	0 (17)	0 (75)	0
	3	Ley 2	0	30 (90)	15 (17)	40 (75)	0
	4	Winter rye (Barley)	0	15 (70)	15 (15)	80 (40)	0
	5	Potatoes	40 (0)	60 (70)	35 (40)	100 (120)	0
	6	Oat/Pea (Rape/Barley/Pea)	0 (40)	15 (50)	15 (15)	60 (50)	0
		Sum rotation	40	165 (410)	115 (119)	400	2
D	1	Barley undersown with ley	0	30 (40)	25 (15)	60 (40)	2
	2	Green manure	0	0 (60)	0 (17)	0 (50)	0
	3	Winter rye (Barley 1)	0	15 (70)	25 (15)	80 (0)	0
	4	Pea (Potatoes 1)	0	15 (70)	25 (40)	60 (120)	0
	5	Potatoes (Barley 2)	0	100 (70)	35 (15)	200 (0)	0
	6	Carrot/Swede (Potatoes 2)	0	70 (70)	35 (40)	160 (120)	0
		Sum rotation	0	230 (380)	145 (142)	560 (330)	2

() = in parenthesis are the revised strategy and crops after 1987 (Hagsand et al. 1987)

[A] = autumn application

[S] = spring application