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A 60-years old field experiment demonstrates the benefit of leys in the crop rotation

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ABSTRACT
In the 1950s, a long-term experiment was initiated at three locations in Northern Sweden. The treatments included four cropping systems, which differed in the number of years with leys or annual crops in the crop rotation. To create awareness of the experiment as a research resource for further scientific studies, we summarise the history (experimental design, materials and methods, main measurements) and scientific findings of the experiment, as well as reflect on its usefulness and opportunities for further studies. So far, scientific focus has been on the effects of cropping systems on soil characteristics. The main findings indicate that soil porosity and hydraulic conductivity were greater in cropping systems with a large proportion of ley, soil bulk density showed the opposite trend. In terms of chemical properties, cropping systems incorporating more ley also have greater soil organic carbon content than annual crops systems, and both soil carbon and N storage decrease over time in cropping systems with only annual crops. The effects of cropping system on crop yields and quality are areas for further investigation.

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Crop rotation; forage crop; legume; soil organic carbon; soil organic nitrogen

Introduction

Long-term experiments serve as important resources to investigate management strategies on system outcomes (e.g. crop yield, soil chemical, biological and physical properties). During the second half of the twentieth century, farming activities became increasingly specialised in Sweden, leading to the separation of crop farms and livestock farms. Concern arose as to how this specialisation would influence soil properties and crop yields (Bergkvist and Öborn 2011). In addition, interest grew in the effect of manure on crop yield and the effect of the preceding crop on the subsequent crop yield. Many of the long-term experiments that started in the 1950s and 1960s in Sweden were set up to investigate the effects of crop rotation and cropping systems on crop yield and soil fertility (Bergkvist and Öborn 2011). Additional long-term experiments were established to focus on different aspects of field management (e.g. plant nutrition, soil management, water management). The Swedish University of Agricultural Sciences (SLU) has hosted and funded the experiments since it was started in 1977. In 2007, a management board was established with the responsibility to enhance the quality of the experiments and increase the awareness of them, in order to increase their scientific and industrial impact.

The crop rotation and cropping system experiment presented here (R8-71B) was initiated in the 1950s and is thus one of the oldest of SLU's long-term experiments, set up at three sites (Ås, Offer and Röbäcksdalen), and treatments differ in number of years with leys in the crop rotation. The experiment (R8-71B) is hosted by the Department of Agricultural Research for Northern Sweden of SLU, based in Umeå. In Northern Sweden (including Västernorrland, Jämtland, Västerbotten, and Norrbotten counties), 79% of arable land is used for perennial forage crops (SCB 2017). A typical cropping sequence in the early 1950s in this region was 3–8 years of ley followed by 1–2 years of annual crops (Ericson 1994). A strength of the experimental design is that all crops of different phases in the crop rotation are grown every year. The experiment has potential appeal for researchers as much of the data are not yet explored. Published papers dealing with the experiment mainly focus on the effects of cropping systems on soil characteristics, whereas other data are under-explored. The objectives of this paper are to:

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(1) Create awareness of the experiment,
(2) Summarise the history of the experiment and experimental treatments,
(3) Summarise the published studies from the experiment so far, and their implications for agriculture,
(4) Identify research questions, and opportunities for further studies and analysis of the data.

Materials and methods

Locations

The experiment was located at three experimental stations at Ås, Offer and Röbäcksdalen (Figure 1). The monthly accumulated precipitation and monthly average temperature are presented in Figure 2. The annual precipitation at Ås, Offer and Röbäcksdalen is 558, 606 and 637 mm, respectively. The soil texture and coordinate details of each site are summarised in Table 1. The soil at each site is a *Podzol* according to the FAO classification. At the initial year of experiment (Röbäcksdalen 1958; Offer 1956; Ås 1955), The C concentration at topsoil were 3.9%, 2.8% and 4.8% (Bolinder et al. 2010) in Ås, Offer and Röbäcksdalen, respectively. The N concentration at topsoil were 0.33%, 0.26% and 0.25% (Bolinder et al. 2010) in Ås, Offer and Röbäcksdalen, respectively. pH $_{(H2O)}$ were around 6.4, 6 and 6 in the topsoil of Ås, Offer and Röbäcksdalen, respectively. The ammonium lactate (AL)-extracted K and P contents of topsoil were 8.9 and 14.0 mg 100 g^{-1} dry soil in Ås. The AL-extracted K and P contents of topsoil were 7.3 and 8.5 mg 100 g^{-1} dry soil in Röbäcksdalen.

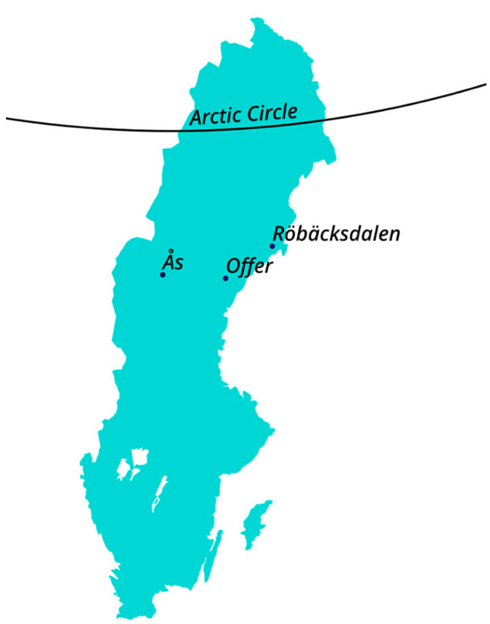

Figure 1. Location of experimental stations in Sweden.

The exact cropping history prior to the experiment is unknown at Offer or Ås, however in these areas land use was mostly forage crop. The field at Röbäcksdalen was poorly drained grassland prior to the experiment.

Experimental design and revision of the experiment

Four treatments (A, B, C and D) represent different six-year cropping systems with increasing intensity of annual cropping (Table 2). System A is livestock-focused, with five years of ley and one year of barley with ley under-sown. System B is also focused on producing forage for livestock, and includes a typical length ley (three years) with three years of annual crops for forage. System C has a greater focus on annual crops, but still produces much forage, with a shorter than normal ley (two years) and four years of annual crops. System D is a completely annual cropping system, with one year of ley that is cultivated as a green manure. It represents a cropping system that is not linked with livestock production. The different cropping systems and the amount and timing of dairy cattle manure applications are listed in Table 2.

All crops in a rotation are present each year, to enable analysis of annual variation and to reduce the importance of individual years on overall effects of treatments. Each treatment is replicated twice, resulting in 48 plots in total at each site (4 rotation treatments × 6 phases × 2 replicates). Plot sizes were 8 × 20 m, 9 × 22.5 m and 9 × 21 m at Offer, Röbäcksdalen and Ås, respectively. The experimental design at Ås and Röbäcksdalen was a split-plot with rotation as main plots and phases as subplots. At Offer, phases form the main plots and rotation the subplots. The crops at all sites include spring barley (*Hordeum vulgare* L.), winter rye (*Secale cereale* L.), potato (*Solanum tuberosum* L.), spring peas (*Pisum sativum* L.), spring oats (*Avena sativa* L.), spring fodder rape (*Brassica napus* L.), and carrot (*Daucus carota* L.) The components of the ley include red clover (*Trifolium pratense* L.), timothy (*Phleum pratense* L.) and meadow fescue (*Festuca pratensis* Huds.) All of the cropping systems start with barley under-sown with the forage mixture.

In 1987, the experiment was revised in order to simplify management and reduce costs. The experiment had already been running for approximately thirty years, and it was decided that the experiment would be reduced in size rather than abandoned. There was some updating of crops and sequence changes in the rotations (Table 2) to better represent cropping practices of the time, but staying within the concept of the initial cropping systems. The experiment was reduced to one

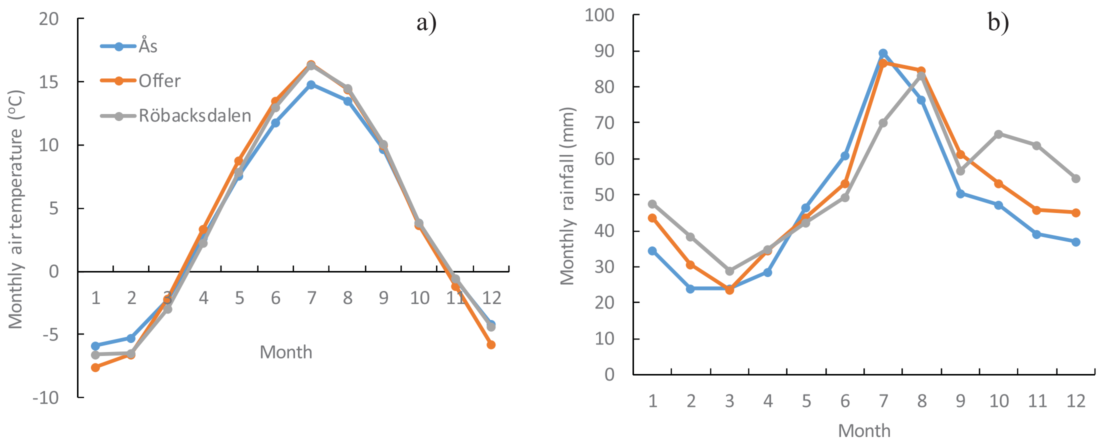

Figure 2. Monthly average (a) air temperature and (b) precipitation (1997–2016) at Ås, Offer and Röbäcksdalen.

Table 1. Overview of the three sites comprising the long-term experiment.

				Topsoil		
Site	Initial year of experiment	End year	Latitude and longitude	Depth (cm)	Clay content (%)	Soil texture
Ås	1955	1994	63.25 N 14.56 E	0–25	20[a]	Gravely loam
Offer	1956	Ongoing	63.14 N 17.75 E	0–25	30[b]	Silty clay loam
Röbäcksdalen	1958	1994	63.81 N 20.24 E	0–30	10–15[a]	Clay silt loam

[a](Ericson 1994).
[b](Jarvis et al. 2017).

Table 2. Crop rotations of the four cropping systems at Röbäcksdalen, Offer and Ås. The crops in parentheses are those grown after 1987, when the plan was revised.

Cropping System	Phases of crop rotations in different year (Phases)					
	1st Year	2nd Year	3th Year	4th Year	5th Year	6th Year
A	Barley under-sown with ley	Ley 1	Ley 2	Ley 3[a]	Ley 4[a]	Ley 5[a]
B	Barley under-sown with ley	Ley 1	Ley 2	Ley 3[a]	Oats/peas (barley fodder)	Forage rape (rape/barley/peas mixture[b])
C	Barley under-sown with ley	Ley 1	Ley 2	Winter rye (barley)	Oats/peas (potatoes)	Potatoes (rape/barley/peas mixture[b])
D	Barley under-sown with ley	Ley as green manure	Winter rye[c] (barley)	Peas (potatoes)	Potatoes (barley)	Carrots/swedes (potatoes)

[a]Manure (20 t/ha) was applied in the autumn.
[b]Manure (40 t/ha) was applied in the autumn.
[c]All annual crops except winter rye were spring crop.

replicate (24 plots) per site, making the data less suitable for statistical analysis. All crop systems are replicated six times, once for each phase in the rotation, with phase as main plot and cropping system as sub-plot. The second major change was in 1994 when the plots at Röbäcksdalen and Ås were closed, due to lack of funding. The experiment (24 plots) continues at Offer.

Agronomic management, data collection and sample storage

Crop varieties have changed over time when improved ones are introduced to the market. Both mechanical and chemical weed management are used. If necessary, pesticides are used to control pathogens, such as late blight in potatoes. The details of synthetic N, P and K fertiliser application rates are listed in supplementary materials Tables 1–3. Ploughing is done in the autumn before harrowing and sowing of annual crops. If there is much winter damage in a ley, it is harrowed in the spring and subsequently re-sown.

The timing of harvest for each crop species is determined by local best practice. All harvesting is done using machinery.

The yield of each crop has been recorded from the beginning of experiment. Leys are harvested twice

Table 3. Summary of data collected during the experiment. Data collection began in 1962. Data collection ended at Röbäcksdälen and Ås in 1986 and is ongoing at Offer.

Sample/Characteristics	Details	Sample Storage	Completed Analyses
Topsoil	0–20 cm, every 6th year.	Dried samples	pH, Total N, P, K and C
Subsoil	30–40 cm, every 12th year.	Dried samples	pH, Total N, P, K and C
Manure	From dairy cattle farm	Dried samples	No analysis
Ley biomass yield	Ley yield for 1st and 2nd cutting	Dried ground samples (1 mm)	Crude protein, crude fat, crude fiber content (only for 1963–1986)
Botanical composition (BC) of leys	Determined by hand separation for both cuts until 1987. Thereafter, BC was determined by hand separation for 1st cutting and eye estimation for 2nd cutting.		
Yield of other crops	Cereal kernels and straw; oats in green fodder; potato (tubers); rape in green fodder; swedes (data are not complete); carrots (data are not complete); peas; winter rye.	Dried ground samples (1 mm)	Crude protein, crude fat, crude fiber content (only for 1963–1986)
Agronomic management	Sowing and harvest date, application rate and dates of chemical fertiliser and manure, cultivars used for each crop.		

each season. In potatoes, only the yield of tubers is determined, and leaves are left in the plots. For cereals, grain and straw fresh and dry matter yields are measured. Straw is harvested and then returned to the respective plots. For the first harvest of leys, botanical composition on a dry matter basis is determined for each plot by hand separation (this was done for both harvests up to 1987). The fraction of clover is also estimated by eye for both harvests. For the 'ley as green manure' in treatment D, the first harvest is done in the same manner as for other cropping systems, whereas ley from the second harvest is directly ploughed into the soil as a green manure in the autumn.

Every 6th year the top soil (0–20 cm) is sampled in each plot. Every 12th year the subsoil (30–40 cm) is also sampled. Manure used in the experiment is dried. All samples of crops, manures, and soils are archived in a dried state. Details of sampling, storage of sample, and analyses are in Table 3.

Results and discussion

Effects of treatments on soil characteristics

The publications that have used data from the long-term experiment have mainly focused on soil dynamics. A synthesis of the soil-related results is presented in (Table 4). Treatments are grouped into ley dominated cropping systems (A and B) and annual crop dominated cropping systems (C and D) for ease of comparison.

The summary table highlights that both soil porosity and hydraulic conductivity were greater in systems A and B, investigated by Ericson (1994) with data from 1987. Both a recent soil sampling from 2013 to 2014 (Jarvis et al. 2017) and an older soil sampling from 1987 (Ericson 1994) indicate that soil bulk density is lower in A and B than C and D. The A and B plots also have greater soil organic carbon content than C and D plots. This was confirmed by both a study using soil samples taken at 3–5 occasions (spanning from the start of the experiment to 1987 in Offer, Röbäcksdalen and Ås) (Ericson 1994) and a recent study with soil sampling in 2010 (Jarvis et al. 2017). These results imply that compared to cropping systems with only annual crops, ley dominated cropping systems improve or maintain both the physical and chemical soil properties.

In addition to the results mentioned above, the effects of cropping system on earthworm species have been investigated by Jarvis et al. (2017), who found that the grass-clover leys promoted larger numbers and biomass of topsoil-dwelling earthworm species.

Table 4. Comparison of soil physical and chemical properties between ley dominated (A and B) and annual crop dominated systems (C and D).

Soil properties	Comparison of ley dominated systems (A and B) and annual crop dominated systems (C and D)	Year of soil sampling or measurement	Reference
Bulk density	(A and B) < (C and D)	1987 2013 and 2014	Ericson (1994) Jarvis et al. (2017)
Porosity	(A and B) > (C and D)	1987	Ericson (1994)
Saturated hydraulic conductivity	(A and B) > (C and D)	1987	Ericson (1994)
Topsoil organic carbon	(A and B) > (C and D)	1972 and 1987 2010	Ericson (1994) Jarvis et al. (2017)
Barley root depth	(A and B) > (C and D)	1987	Ericson and Mattsson (2000)

> indicates greater than, < indicates less than.

Trends in soil organic carbon and nitrogen over time

System A tended to increase soil organic carbon (SOC) from the 1950s to 1987 in two out of three sites, whereas system B maintained SOC in two out of three sites, and C and D decreased SOC over time (Ericson 1994). A study conducted in 2008 also confirmed that A was the only system that increased soil organic carbon over the period of 1956–2008 (Bolinder et al. 2010). System A increased soil organic nitrogen (SON) at two out of three sites, whereas other treatments decreased SON (Bolinder et al. 2010). It should be noted that systems A and B received more cattle manure than C and D, and thus the effects of perennial leys and the effect of manure are impossible to separate in the analysis. This is due to the farming system design of the experiment, which focused on comparing the complete systems rather than attempting to isolate component effects of the systems.

Effects of treatments on crops

The positive effects of ley dominated systems on soil physical characteristics may partially explain the positive plant responses to these systems. The root depth of barley was greatest in A and lowest in D at Offer and Röbäcksdalen (Ericson and Mattsson 2000). An increase in barley yield over time was observed for systems A (Ås and Offer) and B (only in Offer), whereas systems C and D resulted in unchanged yield or decreased yield over time 1963–1986 (Ericson 1994; Ericson and Mattsson 2000).

Implications of the experiment for agriculture

To develop a sustainable cropping system, the effects on soil organic matter and soil physical properties should be considered. The results to date have demonstrated that ley cropping systems positively contribute to accumulated soil organic matter. This corroborates studies which found that conversion of continuous annual cropping to a ley cropping system can maintain soil organic matter storage (VandenBygaart et al. 2003; Smith 2004; Kätterer et al. 2012). This can be explained in a number of ways. Firstly, a longer root growth period of perennial leys than annuals means more C is allocated to roots resulting in more input of C to the soil over time. Biomass allocation to roots is particularly important for maintaining soil C as root-derived C has a longer turnover time than above-ground C. Secondly, more evapotranspiration in leys leads to lower soil water content and soil temperature, which in turn decreases decomposition and conserves soil organic matter (Kätterer and Andrén 2009). In addition, the reduced tillage in ley systems leads to less decomposition and higher soil organic matter than soils under high-intensity tillage systems (http://www.eviem.se/en/projects/SOC-Tillage/). In annual crops, tillage makes soil organic matter more likely to decompose and vulnerable to water and wind erosion (Bronick and Lal 2005; Bolinder et al. 2012). The ley also benefits soil physical properties, including increased porosity, increased size and stability of soil aggregates, and increased water retention (Greenland 1971; Ericson 1994; Watson et al. 2002; Ball et al. 2005), especially areas with poor soil structure that are subject to crust formation. In addition, a ley cropping system can increase soil biological activity (Ponge et al. 2013).

A ley cropping system may perform some or all of the following agronomic functions: nutrient addition, conservation and nutrient cycling, improvement in soil physical characteristics, increased soil biological activity, and a break in soil pathogen cycles. The cropping system should also produce satisfactory yields for crops in the rotation. St-Martin et al. (2017) found that cropping systems incorporating grass and clover can lead to higher wheat yields compared to cropping systems without grass-clover. Davis et al. (2012) found that incorporating more legume-based forage crops in a crop rotation can have similar or greater grain yield and profit compared to a conventional maize-soybean rotation. The benefit of a ley phase on cereal yield can be due to added N by the legume component, increased soil organic matter (Arvidsson 1998; Chalk 1998), and other functions such as mentioned above. With respect to environmental effects, crop rotations with leys can also lead to less fresh water pollution arising from nitrate leaching, as the permanent root system of leys can efficiently take up N throughout the year.

Opportunities for further research

In addition to the already published results, there are still many aspects and data that can be explored from this long-term experiment. In our view, the following areas warrant further study:

(1) Crop yield data have not been published except for barley yield results from 1963 to 1986, even though yield effects were a main motivation of the experiment. Yield data is the most complete dataset among the measured variables and could be analyzed over the whole time series of the experiment at the three sites. Yield data can be used to calibrate crop simulation models for several crop

species. Model calibration work can take advantage of available climate data and specifically the soil chemical and physical properties data that are archived or already reported in publications, or that can be analysed from archived soil samples.

(2) Yield data of leys. An original aim of the experiment was to compare yields of leys under different cropping systems; however, ley yield data is unexplored. Again, the data can be used for calibration of models that simulate ley production.

(3) Botanical composition of leys. The data can be used to investigate the effects of cropping systems on botanical composition. Clover content is largely affected by variations in soil fertility (especially differences in soil N content), and by the age of the ley. The botanical composition data are also highly valuable for calibration of mixed species ley models.

(4) Data of changes in soil carbon over time can also be used to test and calibrate existing soil carbon models, particularly how they respond to differing cropping systems treatments. Researchers can make use of the ongoing experiment at Offer, archived soil samples from all experimental sites, and previously analysed data.

The database of the long-term experiment is continuously updated. Data are accessible on request from the experiment coordinator (https://www.slu.se/en/faculties/nj/about-the-faculty/collaborative-centres-and-major-research-platforms/long-term-field-experiments-/).

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