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Making Crop Rotations Fit for the Future

Long-term field experiments in Sweden – what are they designed to study and what could they be used for?

By G BERGKVIST and I ÖBORN

Swedish University of Agricultural Sciences (SLU), Department of Crop Production Ecology, Box 7043, SE-750 07 Uppsala, Sweden

Summary

Long-term field experiments (LTEs) have proven a useful resource when assessing the impact of different management practices on soil, water and production. Departments at the Faculty of Natural Resources and Agricultural Sciences at the Swedish University of Agricultural Sciences run more than forty long-term field experiments. The oldest LTEs typically investigate the effect of cropping systems, crop rotations and fertiliser regimes on yield and soil fertility. More recent experiments concentrate on making efficient use of soil resources and on environmental effects of crop production and different management practices. In 2007 a Management Board was formed to encourage Departments to re-evaluate their existing LTEs and even start new field experiments that are destined to become long-term. The new LTEs should serve as research platforms and be useful for several disciplines. In this paper we reflect on the present LTEs and discuss how useful they are, and the need for new LTEs.

Key words: Cropping system, crop rotation, soil fertility, soil and water management, water quality

Introduction

Long-term field experiments (LTE) have proven a useful resource when assessing the impact of different management practices on, *e.g.* soil structure, soil fertility and water quality. As new issues emerge they can often quickly be addressed by using long-term data, conducting new studies in the LTEs or by performing new analyses on archived soil from the LTEs. However, resources to cover the annual costs of maintenance, recording, sampling, sample storage and data handling are often lacking because research budgets mainly support short-term projects.

The Departments at the Faculty of Natural Resources and Agricultural Sciences (NL), the Swedish University of Agricultural Sciences (SLU), are responsible for about forty LTEs that, to large extent, are financed by the NL-faculty through the core funding (Table 1). Many of the experiments are located at more than one site, which make a total of about 80 trials. The oldest LTE still running originates from 1936 and the most recent LTE was started in 2010. Experiments at 26 sites are more than 40 years old, which does not make them exceptionally old in an international perspective, but old enough for the treatments to have had a substantial impact on soil traits. The design and objectives of the individual experiments is most often a reflection of the problems that were considered important at the time of the LTEs initiation. The oldest LTEs typically investigate the effect of cropping systems, crop rotations and fertiliser regimes on yield and soil fertility.

More recent experiments focus more on making efficient use of soil resources or environmental effects of crop production and different management practices.

In this paper we introduce and briefly describe the ongoing Swedish LTEs and reflect on the topics and design of trials that were started in different time periods. We discuss how the LTEs have been used and can be used as well as suggest topics and designs for new LTEs. Finally, we raise the question as to when it is acceptable or timely to close down old experiments in order to liberate funding for new trials meeting the demands of the future.

History of the Swedish Long-term Field Experiments

There were some long-term experiments in Sweden in the first half of the 20^{th} century, but they were considered mainly to be of regional interest and did not have any national support. Thus few of these remain today. After World War II, Swedish farmers became more and more specialised and the use of mineral fertiliser increased rapidly. There was great concern about how this specialisation would affect soil fertility and yields, particularly as the trend of specialisation resulted in the separation of predominantly livestock and predominantly cropping farms. There was a great awareness of the importance of animal manure for sustaining high yield levels and also understanding that the preceding crop affected yields, but there was insufficient experimental evidence to study these issues. Therefore, a need for LTEs was identified and the oldest LTEs were largely designed to investigate the effect of crop rotation and cropping systems on productivity and soil fertility.

At present, the responsibility of the LTEs has been delegated from the NL-Faculty to research groups within different Departments. In most cases these groups have a history linked to units formed during the 1960s. For many years the groups managed their LTEs with little interaction with each other. At the suggestion of an international review of the LTEs (Goulding & Snapp, 2006), the NL-Faculty decided to form a Management Board, starting in 2007. The Management Board has a general responsibility to work for improved quality, to increase awareness of the LTEs in order to increase use of the experiments, and to recommend changes in plans and management when necessary. The scientific responsibility for each individual LTE still remains at the Department level. The Management Board has a chairman appointed by the Dean, a coordinator appointed by the chairman, one representative from the Field Research Unit (contact unit between SLU and external organisations involved in agricultural field research) and one representative from each research group hosting LTEs. In this paper we have chosen to present the experiments according to subject area. The existing trials are listed in Table 1, where the starting year and number of experimental sites are also given.

Plant Nutrition and Soil Biology

The Soil biology experiments

Perhaps the most well-known LTE is the Frame experiment (FRAME-56), where the effect of different carbon sources, such as cereal straw, peat, green manure, sawdust, manure, and sewage sludge are compared to different treatments with mineral fertilisers. The experiment also includes control treatments without fertiliser and without both fertiliser and crop (black fallow) (Kirchmann *et al.*, 2004). Each plot is 2 m × 2 m and the plots are separated with steel frames. There have been more than 60 papers published with data from this experiment. The most recent studies investigate effects on the organic matter or the microbial communities (e.g. Magid *et al.,* 2010; Wessén *et al.*, 2010; Kätterer *et al.*, 2011; Börjesson *et al.*, in press). Molecular techniques developed during recent decades have opened up new avenues of use for the experiment and generated many publications.

Table 1. *Long-term experiments fully or partly financed by the Faculty of Natural Resources and Agricultural Sciences (NL) at the Swedish University of Agricultural Sciences (SLU)*

Serial no.	Name of series	Start 19- or 20-	No. of sites
Plant nutrition and soil biology			
FRAME-56	Organic matter experiment	-56	1
R3-0130	Soil Biology experiment	-96	1
R3-0020	Humus balance, cereal system	-70, -80, -81	
R3-0021	Humus balance, clover/grass system		
R3-9001	Soil fertility experiments, central and south Sweden	-57, -63, -66	9*
R3-2037	Soil fertility experiments, north Sweden	-69	2
R3-1001	Lime and phosphorous	-36, -41	2
R3-1002	Lime and organic matter	-63	2
R3-1037	Lime and soil chemical properties	-83	2
R3-3038	Exploiting P in heavily P dressed soils	-82, -83	3
R3- 0056	Cropping systems, environmental effects	-79	1
Soil management			
R2-4007	Different tillage systems – need for soil loosening	-74	1
R2-4008	Different tillage systems – different intensities	-74	1
R2-4009	Different tillage systems – placement of fertiliser	-76	1
R2-4010	Different tillage systems – straw management	-74	1
R2-4027	Tillage depth in plough less tillage	-91, -95	2
R2-4017	Direct drilling	-82	1
R2-4111	Time of primary tillage in the autumn – effect on crop yield, soil structure and nitrogen mineralization	-99	1
R2-4014	Subsiding of peat soil	-76	1
R2-7115	Low tyre inflation pressures in tillage systems with and without ploughing	-97	3
R2-8407	Nitrogen efficient tillage systems	-99	1
Water management			
R1-138	Subsidence of peat soils	-86	7
R1-143	Long term effects of liming on soil structure	-89, -91, -99	5
R1-150	Regulated water table	-00	1
Water quality management			
Mellby, Lanna	Organic cropping systems	-90, -96	4**
Mellby	Manure , time of soil tillage, catch crops	-83	1
Fotegården	Manure, time of soil tillage, catch crops	-93	1
Lanna	Soil tillage strategies, catch crops, set-aside land	-93	1
Lönnstorp	South Swedish crop rotations, catch crops	-92	1
Landscape ecology			
	Broadened agricultural field boundaries	-88	2***
Crop rotation and cropping systems			
R4-0002	Crop rotation with different cropping strategies	-59	1
R4-0009	Maize and winter wheat in monoculture and rotation	-11	1
R4-1103	Crop rotations with or without ley	-64, -67, -68	3
R8-71B	Different crop rotations	-56	1
R4-906	Spring cereals in monoculture	-67	1
R8-74	Monocultures in northern Sweden	-65	3

*including the Örja site, which has been moved; **not identical experiments; ***two experiments with different sown or planted species; these are not considered further (see e.g. Bokenstrand *et al.*, 2004).

The application of techniques in soil molecular ecology can be expected to continue and also spread to more field scale experiments like the soil biology experiment (R3-0130), which started in 1996 and is a simplified field scale version of the Frame experiment. The greatest strengths of the Frame experiment are that i) the same amount of carbon is added in all treatments with organic amendments, ii) the frames makes transport flows among plots negligible, and iii) there are sufficient replications (four) and control treatments. The major weakness is that it is labour intensive and that soil sampling has to be restricted due to the small plot sizes. In the Soil biology experiment started in 1996, treatments are comparable with respect to dry matter, plots are large - about 100 m^2, and there are four replicates.

In the two Humus balance series, with cereal (R3-0020) and clover/grass (R3-0021) rotations, the effect of N-fertiliser (four rates) is investigated (four replicates). P and K are added according to the maintenance principle, i.e. replacing P and K lost from the field with harvested products, and other nutrients are applied according to the expected needs. The effect of removing the straw is investigated in main plots in the series with cereal crops. The oldest experiments are from 1970. Even though the treatments are rather straightforward and seem easy to use, there have been rather few papers published with data from these series (e.g. Röing *et al.*, 2005).

The soil fertility experiments

The soil fertility experiments (R3-9001 and R3-2037) started as a result of the concerns about the effect of specialisation and separation of plant and animal production. The first five experiments (originally six) in this series with a total of 12 sites were started in southern Sweden (~56˚N) in 1957 by Professor Lars Agerberg, but acquired their present form under the direction of Professor Sven L. Jansson in the early 1960s (Jansson, 1975). During the 1960s, seven new sites were established, five at latitude 58–60ºN and two at latitude 63–64ºN (Carlgren & Mattsson, 2001). Ten of the soil fertility experiments are still running according to the plan by Jansson, but one has recently been closed due to extensive problems with wild boars, and another one has been moved due to city expansion (the Örja site, we will return to this later) and is no longer included in the series. A third is in danger due to road construction.

In the main plots of the experiments, a crop rotation adjusted to dairy production is compared with a crop rotation without livestock. The main plots are replicated twice at each site. The crop rotation with livestock contains rotational grass/clover leys and application of farmyard manure (FYM), while the crop rotation without animals only has annual crops and mineral fertilizers. Otherwise the crop rotations are similar between the systems. At most sites there are all combinations of four PK-treatments and four N-treatments in each main plot (Table 2). The crop rotations and N-rates are adapted to region.

Most publications from the Soil fertility experiments focus on long term effects on nutrient mineralisation, fixation and availability (recent e.g. Börling *et al*., 2004; Andersson *et al.*, 2007; Kirchmann *et al*., 2009; Simonsson *et al*., 2007; 2009; Boye *et al*., 2010). Surprisingly little has been done regarding emissions (e.g. Djodjic *et al*., 2004) and effects of environment and treatments on soil microbes and humus.

Since there are few replications at each site, many studies use several experiments in the evaluation. Goulding & Snapp (2006) emphasised the importance of multiple sites when evaluating the effects of treatments, since the environment can be expected to profoundly influence the treatments. Thus it is a large problem when experiments are lost. In many cases the loss of experiments is due to city expansion and road construction. Many of the experiments were placed close to roads for easily accessibility, but there is a risk of conflicting interests. The experimental cost has increased more than the income over time, thus there is also an economic argument to close experiments. It is difficult to say how many sites can be lost without the remaining experiments losing their value, but we are probably close to that limit.

Table 2. *Experimental plan from the middle latitude group of the soil fertility trials started in the 1960-ties*

With livestock	Without livestock	PK (kg ha^{-1} year^{-1})	N (kg ha^{-1} yr^{-1})
Barley (undersown)	Barley	No PK	0
Clover/grass	Oats	Maintenance	41
Clover/grass	Spring oil seed	Maintenance + 20 P + 50 K	82
Winter wheat	Winter wheat	Maintenance + 30 P + 80 K	125
Oats	Oats		
Winter wheat	Winter wheat		

The decision to move the soil fertility experiment at Örja was very difficult, because of the great cost and because there are reservations as to whether or not it would really have any remaining long-term value. But the researchers who were responsible for the experiment and other local stakeholders insisted that the experiment should not be lost. They argued so well that Landskrona Municipality and the Department of Soil and Environment at SLU agreed to pay the cost of moving the experiment. Researchers are interested in investigating the effect of sub-soil in determining fertility and the Soil fertility experiments would probably be suitable for those investigations. The relocated experiment should be of particular interest because it can be used for investigations on how much of the fertility difference among treatments remain when the top-soil is moved to new subsoil.

The phosphorous and lime experiments

The oldest experiments in this group (R3-1001) were started in 1936 and 1941 with the aim of investigating the effect of P, with and without liming. They are designed in split-split-plots (two replicates). Initial liming or not is compared in main-plots, liming after about 40 years or not in split-plots, and five different P-fertiliser treatments in split-split-plots. In later series (R3-1002; R3-1037) the effect of liming to different degrees of base saturation are investigated. The series R3-1037 were started on about 30 sites, of which two remain (e.g. Haak & Siman, 1992; Jansson, 2002). The most recent series (R3-3038) focuses on exploiting P resources already available in the soil, while the older series are more focussed on optimising the use of P and lime. The change in focus is probably a reflection of the rapid increase in the use of lime and P after World War II that resulted in soils with a very high content of soluble P, particularly in regions with a lot of livestock. This has contributed to problems with eutrophication and lead to the need for experiments investigating the possibilities for reducing inputs of P and N to agricultural systems. The experiments in this group have generated reports in Swedish, but very few in the last decade (e.g. Mattsson, 2001; Mattsson *et al.*, 2001). There is a sufficient number of replicates, they are rather easy to manage and studies on the effect of nutrient availability at different levels of base saturation should interest an international audience. It is our conclusion that the poor scientific use of the experiments is more due to lack of interest from researchers rather than irrelevant treatments.

Cropping systems and environmental effects

Only one experiment remains in this group (R3-0056). It started at Lanna in 1979 and presently compares five cropping systems (originally seven) in 4830 m^2 separately tile drained plots. Two of the systems include rotational leys and FYM. The other three systems differ mainly in the intensity of fertiliser use. Yields are measured in three harvest plots per system, but there are no true replicates. Data from the experiment is presented by Mattsson (2003).

Soil Management

The oldest LTEs hosted by the Soil Management Group were started as a response to the increased interest in energy issues after the oil crises in the 1970s and study the use of non-inversion tillage (Table 1). The aim of the experiments is to determine under which conditions non-inversion tillage is more efficient than mouldboard ploughing (R2-4007, -4008, -4009 and -4010). Recent research includes particle transport in reduced tillage systems (Etana *et al.*, 2009) and stratification of P and C depending on tillage system. Experiments on non-inversion tillage systems are still considered to be of great interest and in the 1990s new experiments were started to study the optimisation of timing (R2-4111) and depth (R2-4027) of tillage. Direct drilling is only investigated in a single experiment (R2-4017) started in 1982 and the group would like to investigate long term effects of direct drilling in more experiments. The group also consider that there is a lack of treatments in the LTEs that optimise soil tillage according to environmental factors and plan to include more of such treatments in the future.

In 1997 the group started LTEs to study the importance of tyre inflation pressure on production and soil properties (R2-7117) as response to increasing problems with soil compaction experienced in Swedish agriculture. With this problem in mind they are also interested in incorporating already existing experiments using permanent wheel tracks (controlled traffic) into the LTEs if resources become available.

It has also recognised that soil tillage is tightly linked to nutrient leaching, thus an LTE conducted in six separately tile drained plots compares a conventional tillage system with a tillage system optimised to reduce nitrogen losses and was started in 1999 (R2-8407). The special environmental and soil conservation problems associated with agriculture on peat soils are addressed in an experiment comparing different tillage systems with a permanent grassland control (R2-4014).

Water Management

The Water Management Group conduct research on drainage and irrigation as well as on measures that affect soil physical properties and influence the availability of water, air, and nutrients in arable soils. The subsidence of peat soils is monitored in seven LTEs (R1-138) and research at the monitored sites is conducted when research funding is available. Present research focuses on factors influencing greenhouse gas emissions from organic soils (e.g. Berglund & Berglund, 2011*a*). The effects of different liming products on soil structure are investigated at five sites (R1-143) and are presently being evaluated in a PhD-project. The Water management group is expanding their activities within this field and several short term experiments have been established in 2011 to complement the long-term experiments. The group also hosts a site with controlled drainage, where the ground water table is individually regulated among plots (R1-150) in order to minimise leaching of nutrients (e.g. Salazar *et al.*, 2011).

Water Quality Management

The LTEs are hosted by the Biogeophysics and Water Quality Group and all these LTEs consist of separately tile-drained plots with continuous measurements of drainage flow, and flow-proportional sampling of water. There are, in total, 65 plots distributed in eight LTEs at four sites. The oldest experiment started in the 1980s and the number of sites has increased over time as the link between agricultural production and eutrophication of freshwater and coastal areas has generated an increasing interest. There have been some changes in the experimental plans over time in order to improve the relevance of the studies and to increase the number of replicates.

Organic systems are monitored in four LTEs, at Lanna and Mellby (Aronsson *et al.*, 2007; Torstensson *et al.*, 2006; Nemann *et al.*, 2011). There are systems with and without livestock at both sites and all crops in the rotations are included each year, but there are no true replicates within year. The effect of long-term applications of FYM and catch crops are studied in parallel LTEs at Mellby and Fotegården (Torstensson & Aronsson, 2000; Liu *et al.*, 2011) and the effect of soil tillage intensity is the focus of an LTE at Lanna (Aronsson & Stenberg, 2010). Crop rotations of particular interest for southern Sweden, with and without catch crops, are monitored at Lönnstorp.

Presently, research concentrates on N and P leaching, but the sites are also used for additional short-term studies of pesticide leaching, ammonia and greenhouse gas emissions. They are also used for estimations of the expected effect of climate change on all kinds of losses from the systems. Four of the experiments receive additional financial support from the Swedish Board of Agriculture, and they are continuously used for developing strategies for reduction of nutrient losses and improved nutrient use efficiency on farms.

Weed Science

The weed science group is in the process of closing down their old experiments and starting new ones (not in Table 1). The old LTEs concerned the flora in semi-natural grasslands and they were considered difficult to use for new research questions. Thus it has been decided that they will not continue. Plans for new LTEs have recently been accepted by the Management Board. The new LTEs will mainly investigate the effect of cropping system on the occurrence of winter annual grass weeds and also consider the herbicide resistance issue. Winter annual grass weeds are considered to be a major problem in present cropping systems in southern Sweden, where there is increased use of non-inversion tillage in combination with an increasing proportion of winter annual crops in the rotations.

Crop Rotation and Cropping Systems

The LTEs investigating crop rotation and cropping systems are hosted by the Cropping system group at the Department of Crop Production Ecology or by the Department of Agricultural Research for Northern Sweden. In the 1970s, the Unit of crop rotation hosted about 50 LTEs of which only five remain in 2011 (Table 1). All the experiments, except one, started in the 1950s or in the 1960s and were initiated to meet the need for more knowledge about the effect of specialisation. The largest difference between the LTEs in this group and most other LTEs is that all crops in a rotation are present each year to make them appropriate to study annual variation and to reduce the importance of individual years on overall impacts of treatments. Due to size limitations this also means that they only have one or two true replicates, even if the systems are replicated many times (usually six crops in the rotation). This makes them less suitable for studies that require replicates within a year, but they are very useful for studying time series. The experiments can roughly be divided into two groups. The first group investigates how the effect of the preceding crop on crop yield changes over time depending on the cropping strategy, and the second group studies the effect of using break crops in rotations.

In the first group of LTEs a "traditional" mixed crop strategy including rotational leys and FYM was compared with two modern crop rotations adapted to agriculture without cattle. One of the "modern" crop rotations is well balanced to reduce the risk of damage due to diseases and weeds. Crop residues are ploughed under and a one-year grass/clover crop is included to support soil fertility. This rotation is quite close to those used in current organic farming without animals. The second modern sequence includes a large percentage of the most profitable crops. The crop residues are burned or removed to reduce the carry-over of diseases from one crop to the next. Of about ten LTEs originally in this series only one remains (R4-0002, Table 3). The remaining LTE is considered to be a very valuable, but despite this very little has been published using data from this experiment. However, Eckersten *et al*. (2010) used data from this and other LTEs to evaluate the effect of weather on yield trends and variability. At present, there is a great interest among researchers to work with cropping systems and the experiment can be expected to generate much research in the years to come. One early finding from this group of experiments was that the effect of cropping systems on yield was negligible in comparison to the effect of preceding crop (Nyström, 1976). This finding can now be re-evaluated with data from about 35 more years.

Table 3. *Three 8-year rotations, with year in the rotation as main-plot and cropping strategy in sub-plots as compared at the LTE at Borgeby (R4-0002; 55º N, 13º E)*

Traditional mixed	Without livestock – exploitive	Without livestock – sustainable
Winter wheat (r)	Winter wheat 1 (b)	Winter wheat 1 (p)
Sugar beet (am, r)	Sugar beet (r)	Sugar beet (p)
Barley under-sown (r)	Barley 1 (b)	Barley under-sown (l)
Clover/grass ley 1	Winter oilseed rape 1 (b)	Clover/grass green manure (p)
Clover/grass ley 2 (p)	Winter oilseed rape 2 (b)	Winter oilseed rape (p)
Winter oilseed rape (p)	Winter wheat 2 (b)	Winter wheat 2 (p)
Spring wheat (r)	Spring wheat 1 (b)	Spring wheat (p)
Peas (r)	Barley 2 (b)	Peas (p)

Crop residues are removed (r), ploughed under (p), burned (b) or left in the field (l) and FYM is applied to the sugar beet crop in the traditional rotation (am). The experiment has two replicates and 48 plots (20 m × 9 m = 180 m²).

The second group of experiments include a series (R4-1103) that compares crop rotations with and without grass and grass/clover leys at four N-levels. This series has recently been used to study the effect of rotational leys on carbon stocks and winter wheat yields (Persson *et al*., 2008) and is, at present, used to study the effect of leys on, for example, plant species and earthworm diversity within the EU-FP7 project, Legume Futures, and in a life-cycle assessment of the effect of rotational leys in the rotation. The importance of the number of years with grass/clover leys in a rotation is investigated in an LTE at Offer (R8-71B; 63ºN, 18ºE). The second group of experiments also contain monoculture experiments and there were originally many of these. Today, one LTE remains that investigates the effect of growing spring cereals in monoculture depending on N-level. This experiment will be “mothballed” from 2012, i.e. the crop treatments remain, but yields will not be recorded and the N-treatments will not be conducted. One series (R8-74) investigates the effect of growing crops typical for northern Sweden, like barley and potatoes, in monoculture compared to growing them in short or long rotations, with or without FYM.

Some of the old LTEs have been closed down (for different reasons) in order to create resources for a new future-oriented trial. In 2010, a new LTE (R4-0009) was started with the first harvest in 2011. It is planned as a research platform with contrasting treatments designed to be of use for many different disciplines (Bergkvist *et al*., 2011). The main objective with the new LTE relates to anticipated climate change and aims to investigate the importance of weather on crop production depending on if winter wheat or maize is grown with break crops or not, if the system is planned for long summer or mild winters, i.e. long season summer crops or winter annual crops, and if ploughing or non-inversion tillage is used.

Concluding Remarks

The design of LTEs often reflects the current issues at the time when they were started. The old experiments (>40 years old) study the effect of cropping systems, crop sequences, fertiliser regimes and liming on yield and soil fertility; several focus on comparing mixed and more specialist systems, e.g. with and without livestock (FYM), and sequences with grass/clover ley mixed with annual crops or annual crops only. In more recent experiments (< 25 years) the focus is more on investigating management practices designed to prevent negative environmental effects and make more efficient use of nutrients, water, and soil resources, e.g. catch and cover crops, soil structure and reducing compaction, water management and quality. The old trials sometimes have small experimental plots and few replicates, which at the start of the series were addressed by a larger number of experimental sites; unfortunately not all sites remain today. The more recent experiments often have a better design with larger plots, more replicates, and some even with tile drains to each plot, however with fewer sites per series, and typically only a single site. When designing new LTEs today, e.g. on cropping systems and rotations, we need to involve multi-disciplinary research teams together with different stakeholder groups in order to create designs that will address emerging issues but that also will be a good basis for addressing future challenges that we cannot foresee today. In order to create opportunities for new LTEs we need to review and evaluate the existing portfolio of LTEs and raise the question when it is acceptable or timely to close down old experiments in order to liberate funding for new trials meeting the demands of the future.

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