MISTRA FOOD FUTURES

A New Long-Term Experiment to Evaluate and Demonstrate Agricultural Sustainability at Lövsta Field Research Station

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A New Long-Term Experiment to Evaluate and Demonstrate Agricultural Sustainability at Lövsta Field Research Station
Ett nytt långtidsförsök för att utvärdera och demonstrera hållbart jordbruk vid Lövsta fältforskningsstation

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Denna rapport är framtagen inom forskningsprogrammet Mistra Food Futures. Det övergripande målet för programmet är att skapa en vetenskapligt baserad plattform som bidrar till att det svenska livsmedelssystemet kan transformeras till ett system som är ekonomiskt, socialt och miljömässigt hållbart samt resilient och kan leverera hälsosam mat. Målet uppnås genom att utveckla ett nära samarbete mellan akademin och ett antal nyckelaktörer i det svenska livsmedelssystemet. Den här rapporten utgör en del av Mistra Food Futures arbete med att beskriva produktionssystem som minskar klimatpåverkan. Detta utgör en av de centrala frågeställningarna inom Mistra Food Futures.

Mistra Food Futures leds och samordnas av Sveriges lantbruksuniversitet SLU i samarbete med forskningsinstitutet RISE, Stockholm Resilience Centre vid Stockholms universitet och Royal Swedish Academy of Sciences, The Beijer Institute of Ecological Economics. Övriga partners inom programmet omfattar en bred representation av aktörer från akademi, näringsliv, branschorganisationer och regioner.

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Abstract

Agricultural sustainability is a wide-ranging concept which is receiving increasing attention amid the myriad, deepening challenges created by increasingly intensive food production systems. One symptom of this increasing intensification is the homogeneity of agricultural regions, which are becoming ever more specialised for production of one, or at least few, specific commodities, to the detriment of landscape-scale diversity and its many associated benefits to an agroecosystem. Faced with this challenge, there is a need for long-term, landscape-scale experiments, integrating both livestock and arable agriculture into a single food production system. The approaches entailed in such experiments must be assessed holistically, with equal consideration to diverse agronomic, ecological, and socioeconomic aspects of sustainability, in consultation with experts in each of these fields. This is a perspective which has often been emphasised, but rarely executed in long-term, real-world experimentation. It is moreover essential that the approaches used in such an experiment, and their value for sustainability, are easily available for demonstration and co-creation with end-users, given their role in bringing them to widespread application. We therefore considered the need for such an experiment, and how best to design it for both the evaluation of overall system sustainability, and the creation of infrastructure required for a long-term demonstration platform at SLU's primary field site in Lövsta. We then undertook a series of workshops and meetings with experts in specific aspects of agricultural sustainability, as well as technical staff at Lövsta, to inform the design of a long-term experiment which best integrates all major aspects of agricultural sustainability. In this report we document the priorities described through these discussions, before concluding with our system design and recommendations for baseline metrics to be measured prior to the start of the experiment. In this way, we create a long-term experiment sufficiently holistic to assess agricultural sustainability as we currently understand it, while also being sufficiently flexible to be easily modified to reflect changing priorities of future research.

Keywords: Agroecology, Grazing, Landscape, Multi-Discipline, Rotation, Tillage

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1. Introduction— Assessing Agricultural Sustainability

Global agricultural productivity has increased massively since the Green Revolution, the combined results of breeding for high-yielding varieties of staple crops, and the widespread adoption of mechanisation, chemical fertilisers, and synthetic pesticides, which are together intended to create the optimal environment for plant growth and yield. While this has brought obvious socioeconomic benefits, they have created an agricultural system characterised by large, specialised farms, highly reliant on chemical inputs, producing a limited number of commodities (Evenson & Gollin 2003; Pingali 2012; Lebacq et al. 2013; Franzluebbers & Hendrickson 2024). This has, in turn, created a largely homogenous agricultural landscape which is vulnerable to disturbance, with increasing geographic separation between animal and crop husbandry (Robinson & Sutherland 2002), to the detriment of their aesthetic value (Schirpke et al. 2019). For these reasons, agriculture today faces myriad, intensifying challenges to productivity and sustainability including biodiversity loss, nutrient surplus, and resistance to synthetic pesticides (Pretty 2008). That said, the true consequences of these challenges are difficult to quantify, given that they largely exist externally to the farming system which is typically the focus of study (Storkey et al. 2024).

Various movements have developed in response to these challenges, which suggest various levels of system transformation- from organic farming to agroecology (Wezel et al. 2020). There is, however, an increasingly pervasive sense in agricultural science that system transformation for long-term sustainability must be prioritised (Pretty et al. 2018; Storkey et al. 2024), in the hope of keeping future production within its planetary boundaries (Richardson et al. 2023). Hansen (1996) discusses the meaning of agricultural sustainability at length, which is deeply embedded in ideology, and broadly concerns the ability to persist in the long-term with minimum environmental or socioeconomic consequences (see also Brundtland (1987)). As Pretty & Bharucha (2014) define, sustainable agroecosystems are those which positively influence natural, social and human capital, in opposition to unsustainable systems which negatively impact and reduce these resources. In keeping with fervent debate over its meaning, however, there is increasing recognition that agricultural sustainability is a complex matter involving a wide range of metrics, scales and actors (Talukder et al. 2020), and potentially including trade-offs between them (Pretty & Bharucha 2014). As such, there is also a great need to connect these actors for peer-to-peer learning and exchange of ideas, for instance through the development of demonstration farms (Sutherland & Marchand 2021). When designing experiments aimed at defining agricultural sustainability, we must therefore consider the indicators we select to evaluate them.

It is perhaps unsurprising given the scope of agricultural sustainability, that lively debate persists over which indicators should be prioritised in its assessment (Bockstaller et al. 2009; Schader et al. 2014; de Olde et al. 2017). Unfortunately, this has led to an 'explosion' of indicators, antagonised by inconsistent framing and definitions (Riley 2001), a source of frustration and confusion at times (Kaufmann & Cleveland 1995). At the core of this frustration is the necessity of simplification in indicator design (Hanley et al. 1999), and in science more widely (Drake & Kramer 2012). This could exclude important metrics which capture important benefits or drawbacks of a system. There is some consensus regarding the scope of indicators that should be used for agronomic, ecological, and socioeconomic factors, that is largely in line with 'classical' sustainability literature (Gómez-Limón & Sanchez-Fernandez 2010). More recent work has also suggested the inclusion of a political or institutional dimension (Chopin et al. 2021), which has traditionally been neglected in agricultural sciences (Merrill-Sands & Collion 1994). From these metrics, constituent goals or objectives are usually defined (Alkan Olsson et al. 2009).

1.1. Putting Theory into Practice

There is a significant challenge in defining goals and selecting indicators in practice, however. Such assessment must be sufficiently generalised to apply to a wide range of environments and farming systems (Rosenstock et al. 2017; Eichler Inwood et al. 2018), otherwise it has limited value for future research. Scientific practicality is also important (Bélanger et al. 2012; Alrøe et al. 2016). Especially if a wide range of diverse metrics are to be considered, they must be quick and easy to measure, repeatable in the long-term and at a large scale, and without specialist knowledge.

At the same time, though, assessments must be sufficiently sensitive to capture the effects of subtle differences in context (von Wirén-Lehr 2001). As each farm effectively represents its own socioeconomic niche (Cowell & Clift 1997; Descheemaeker et al. 2019), many works have emphasised the value of considering system context early in the process of experimental design (Zhen & Routray 2003; López-Ridaura et al. 2005; Bockstaller et al. 2008; Gómez-Limón & Sanchez-Fernandez 2010). With all of this in mind, Storkey et al. (2024) recommended that sustainability assessments should involve cheaply, practically measureable data, relating to clear and meaningful outcomes, and sensitive to changes in management. Some works have attempted to assess sustainability using a wide range of metrics, all scored on a set scale (e.g. 0-100), based on perceived value to sustainability, to provide a harmonised assessment (Häni et al. 2003; Bélanger et al. 2012; Colnenne-David & Doré 2015). While elegant, caution must be employed in this approach given its subjectivity and its tendency to dilute the raw data used, potentially obscuring trends of interest (von Wirén-Lehr 2001).

It is common for indicators to be too simple, too short-term and too specific to an individual context (often examining a single farm for a single season), leading to a failure to evaluate the whole system or the dynamics involved in it (Merkle & Kaupenjohann 2000; von Wirén-Lehr 2001). Indeed, there is limited value in assessment of a system without an understanding of its dynamics (Storkey et al. 2024). It is thus particularly common for externalities, with major consequences for agricultural sustainability as a whole, to be ignored. It is, moreover, common for metrics concerning farm-level function to be prioritised over ecological indicators (Eichler Inwood et al. 2018). Social metrics are also underrepresented in many such studies (Arulnathan et al. 2020; van der Werf et al. 2020), probably derived from more limited academic attention compared to agronomic or ecological factors (Latruffe et al. 2016; Chopin et al. 2021). By employing a more holistic approach, it would be possible to address many of the limitations and shortcomings by considering metrics which are currently underappreciated.

1.2. Goal Definition: Evaluating Sustainability Correctly

There are three typical approaches to sustainability assessment, which are, from least to most ideal: 1) data-driven (utilising existing data), 2) means-orientated (utilising an existing system), or 3) goal-orientated (defining the aims of the experimental system from the outset) (Chopin et al. 2021). Approaches 2) and 3) are preferred because of their flexibility, but this also means that there is greater scope to target unsuitable metrics. The value of a goal-orientated approach is in the focus on achieving an ideal situation rather than working within a pre-defined frame (Lebacq et al. 2013), but careful consideration must be given to the initial goal definition and how practical it is to investigate.

The vital questions when defining a goal are, of course, what the desired outcome is, and what value it would have for the development of more sustainable farming practices. Indeed, it is common limitation of work to date that it has remained disconnected from actual, meaningful applications for agricultural management (Coteur et al. 2020). Of relevance here are the Swedish Sustainability Goals (*Sveriges Miljömål*, https://www.sverigesmiljomal.se/), the most pertinent being those of 1) a rich agricultural landscape, 2) rich plant and animal life, and 3) no eutrophication (through the need to control nutrient flows in farming systems). The achievement of an intended goal must be practical and relevant for both farmers, and wider society. It is therefore essential for a diverse range of experts and stakeholders to be engaged from an early stage (von Wirén-Lehr 2001), so that a plurality of perspectives and priorities can be considered from the outset.

As noted, however, defining a goal and identifying relevant metrics to evaluate it means a risk that some important factors are not adequately assessed. This is particularly concerning in designing long-term experiments which may require adaptation for changing research interests in the future. The last century, in its shift in scientific focus from productivity to sustainability and ecology, is a prime example (Rasmussen et al. 1998). Considering this need for adaptability, a recently-established long-term field experiments at Rothamsted Research in the UK, has deliberately eschewed goal definition completely in favour of a focus on creating a stable platform to adequately examine future challenges to agriculture (Li et al. 2023; Storkey et al. 2024). In effect, then, a delicate balance must be struck in designing such an experiment, between evaluating worthwhile goals in the short to medium term, while remaining adaptable to the currently unknown additional questions of the future.

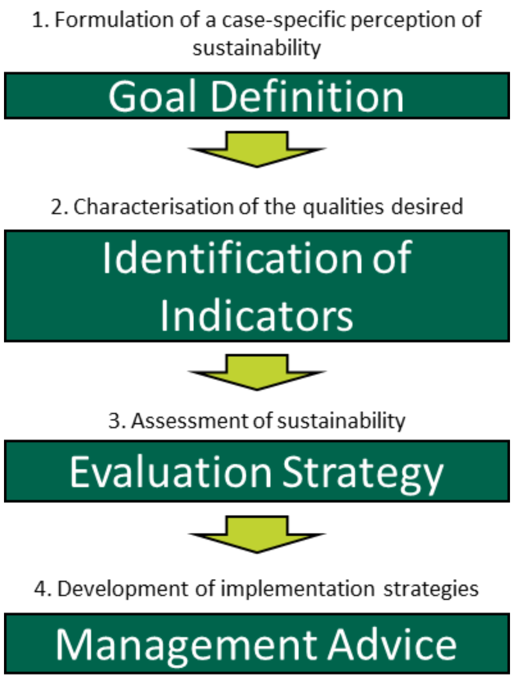

Figure 1: The four steps of goal-oriented agricultural sustainability assessment, modified from von Wirén-Lehr (2001).

1.3. A New Long-Term Field Experiment for Lövsta

With the complexities of examining agricultural sustainability acknowledged, the next step is to use them to inform the design of a new long-term experiment at Lövsta, the primary site for field experimentation at SLU in Uppsala.

This experiment will study both arable and semi-natural habitats, taking into account landscape-scale agricultural dynamics and evaluating the benefits of landscape complexity to sustainability. Indeed, contrary to the trend of agricultural landscape simplification, there is substantial evidence that mosaics of shared land uses are more ecologically beneficial than strict partitioning of land for farming and conservation (Mehrabi et al. 2018; Storkey et al. 2024).

It is fitting that such an experiment be undertaken at Funbo-Lövsta, SLU's principle agricultural field station, given its importance to agricultural sciences for over 300 years. Sten Carl Bielke and Pehr Kalm conducted early agricultural experiments here in the 1700s. While these predominantly focused on the production of crop plants, Lövsta has also long been used for animal husbandry, exemplified by the large herd of cows amassed by Claes Cederström at the site in the 1800s. As such, shared land use is a concept deeply ingrained in the history of Lövsta. This is clearly apparent when visiting the site today, with both expansive arable land, and mosaics of pasture present around the site, as well as infrastructure to support cattle, poultry, and other animals throughout the winter. As such, Lövsta is perfectly equipped for the execution of an experiment like the one envisioned.

In addition, its location, only a fifteen-minute drive from SLU's primary campus at Ultuna, and just on the outskirts of the city of Uppsala, mean that it is ideally situated for easy access to visitors. This facilitates its use as a demonstration farm for a diverse group of visitors and stakeholders.

The Lövsta Field Research Station from above. Photo: Pereric Öberg, Aerobilder

2. Aim, Objectives, and Methodology — Adapting Sustainability Indicators for Lövsta

2.1. Aim and Objectives

The overarching aim of this report is to produce a plan of experiments and protocols to form around the new long-term experiment at Lövsta, with particular focus on 0-time-point baseline measures which can be utilised to inform ongoing studies into, and demonstrations of, agricultural sustainability at the site.

The constituent objectives are to review and contextualise current understanding of agricultural sustainability assessment, and to identify metrics which should be prioritised in the design of the Lövsta experiment considering the opinion of local experts.

2.2. Methodology- Workshop Design and Execution

In order to identify suitable agricultural sustainability metrics, a series of workshops and meetings were held during Spring of 2024 with the participation of experts associated with SLU. The first of these took place at the Lövsta Field Station itself, and was focused on identifying suitable locations for replicates of the experiment, and determining practical considerations for its execution. This ensured that any further decisions made would be grounded in the practicalities of the site. Indeed, the connection between practice and theory has historically been neglected in agricultural science (Merrill-Sands & Collion 1994), but its importance has been increasingly recognised (Maat 2011).

Following this initial meeting at Lövsta field station, workshops were held to target specific aspects of agricultural sustainability, with SLU researchers invited according to their area of expertise. Invited researchers were also encouraged to spread invitations more widely to colleagues who could provide additional insight. These workshops focused on 1) the system level, 2) grazing and livestock management, and 3) soil and ecology. In between each workshop, a meeting was held between project members to debrief and discuss how to run following workshops more effectively. Each workshop was held for two to three hours, of which the first half-hour was used to introduce the experimental plan to date and its scope. Attendees were then separated into groups to discuss specific aspects of the design, on which they would feedback in the last half-hour. The outcome of this process was to identify important considerations and potential indicators for the design of the experiment, as identified by a diverse set of perspectives.

2.3. Methodology- Follow-up Meetings

Following workshops, smaller meetings were held to discuss specific aspects of system or sampling design with experts, including both those who attended workshops and those who were unable to, but whose input was considered valuable.

The format of these meetings varied by circumstance but was typically one-on-one between a project member and an expert, and involved a brief description of relevant problems and questions followed by a detailed discussion. Meeting notes were taken by the project member and used to inform both sampling design and the writing of this report. Shorter, informal discussions were also made between project members and experts and, where experts were especially busy, specific questions were posed by email.

3. Results and Discussion – What the Experts Say and What It Means

The initial workshop with staff at Lövsta Field Station highlighted the practicalities and limitations of the site. Following the initial idea to include both semi-natural grassland and arable land in the experiment, this meeting primarily took the shape of identifying suitable locations for both of these aspects, in consideration of available land and its quality. It was noted in particular that some areas of the site may be liable to waterlogging, which is not easily resolved by management. Issues may also be encountered with high acidity to the detriment of crop growth, although this could be partially offset through liming of the topsoil if necessary. It was suggested that other areas be avoided due to stony soil in uneven patterns. Baseline and ongoing measurements should take consideration of unsuitable areas such as those frequently used for tractor turning; further guidance will be required to identify such areas. The context of the site was also emphasised: this field station is, of course, used for many other experiments, so we must not occupy all of the most suitable land with ours. With this in mind, locations were identified for the six replicates envisioned for the experiment, with a seventh location designated in case of unforeseen difficulties.

3.1. Rotation and System Design

The initial workshop at Lövsta also allowed for initial discussion of the rotation and design of the experiment, which was explored in greater detail in the 'Systems' workshop that followed.

At a fundamental level, participants at this initial workshop, and in later follow-up meetings, highlighted that definition of the system boundaries is essential for a coherent experiment which accurately considers energy flows into and out of the system (see Dale et al. 2013). As such, great attention must also be paid to anthropogenic inputs. Fertiliser input was especially considered; as many of the core metrics focus on soil fertility, baselining must enable comparison of this characteristic between systems. Bio-digestate was suggested as main fertiliser, as it can be produced in any agricultural system or imported from society in quantities adapted to system productivity. Considering the importance of understanding the initial state and dynamics of the system, information about historical management was also collected from field staff at Lövsta.

It was emphasised in follow-up meetings that definition of a clear goal, and accompanying hypotheses, are the most important steps of framing the experiment, without which the treatments and experimental structure are difficult to define. Moreover, although these hypotheses would necessarily be on rather vague terms, it was noted that they would likely indicate the most important aspects to be measured for baselining. We also agreed that management of the experiments should change as new knowledge and technologies becomes available and to be prepared to adapt the experiment to changing research priorities (Rasmussen et al. 1998; Li et al. 2023). Thus, while we see the importance in defining long-term goals, there should also be space provided for complementary, short-term experimentation to support development of management and research questions. Therefore, it was envisioned that each experimental replicate block will consist of a reference sub-plot, and a surrounding region where such experimentation would be possible. Incidentally, the use of this central sub-plot for core experimentation would ensure the elimination of edge effects, which could be highly consequential for ecological metrics.

The identification of suitable primary and service crops, and the order and combinations of them, was also considered important. In particular, compatibility was discussed, for instance in terms of competition between the primary and service crops. The potential for transmission of diseases between these crops was also discussed, but follow-up meetings established that effective rotation should make this a minor concern (e.g. Krupinsky et al. 2002). It was also emphasised that efforts should be made to maximise capital (financial or otherwise) gained in all compared systems. A good example for this would be in using cut ley to provide food for ruminants elsewhere in the system.

3.2. Grazing Management

Grazing would be managed both on arable land and in semi-natural pasture. On arable land, the integration of grazing into the crop rotation would permit its examination as an agroecological management tool. The effects of grazing would here be compared to the harvest of ley crops in ungrazed treatments with the same animal density, while a ‘control’ system would also be needed where only annual crops are included in the rotation.

It was suggested in the grazing workshop to use rotational grazing, a common strategy on arable land (e.g. Taylor et al. 2006; Jordon et al. 2022). As lactating dairy cows need to be milked several times per day, bringing additional working time and a limitation in distance to the grazing area, the grazing animals were suggested to consist of a mix of dairy heifers older than six months, and dry cows. While there was discussion about purchasing or renting animals from other farms, the staff at the Lövsta dairy barn emphasised that this would pose an unacceptable risk of infection. The number of animals should be determined based on grass availability and could be adjusted during each grazing rotation, as grass availability typically decreases as the season progresses. The strategy could be either to have few animals grazing at a longer period in each rotation, or include a higher number of animals at a shorter period in each rotation. Weighing animals both when they enter and exit the pasture would allow monitoring of their condition. Other animal-related parameters, such as health and behaviour, were also discussed. However, it was emphasised that the animals would follow standard health monitoring, and adding more measurements would increase costs more than could be motivated. It was suggested that the impact of grazing on soil quality and biodiversity should be included as a focus of the experiment. In semi-natural pasture, it was suggested to evaluate two different grazing strategy extremes: set stocking, where animals remain in the same area for the grazing season, and rotational grazing with short grazing periods and long intervals in between, e.g. animals get access to new pastures for every 2-3 days. Of course, replication would also be required, at least three times.

In the rotational strategy within each paddock, an outer fixed fence was recommended, but virtual fencing (Umstatter 2011) was suggested within plot, since it would facilitate digital adjustment of access to fresh grass. However, since the virtual fencing technique is not yet approved in Sweden, an ethical application needs to be submitted to conduct a research-based trial of the system. Discussions about the use of virtual fencing primarily centred on potential risks, such as the possibility that the system might be unstable, that some individuals may not respond to the method and move outside the designated area (Wahlund 2021), or that the position of the fence was not precise enough. As a result, it was suggested to be prepared to use additional (physical) fencing as a backup. The choice of brand of virtual fencing systems was also discussed with a group of researchers involved in another project, who have evaluated them for use with cattle on semi-natural pastures for several years. Choice of area to study within Lövsta's 100 ha semi-natural pasture areas was discussed with researchers that are experts in landscape analysis. Examining the map, they suggested areas with high biodiversity value and similar appearance, to allow for the use of different paddocks as replicates. Another factor to consider, once these criteria are met, is the accessibility of the area for water and visitor demonstrations of the project.

3.3. Ecological and Soil-related Metrics

In the soil and ecology workshop it was outlined that, in natural pastures, there is always a variation in vegetation types and tree and shrub layers. This is important to consider in design, data collection, and evaluation, to allow future examination of effects caused by the different grazing strategies over time. Normally, variation in soil moisture is the most important factor for ecosystem function, and it is also closely linked to topography and soil type (e.g. clay content and soil depth), and thus also to species composition, pasture production and pasture quality. Moist soils generally have higher clay content and are more productive, but are also prone to overgrowth if grazing is too weak early in the season. This could lead to poorer forage quality and the accumulation of grass litter, which smothers less competitive plant species and reduces biodiversity value (A. Glimskär, pers. comm.).

Biodiversity on drier soils is unlikely to be substantially affected by management, but late grazing can sometimes contribute to more flowering and higher species richness through the regulation of tall, dominant species (Milchunas et al. 1988). In addition, it is important to know whether some parts of the land were previously arable, and therefore fertiliser-affected, as this would translate to higher production but lower species richness. Such land is often located on fresh and level ground, as this is most suitable for cultivation. It was therefore suggested that the project should use soil moisture map layers derived from topography to make a general classification of the land regarding these variables. To assess the density of trees and shrubs, of which there are usually more on dry and rocky soils, aerial photographs and pixel-based map layers for tree layers should be used, produced from laser scanning data.

It was recommended by participants that – based on collected information – relatively wet, dry and also rocky land, including a variation in tree cover, should be identified within the semi-natural pastures. These categories of land are expected to have different productivity (shown in feeding tables with approximate values of biomass production in the most common grassland types including semi-natural pastures). They will also respond differently to grazing treatments. It was discussed in a follow-up meeting that inclusion of at least one parcel of each land category into each paddock would create pseudo-replicates which will enable evaluation of data beyond that of case-studies.

The arable land is not expected to display the same level of variability, although it is expected to become more variable over time in the grazed systems. However, e.g. soil texture and hydrological properties are nevertheless expected to show some variation from the start of the experiment (t=0). Follow-up meetings focussed on approaches to ascertain that blocks can be placed to minimise variability within them, especially in the reference sub-plots. It was also acknowledged that mapping of the underlying soil conditions would be a valuable asset for subsequent evaluation of future treatment effects, and that this also applied to the semi-natural grasslands. For example, the data derived from soil mapping may be used as covariates in the evaluation of other data collected in the field. Benefits and limitations of potential methods for mapping the arable land were deliberated upon and valued in terms of delivered data resolution, financial costs, staff and competence needs, and logistical feasibility. The final suggestion from the involved experts was to carry out soil mapping through electromagnetic induction measurements with the instrument 'EM38-Mk2' (Geonics Ltd, Mississauga, Canada), available at the department of Soil and Environment.

It was also discussed in the soil and ecology workshop that the variability needs to inform the strategy for soil and ecological sampling, measurements and observations. Not knowing the direction of new, future studies, the group suggested that as much as possible (within the limits of funding) should be sampled, measured and observed for both the semi-natural grassland and arable land. To enable this to the fullest, collection of samples must be simple and time-efficient, yet samples should provide a maximum of opportunities for later analysis. The samples collected must also be storable with limited resource use until analysis. Likewise, observations and measurements made directly in the field must be similarly time-efficient, yet provide key information on soil and ecological variables, not the least reflecting potential changes brought about by the grazing animals.

Follow-up discussions pointed out that the work related to biodiversity is coherent with the endeavours of the Swedish Board of Agriculture to assess biodiversity of agricultural landscapes in Sweden. Streamlining of sampling campaigns at Lövsta with those of the Swedish Board of Agriculture was suggested, and it was proposed that additional funding might be sought from the Board.

The workshop participants agreed that soil coring should be made to provide material for soil chemical, biological and texture analysis. The samples can subsequently be split into 1) subsamples to be dried and stored at room temperature, allowing determination of a host of soil chemical variables and soil texture; 2) subsamples to be stored fresh at -20°C and which may be used for e.g. determination of Multiple Substrate-Induced Respiration (MSIR), a method ranked highly by Stone et al. (2016) in a review of soil biological indicators; and 3) subsamples to be stored fresh at -80°C, allowing molecular studies of the functionality and diversity of a range of soil organisms (Ritz et al. 2009), several of which were also highly ranked in the review of soil biological indicators (Stone et al. 2016). As indicated in follow-up discussions, soil microbial diversity is complicated by a lack of scientific understanding of 'what good looks like', but that it is generally considered that greater functional diversity is preferable (Van Der Heijden & Wagg 2013), a sufficient goal for our aims.

As a complement to lab analysis of soils, follow-up discussions suggested that visual field assessment of soil structure may follow one of several protocols which provide semi-quantitative information, and the protocol of Guimarães et al. (2011) was put forward as suitable in the current context. Penetrometer measurements were further suggested to provide information on penetration resistance throughout the soil profile, a soil variable likely to change in response to animal trampling during grazing (Sigua & Coleman 2009). The data from the field-scale electromagnetic induction measurement (see above) will also allow later assessment of grazing-induced soil compaction (Romero-Ruiz et al. 2023).

The recommendation of experts for invertebrate sampling was to use Malaise traps and pitfall traps (Rusch et al. 2013; Panassiti et al. 2023). Follow-up discussions identified the value of pursuing both of these trapping techniques: pitfall traps are effective to identify functionally important groups for agroecosystem function such as carabid or staphylinid species (e.g. Raderschall et al. 2022) reasonably quickly. Malaise traps, meanwhile, provide the additional benefit of capturing flying insects, and therefore give a more general perspective of biodiversity (e.g. Buchner et al. 2024), albeit antagonised by the difficulty of morphologically identifying some groups, like diptera or lepidoptera, to a sufficient level of specificity. It was therefore recommended that DNA analyses would be more suitable for Malaise traps. The captured specimens should be stored in ethanol at varying concentrations in cooled conditions (70% for pitfall trap samples intended for morphological identification, expected to keep for at least 20 years; 99% for Malaise trap samples intended for DNA analyses, expected to keep for at least three years). The time-consuming nature of insect identification from pitfall and Malaise trapping is a major motivation for focusing on landscape-level indicators rather than the insect species they support (Storkey et al. 2024). It was reasoned in our discussions, however, that coarse identifications focusing on functional groups rather than individual species would be a reasonable compromise, which could then be verified and supported by vegetation data detailed elsewhere.

It was suggested that vegetation structure and quality at the semi-natural grasslands should be assessed, with its diversity and function scored according to established metrics. Annual plants may be assessed through seed bank determinations for both arable land plots and semi-natural grassland parcels. This would use separate soil samples collected in the same manner as those above (to 20cm depth), stored at 0-5°C in darkness if necessary. Seedbanks from these samples can then be germinated in glasshouse conditions and identified at early growth stages, as is common practice to provide insight into what is actually viable and likely to occur in the field (e.g. Grundy & Jones 2002; Csontos 2007). For the arable land, these can provide information on weed populations (Espeland et al. 2010; Mahé et al. 2021). Perennial weeds may instead be sampled through walking of transects and counting of shoots (sensu Melander et al. 2012).

It was noted in discussions that aboveground monitoring, and identification of fungal pathogens and their severity in crops (using, e.g. https://ahdb.org.uk/recommended-lists-disease-ratings), can be a quick and effective measure of prevalence. As noted previously, crop rotations would probably prevent soil borne pathogens from becoming a major concern (Krupinsky et al. 2002), so it is unlikely that regular assessment within the season would be required for them. Wind dispersed diseases would need to be assessed when observed. It was suggested that monitoring of diseases would have limited value in the semi-natural grasslands, since they are rarely noteworthy in unmanaged, or less-intensively-managed ecosystems containing a diversity of plant species. Low levels of such diseases may even benefit a semi-natural ecosystem by regulating interactions between plant species (Mitchell et al. 2002). Belowground pathogen monitoring would be incorporated into broader soil microbial analysis, which would provide insight into the whole microbial community present.

3.4. Economic Considerations

The economic consequences of each system must be taken into consideration. Exploring the economic consequences of the different systems helps in attaining economic resilience (Meuwissen et al. 2019). Economic resilience in this context is described as the capacity of each of the systems to adjust to new production systems through adjustments in the products and the production inputs, while ensuring its profitability (Van Der Lee et al. 2022). The economic impact of the suggested systems should be assessed in two steps.

In the **first step**, an economic model needs to be developed that describes the economic parameters, which are affected by the proposed designs. Soil health and fertility, grazing and production data, as well as farm economic data from each system, can then be used extensively in the analysis to provide additional strength and relevance for the calculations. The economic performance should be based on the contribution margin where economic analysis is limited to include only the farm outcomes and expenses that are affected by the new system designs. This model would require validation, giving detailed information on relevant prices and quantities, as well as information about the probability of the distribution of the variables. The basic model would be deterministic, although some key variables would need stochastic modelling to be analysed adequately.

In the **second step**, partial budgeting and risk analysis could be achieved using Monte Carlo simulations (e.g. Ettema & Østergaard 2006; Mardani Najafabadi & Taki 2020). These analyses would produce a simulation of the economic effect of each 'treatment' system in relation to the reference system. The partial budgeting and risk analysis framework with stochastic elements is a powerful tool for analysing decision-making on the farm and economic effects, particularly in situations where there is lack of detailed empirical data (Ahmed et al. 2020; Owusu-Sekyere et al. 2023). It allows us to account for different "what if" scenarios in the profitability and policy analysis. For each of the systems, it is expected that labour, feed and fertiliser requirements will change. Output variables such as milk output and farm economic returns will change. The model would categorise these changes into (i) increased revenue due to the changes, (ii) decreased cost due to the changes, (iii) increased cost due to the changes, and (iv) reduced benefit due to the changes.

4. Conclusion and Recommendations – Establishing a Long-term Experiment at Lövsta Field Research Station

The first step in establishing a new long-term experiment must be to define an overarching goal, as alluded to in the introduction. Indeed, a goal-orientated approach provides the most flexible foundation for experimental design and identification of suitable sustainability indicators. It should also be noted, however, that the contrasting data-driven and means-orientated approaches are not feasible in this case given the absence of existing data or an existing experimental system. In consideration of the breadth of topics discussed, we outline the following overall goal:

> **To develop and evaluate cropping systems and grazing strategies that improve overall sustainability of a mixed agricultural landscape of semi-natural grasslands and arable fields.**

The ambition, derived from this goal, is to evaluate management strategies in a manner that takes large scale effects into account, and identify holistic associated benefits which probe both more widely, and deeper, than isolated studies into individual elements. As noted, this experiment is also conducive to simultaneous application for demonstration, enabling the understanding of ecological management practices and their implications for farmers and other stakeholders. Four hypotheses have also been developed, which provide greater focus to the long-term experiment:

1. Rotational grazing increases biodiversity and production in semi-natural pastures.
2. Grazing animals and other agroecological practices reduce pests, and improve nutrient cycling and resource utilisation in field cropping systems.
3. Grazing animals contribute to the competitiveness of agricultural enterprises, mainly through reduced dependence on inputs, higher soil fertility, and increased flexibility.
4. Grazing animals increase the attractiveness and functionality of landscapes and thus contribute to a living countryside.

Key in achieving our goal, and examining our hypotheses, is in developing an extensive set of baseline measurements from which deviations can be monitored, as we have described in the previous section.

In conclusion, we propose the following designs:

4.1. Part A: Semi-natural Pastures

This part of the experiment will consist of six plots in the northerly region of the Lövsta site (Figure 2), each of which will be designated through the use of fixed and virtual fencing to guide grazing animals (See Figure 2). Sub-plots will be utilised for vegetation assessment and in-depth monitoring. The six large plots will be divided into two grazing strategies with contrasting rest periods (thus comprising three plots per grazing strategy):

4.1.1. Strategy 1: Rotational Grazing

Regular relocation of the entire herd as a single grazing unit to each of the three sub-plots in turn, in an approach akin to mob grazing (Wagner et al. 2023), although additional areas will be used to allow sufficient rest-periods, particularly when growth is limited due to drought or for other reasons. The intention of this strategy is to promote and maximise pasture and ecosystem recovery outside of grazing periods and ensure large impact on the whole area when grassing. Virtual fences will be used to give access to defined areas at defined time intervals. A regulation of animal density will be done depending on availability of forage, to be evaluated and decided on pragmatically.

4.1.2. Strategy 2: Set Stocking

In contrast to strategy 1, a 'business-as-usual' approach, where animals will remain in the same area for longer periods, thus grazing at lower intensity and leaving less time for recovery.

Figure 2: A map of area where semi-natural pastures are located at Lövsta, marked with yellow boarders

4.2. Part B: Arable Land

The arable portion of the experiment will be located to the west ('Lövsta 4', Block I), south ('Lövsta 2', Blocks II to IV), and southeast ('Lövsta 1', Blocks V-VI) of the experimental station (Figure 3). It will consist of four different systems examined in six-year rotations, with each crop present every year, requiring six blocks to capture each position in the rotation. Each block will cover 12 ha of space, with plots at 3 ha designated for each of the four cropping systems. Parts of each plot will be designated specifically for measurements relating to the long-term experiment, and the remaining space provided for short-term experimentation and demonstration to be determined in the future. Headland will also be provided for tractor turning and other practicalities.

Figure 3: The six proposed blocks for replication of the long-term experiment, superimposed on an aerial view of Lövsta taken from Google maps. Each block will contain the four systems detailed on the following page

The four systems will consist of:

4.2.1. System 1: Arable Reference

A rotation of annual crops without grazing animals. Intended as a reference system where plant nutrients are effectively circulated, and technological development is assumed to meet the need for other inputs in the long term.

4.2.2. System 2: Cattle with Grazing

Ruminant animals present with the intention of maximising grazing of pastures and service crops, to contribute to the function and characteristics of the farming system. Supplementary feeding with silage and grains.

4.2.3. System 3: Cattle without Grazing

The same density of ruminant animals as in System 2, but no grazing, with silage production and grains prioritised as a feeding strategy, contributing to the function and characteristics of the farming system.

4.2.4. System 4: Integrated

A mixed system with cattle grazing at 50% intensity compared to systems 2 and 3, intended to utilise grazing as a tool for modifying the system. Will prioritise pasture, service crops and plant residues, not suitable as food for humans, as feed sources. The requirements of ruminants are therefore balanced as needed in crop rotation. The cropping system will include minimum-tillage and a diversity of crops to support soil fertility and regulate weeds, pests and diseases. This will minimise the input from outside system boundaries, for increased resilience, and keeping agriculture within planetary boundaries. This system in particular will be fine-tuned through discussion with farmers and advisors, and may require some specialist machinery to effectively create the desired characteristics while maintaining research integrity.

Figure 4:A graphical summary of the four suggested systems which form the element of the experiment on agricultural land.

4.2.5. What to Measure and What to Evaluate

The objective is to evaluate the effects of the two grazing strategies on the semi-natural land, and the four cropping systems on the arable land in terms of soil health, vegetation structure, insect diversity, disease pressure, and economical implications.

To this end, we propose a 0-timepoint sampling campaign to be carried out in early spring 2025, prior to establishment of the experiment to provide baseline information of how the study design alters the system. This will primarily centre on soil characteristics obtained through soil coring but also by electromagnetic induction measurements. The results will provide insight into soil chemical, physical, and biological parameters such as nutrient status compaction, microbial community composition, and seedbank composition. All of these factors are hypothesised to be altered with the implementation of the diverse rotations and grazing strategies proposed. Thereafter, baseline data will also be taken on invertebrate communities (providing insight into both biodiversity and pest pressure), as well as economic inputs to facilitate the evaluation of profitability.

These baselines, explained in more detail in the previous section, will be used to inform analyses of shifting dynamics relating to grazing and no-till practices in the proposed study systems. It is envisioned that similar measurements will be undertaken in following seasons, although this is contingent on additional funding to prolong long-term experimentation.

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MISTRA
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