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# Effect of perennial ryegrass cover crop on soil organic carbon stocks in southern Sweden

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ABSTRACT

Soil organic carbon (SOC) is an important ecosystem property and a potential sink for atmospheric $CO_2$. Many agricultural soils are depleted in SOC and thus have the need and potential to sequester carbon. Cover crops used to prevent nitrate leaching in agroecosystems might be an additional cost-effective and multi-beneficial carbon input, but little is known about their effect on SOC stocks. This study examined the effect of an ryegrass cover crop on SOC stocks in three Swedish long-term experiments (16–24 years) and compared it with that at a North American site (Sultan, Washington). Growth was temperature- and light-limited in Sweden and thus the ryegrass was undersown, while it was sown after harvest of the main crop at the Sultan site. In total, seven pairs of cover crop/no cover crop treatments were investigated. The introductory carbon balance model (ICBM) was used to calculate humification coefficients for ryegrass at each site as a measure of carbon sequestration efficiency. Mean aboveground biomass of ryegrass ranged from 550–1050 kg DM $ha^{-1}$ $yr^{-1}$ in the Swedish experiments and was 4650 kg DM $ha^{-1}$ $yr^{-1}$ at the Sultan site. Yield of the main crop was not significantly affected by the cover crop. Cover crop incorporation increased SOC stocks, with a significant mean carbon sequestration rate ($0.32 \pm 0.28$ Mg C $ha^{-1}$ $yr^{-1}$) at the Sultan site and all Swedish sites except one. Mean humification coefficient of the ryegrass cover crop was $0.33 \pm 0.27$, which is comparable to that of highly efficient organic amendments such as farmyard manure and sewage sludge. This was attributed to high belowground productivity of ryegrass, although that was the most uncertain model input variable. A ryegrass cover crop is thus an effective, multi-beneficial measure to increase SOC stocks, even when undersown at northerly latitudes (55–58°N).



## 1. Introduction

The organic carbon pool of arable soils is an important quality measure for sustainable crop production and ecosystem resilience and a potential sink for atmospheric $CO_2$ (Lal, 2007). It is often highly depleted compared with that of soils under natural vegetation such as forest or grassland (Wiesmeier et al., 2012). Therefore including cover crops (also known as catch crops or intercrops) in the rotation is gaining increasing interest as a measure to increase the soil organic carbon (SOC) pool (Lugato et al., 2014). Maximising the period of photosynthetic activity, and thus net primary productivity (NPP), of arable land is a cost-effective and sustainable way to increase carbon inputs to the soil. Moreover, it does not result in carbon losses from other ecosystems, which is the case when e.g., farmyard manure from livestock production based on imported feed is applied (Kätterer et al., 2012). Cover crop cultivation and incorporation provide multiple benefits for the soil, such as increased biodiversity and earthworm abundance, erosion control and improved soil structure (Dabney et al., 2001). In water-limited systems, a cover crop can either prevent drought stress for the following crop when used as a mulch (Frye et al., 1988), but might also cause draught stress for the main crop. In systems with excess water it can prevent nitrate leaching (Blombäck et al., 2003), giving rise to the name 'catch crop'. Reported effects of cover crop incorporation on SOC stocks are inconsistent and range from losses (Mazzoncini et al., 2011) to gains of >1 Mg C $ha^{-1}$ $yr^{-1}$ (McVay et al., 1989). In a global meta-analysis, Poeplau and Don (2015) found a mean annual sequestration rate of $0.32 \pm 0.08$ Mg C $ha^{-1}$, but were unable to explain the scatter by environmental parameters or the functional type of cover crop (legume/non-legume). However, it has been shown that at site level, carbon sequestration varies between species and can thus be optimised by the right choice of crop species. Perennial ryegrass (*Lolium perenne* L.) is a potential cover crop species with high biomass production and thus has high potential for SOC sequestration (Kuo et al., 1997).

The growing season at northerly latitudes is short, with sunlight and temperature being the limiting factors for plant growth in autumn. Furthermore, the ripening and harvest of spring crops are comparatively late due to the relatively late sowing in spring. Therefore, cover crops are usually undersown, so that their growth has already started when the main crop is harvested. In Sweden and Denmark, cover crops are widely

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implemented in agri-environmental programmes to reduce nitrogen (N) leaching from arable land. Undersown cover crops of e.g., (annual) Italian ryegrass (*Lolium multiflorum*) or perennial ryegrass have been shown to be very efficient in reducing N leaching in regions with intensive agriculture and high precipitation (Lewan, 1994; Torstensson and Aronsson, 2000). However, there is little information on the effectiveness of undersown grass cover crops grown close to their geographical limits in terms of biomass production and SOC sequestration. The main aim of the present study was thus to evaluate Swedish long-term experiments with undersown ryegrass regarding: i) ryegrass productivity and ii) effects on SOC stocks. To compare ryegrass cover crop with other organic amendments in terms of efficiency in building up soil carbon, we aimed (iii) to calculate site-specific humification coefficients for ryegrass using the introductory carbon balance model (ICBM) (Andrén and Kätterer, 1997). Moreover, ryegrass biomass production and SOC sequestration at the Swedish sites were compared with published results from regions without abiotic growth limitations.

## 2. Materials and methods

### 2.1. Experimental sites

Three long-term experiments at two different sites in south-western Sweden were investigated. Perennial ryegrass (*L. perenne* L.) was used as the catch crop species at all sites and was mainly undersown (seed rate 5–10 kg ha$^{-1}$) in spring cereals during or shortly after sowing of the main crop. At one site, the cover crop was undersown in spring in growing winter wheat. The cover crop was not fertilised and was incorporated in late autumn or spring. Two of the experiments were at Mellby (56°29′N, 13°0′E), on the south-west coast of Sweden. The soil consists of sand deposits of about 1 m thickness overlying a glaciofluvial clay (Myrbeck, 2014). Soil and climate of the two experiments are further described in Table 1. The two different experiments in Mellby are named R0-8403 and R2-8405, but will be referred to as Mellby I and Mellby II, in the following. Mellby I was started in 1983 on separately tile-drained plots and is designed for studies of nutrient leaching in cropping systems with applications of animal manure (Aronsson and Torstensson, 1998). Undersown grass cover crops were introduced in 1989 and the experiment is still ongoing. The present study covered the period 1989–2013. In total, four different unreplicated pairs of cover crop/no cover crop plots were used in this study: i) Unfertilised controls, ii) plots receiving 90 kg ha$^{-1}$ mineral nitrogen fertiliser (M), iii) plots receiving mineral fertiliser and pig slurry (~150 kg N ha$^{-1}$ in total) (MO1) and iv) as MO1, but with double the amount of pig slurry (~250 kg N ha$^{-1}$ in total) (MO2). The mentioned fertiliser rates refer to the main crops. Spring barley (*Hordeum vulgare*), spring wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), spring oilseed rape (*Brassica napus* L.) and potatoes (*Solanum tuberosum* L.) were grown as main crops. Cereal residues were removed but potato and rape residues were left on the field. When cereals or oilseed rape was grown, perennial ryegrass (*L. perenne* L.) was undersown as a cover crop in spring, on the same day as the main crop (April 23 on average). When potatoes were grown (only two years in total), winter rye (*Secale cereale* L.) was sown as a cover crop after harvest. In the MO2 treatment, cover crops were only grown until 2005, which explains the cover crop frequency of 0.7 for those plots in Table 1. At Mellby I, the cover crop was left in place over winter and incorporated by ploughing in spring (April 9 on average).

Mellby II was started in 1993 and is ongoing. It consists of a number of triplicate treatment plots, from which one pair was studied here: Straw incorporated, ploughed in November vs. straw incorporated, ploughed in November, ryegrass incorporated. The main crops grown in Mellby II were spring barley, oats and spring wheat. Spring oil-seed rape (two years) and field peas (*Pisum sativum* L.) (one year) were also grown. Average sowing date for ryegrass was April 26, at a seed rate of about 7 kg ha$^{-1}$, and it was incorporated in autumn (November 3 on average).

The experimental site at Lanna (58°21′N, 13°08′E) is located on a heavy silty clay loam of postglacial origin (Table 1). The experiment was started in 1997 and ended in autumn 2013. Similarly to Mellby II, it consisted of several triplicate treatments which were established to study the effects of different ploughing dates, straw incorporation and cover crop growth, mainly on nitrogen dynamics (Myrbeck et al., 2012). The following pair was used in the present study: Straw removed, ploughed in November; and straw removed, ploughed in November, ryegrass incorporated. Main crops were spring barley, oats and spring wheat. Average sowing date for ryegrass was May 1, at a seed rate of about 10 kg ha$^{-1}$, and incorporation occurred in autumn, on average at November 2.

For the reference site without abiotic growth limitations, we used data from a long-term experiment in Sultan, Washington, USA (Kuo et al., 1997). The duration of that cover crop experiment was only six years (1987–1992), but it was the only published study we could find reporting SOC changes with recorded ryegrass yields, which were essential input for modelling. The Sultan soil is a fine silt belonging to the Sultan Series, which is characterised as described in Table 1. In the experiment, permanent maize cropping was supplemented by a winter cover crop to maintain soil quality. Different cover crops were compared, with ryegrass being the species with the highest biomass production. The cover crop was sown in October after maize harvest.

### 2.2. Measurements

Annual main crop yield and ryegrass aboveground biomass were measured for all sites. At Lanna, ryegrass biomass determination was stopped in 2005 for financial reasons. From 2005 onwards, we used the average value for all previous years as input to the model.

Cover crop aboveground biomass was collected in late autumn (October–November) by cutting 3 × 0.25 m$^2$-squares at three places in each experimental plot as close to the soil surface as possible. The samples were dried at 60 °C and weighed and a mean value for each plot was calculated.

The main crop of cereals or oilseed rape was harvested with a combine harvester in three strips per plot. Grain samples were dried and examined for general quality properties. Potatoes and sugar beet were harvested plot-wise by hand in an area of 3 × 10 m$^2$.

Soil sampling and SOC measurements were performed in all investigated experiments in autumn 2013 (Table 2). Ten samples per plot were taken with an auger from the 0–20 cm soil layer (plough layer). These 10 samples per plot were pooled before SOC

**Table 1**
List of experiments with mean annual temperature (MAT) [C], mean annual precipitation (MAP) [mm], clay content of the soil (FAO soil classification for the Swedish soils, USDA for the Sultan soil) [%], duration of the experiment [yrs], soil pH ($H_2O$), initial C content [g kg$^{-1}$] with standard deviation in brackets, duration of the experiment [yrs], number of replicates, cover crop frequency [CC yr$^{-1}$], and the calculated average $r_e$ value as a condensed climate variable.

| Experiment | MAT | MAP | Clay | pH | Initial C | Duration | Replicates | CC frequency | $r_e$ |
|---|---|---|---|---|---|---|---|---|---|
| Mellby I | 7.2 | 803 | 6 | 5.6 | 31.6 (2.7) | 24 | 1 | 1 | 1.23 |
| Mellby II | 7.2 | 803 | 6 | 5.6 | 32.1 (3.5) | 20 | 3 | 0.7 | 1.23 |
| Lanna | 6.7 | 558 | 45 | 6.6 | 20.8 (1.2) | 16 | 3 | 1 | 1.18 |
| Sultan | 10 | 1140 | 28 | 6.2 | ~15.7 | 6 | 3 | 1 | 1.75 |