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Italian Ryegrass, Perennial Ryegrass, and Meadow Fescue as Undersown Cover Crops in Spring Wheat and Barley: Results from a Mixed Methods Study in Norway

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Abstract: Cover crops could provide environmental benefits in spring-grain systems through diversification, reduced nitrate leaching, and carbon sequestration. However, few farmers apply the technique, partly as they believe the cover crops will compete with the main crop and cause yield losses. Cover crops can either be sown together with the grain (undersown) or in autumn and establish after grain harvest. The current study uses a mixed-method approach combining field trials, interviews, and literature synthesis. The field trials focused on perennial ryegrass (*Lolium perenne* L.), Italian ryegrass (*Lolium multiflorum* Lam.), and meadow fescue (*Festuca pratensis* L.) that were undersown with 15 kg ha^{-1} but with different seeding dates in spring wheat and barley. The interviews focused on gathering practical experiences from farmers in Norway and the literature synthesis gathered results from other studies. For carbon sequestration, nine studies were judged relevant for our target climate and included in our synthesis. They showed a median value at 264 kg C ha^{-1} year^{-1}. In our field trials, 300–900 kg DM ha^{-1} year^{-1} was produced, with Italian ryegrass sown at the same date as the grain on top. Our trials showed no significant grain yield reduction due to the use of cover crops. However, our synthesis of the literature showed a 5–10% yield reduction with Italian ryegrass that was sown at the same time as the grain. One- or two-weeks delay in the sowing of Italian ryegrass, or reduced seeding rates, could reduce the problem. The interviews showed that farmers do not prefer undersown species, especially not perennial species, as they have experienced that such species may come up again in the following years and cause a weed problem. We recommend farmers to use cover crops and for undersowing, we recommend Italian ryegrass that is sown one or two weeks after the grain. Perennial ryegrass can also be recommended, as long as the growth is properly terminated.

Keywords: agronomy; diversity; nitrogen; soil carbon; soil structure

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1. Introduction

Cropping systems have developed monocultural landscapes where one or a few crops are grown on large areas with a high degree of mechanization and input [1]. In Norway, as in other areas in Northern Europe, grains are cultivated in certain regions and forages in other regions. This is in contrast to the mixed farms that were common in the 19th century with diverse rotations. Inputs in the form of fertilizers and pesticides have increased the productivity. However, the trade-offs are many and policy-makers and farmers are looking for new and more sustainable ways of farming to increase agrobiodiversity and resilience [2,3]. Geographically, Northern Europe includes Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Sweden, and the United Kingdom. Among the grains in the area, we find wheat (*Triticum aestivum* L.) with an annual production of 4,755,393 ha, barley (*Hordeum vulgare* L.) 3,131,289 ha, oats (*Avena sativa* L.) 955,113 ha, rye (*Secale graine* L.) 371,123 ha, and Triticale (×*Triticosecale* Wittm. ex A. Camus.) 168,526 ha, all the most recent numbers from FAO Stat [4]. In addition, oil seed crops (*Brassica napus* L. subsp. *napus* and *Brassica rapa* subsp. *oleifera*) are grown on 1,298,551 ha and grain legumes (*Pisum sativum* L. and *Vicia faba* L.) on 488,420 ha. Maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) are marginal crops in the region. All the crops that are mentioned above are annual plants that are seeded and harvested within one year and some of them have both spring and winter types. Oil crops and grain legumes are often included in the term grains although they are botanically distinct. Spring grains dominate in northern latitudes as in Norway, Finland, and Scotland, while winter types are more common in the southern regions [4]. Wheat and barley alone represent more than 70% of the grain area. Some farmers practice rotations and grow more crops on one and the same farm. However, monoculture is more common, or there is a rotation between spring wheat and barley. In both crops, as in other spring-sown crops, there are several months with no active plant growth, and this bare period is typically from harvest (August/September) to the seeding of the subsequent crop (April/May). Nutrient uptake and carbon assimilation terminate some weeks before harvesting when the plants change color from green to yellow [5,6]. All in all, over half of the year has no active plant growth in these production systems.

One way to change the current patterns is to use cover crops. Cover crops provide several benefits (ecosystem services) and function as living protection of the soil surface [7,8]. One of these benefits is that it reduces nitrogen (N) and phosphorus (P) from reaching waterways through runoff, leaching, or erosion. For example, a Nordic study showed a 50% reduction in N leaching by applying ryegrasses as a cover crop [9]. Another benefit is carbon capturing, which has both agronomic and environmental benefits [10–12]. Cover crops also increase the stability of the soil aggregates [13]. Furthermore, plant residues feed the soil biota and increase the diversity and density of key species in the soil such as earthworms and springtails [14,15].

In Northern Europe, there are several species that can be used as cover crops and the species can be sown in spring with the grain (undersown) or just after harvest. In spring grains, undersowing methods are relevant and can include grasses such as perennial ryegrass (*Lolium perenne* L.), Italian ryegrass (*Lolium multiflorum* Lam.), meadow fescue (*Festuca pratensis* Huds.), but also forage legumes such as white clover (*Trifolium repens* L.) or red clover (*Trifolium pratense* L.). Grasses are effective in taking up nutrients from the soil, and preventing leaching, while legumes fix their own nitrogen from the air. Furthermore, when grasses decompose in the soil, their residues tend to last longer than legumes [16,17]. For sowing after harvest, fast-growing annual species are used such as oil radish (*Raphanus sativus* L. var. *oleiformis* Pers.), white mustard (*Sinapis alba* L.), phacelia (*Phacelia tanacetifolia* Benth.), but also a range of other species [18]. The undersowing method is especially useful in regions with a short season, as the cover crop canopy is already established when grain is harvested. Furthermore, undersowing is a form of mixed cropping with the cultivation of two crops in the same field during the same time [8], which means that competition between the cover crop and the grain may occur. Känkänen and Eriksson [19] showed no negative yield effect of undersown cover crops but Ohlander et al. [20] found some competition between cover crops and spring barley but a delay in the sowing of the cover crop could reduce the competition. Our field trials were conducted in an important region of grain production in Norway and little research of a similar nature has been conducted so far north.

One benefit of cover crops is the positive impact it may have through an increase in the soil carbon sequestration. Reliable numbers on the quantity of the sequestration require relevant long-term studies. Poeplau and Don [21] compiled data from 37 studies worldwide and estimated that cover crops can contribute to an increase the soil organic carbon content in the range of 320 ± 80 kg C ha^{-1} year^{-1}. Another review [22] on the effects of undersown cover crops on N leaching, showed that Italian ryegrass was the most effective species at reducing the risk of N leaching and this was reduced by 60% compared to no use of cover crops, followed by perennial ryegrass and the annual Westerwoldian ryegrass, both with around 25% reduction. We were interested in studies that were targeted for a temperate climate as is found in Northern Europe, as we hypothesize that cover crops will sequestrate less carbon in our regions with a short and cool autumn season compared to what is found in other parts of the world. We, therefore, made a targeted synthesis of the literature on carbon sequestration in a climate that is similar to what is found in Northern Europe. This was done as an independent task, but we wanted to discuss our cover crop biomass production in a context of carbon sequestration. Furthermore, we wanted to compare our undersown crops to the positive findings on reduced N leaching risks, but also to examine if we could obtain the same effect by delaying the sowing time of the cover crops compared to sowing at the same time as the grain. Our research hypotheses were the following: (1) Undersown cover crops can affect the grain yield negatively but a delay in the sowing time of the cover crops can reduce this problem; (2) the establishment, biomass production, N uptake, and N leaching potentials are affected by species and the sowing time of undersown cover crops; (3) farmers overestimate the grain yield competing of undersown cover crops; and (4) cover crops will sequestrate less carbon in Northern Europe compared to what is found in worldwide meta-studies. Field trials and a literature review were conducted to examine Hypothesis 1 and 2, interviews to examine Hypothesis 3, and a literature synthesis on carbon sequestration to examine Hypothesis 4. The main objective of our study is to find a suitable agronomic practice for undersown cover crops in a temperate climate as found in Norway (species, sowing time) that could balance environmental benefits without causing yield reduction in the main crop. Another objective was to increase the knowledge on how farmers cultivate cover crops, but also their motivation and risk perceptions, especially regarding potential competition between undersown cover crops and the grain [23]. Here, interviews with farmers were conducted. Finally, we wanted to know more about the amount of carbon cover that crops can produce and feed into the soil system under a temperate climate as found in Northern Europe.

2. Materials and Methods

A mixed-method approach was applied, and this methodology combines sampling strategies and can include both quantitative and qualitative data [24,25]. We applied field trials, interviews, and literature syntheses.

2.1. Field Trials

The field trials were laid out in split plot design with seven cover crop treatments in spring-sown grain crops, with three replications for each treatment. The grain crops were placed on the large plots whereas the cover crop and their different sowing times were placed on the sub-plots. The trials were carried out for two years (2019 and 2020) at the University research farm at Blæstad, (Ridabu, Norway, 60°49′11.7″ N and 11°10′48.4″ E, Figure 1). Soil samples for background information were taken in 2020 and sent to Eurofins (Moss, Norway). The results showed a soil that was classified as sandy clay loam with an alkaline pH (7.8), medium organic matter content (4.3%), and a medium–low phosphorus (P-AL = 9), and potassium (K-AL = 5) status. The same cover crop species were included in both years (Table 1). The field was fertilized with 560 kg ha^{-1} of YaraMila 20-4-11 (Yara, Oslo, Norway), which corresponds to approximately 110 kg N ha^{-1}. Ariane-S (Corteva Agriscience, Indianapolis, IN, USA) was used once a year, and four weeks after sowing, as a weed treatment.

In 2019, the experiment was carried out in spring-sown barley (*Hordeum vulgare* L., 'Salome', Strand Unikorn Moelv, Norway, batch 8168402), with a seeding rate of 210 kg ha^{-1}, and in spring wheat (*Triticum aestivum* L., 'Mirakel', Strand Unikorn lot 8328905, 220 kg ha^{-1}. Each plot's size was large (9 × 35 m), and the grains were sown on the 8th of May with Wäderstad Rapid (Wäderstad, Sweden) with cover crops on small plots (9 × 2.5 m) with a Nordsten machine (Kongskilde Agriculture, Överum, Sweden). In addition to the two seeding times, we also tested sowing the cover crops three and four weeks later than the grains, but both these treatments failed to germinate (Figure 2). In 2020, the experiment was carried out in spring wheat 'Mirakel', 220 kg ha^{-1}, and barley 'Rødhette' 6-rows barley, 180 kg ha^{-1}. In this year, the seeding date was the 4th of April, and we used an experimental seed driller plot size of 1.5 × 8 m. The cover crops were sown separately at approx. 1 cm depth. At the time of grain harvest, the area that was covered by the cover crop was assessed through visual observation and given a score from 1 to 9 where 1 is the least coverage and 9 is full coverage. The height of the cover crop (in cm) was measured at the day of cereal crop harvest and four weeks after the harvest of the cereal crops. For this measurement, five plants were measured from the ground surface to the top of the plant and the data were averaged per plot.

Figure 1. The study location marked in red: Inland Norway University of Applied Sciences, Blæstad, Ridabu (extracted from Google Maps).

Table 1. Overview of the cover crops.

Details of the Cover Crops	Seed Amount	Seeding Time
Italian ryegrass 'Barpluto' (*Lolium multiflorum* Lam., Strand unikorn parti DE-148-214011)	15 kg ha^{-1}	Same time as grain Two weeks later
Perennial ryegrass 'Variety mix' (*Lolium perenne* L., Strand Unikorn parti 18509070)	15 kg ha^{-1}	Same time as grain Two weeks later
Meadow fescue "Fure' (*Festuca pratensis* L., Strand Unikorn parti 6571801)	15 kg ha^{-1}	Same time as grain Two weeks later
No cover crop (Control)		

Grain yields were harvested in late August or early September and dried to 15% water content. The cover crop yields were assessed by cutting the above-ground biomass on a 0.5 × 0.5 m area at the center of each plot in late October. The weed percentage was recorded from the harvested sample and analyses of the total nitrogen and total carbon content of the cover crop yield were sampled at Eurofins laboratory (Moss, Norway). The soil nitrate samples were taken in late October 2020 from each plot, with ten sub-samples from around each plot that were mixed, and sent for analysis at Eurofins (Moss, Norway).

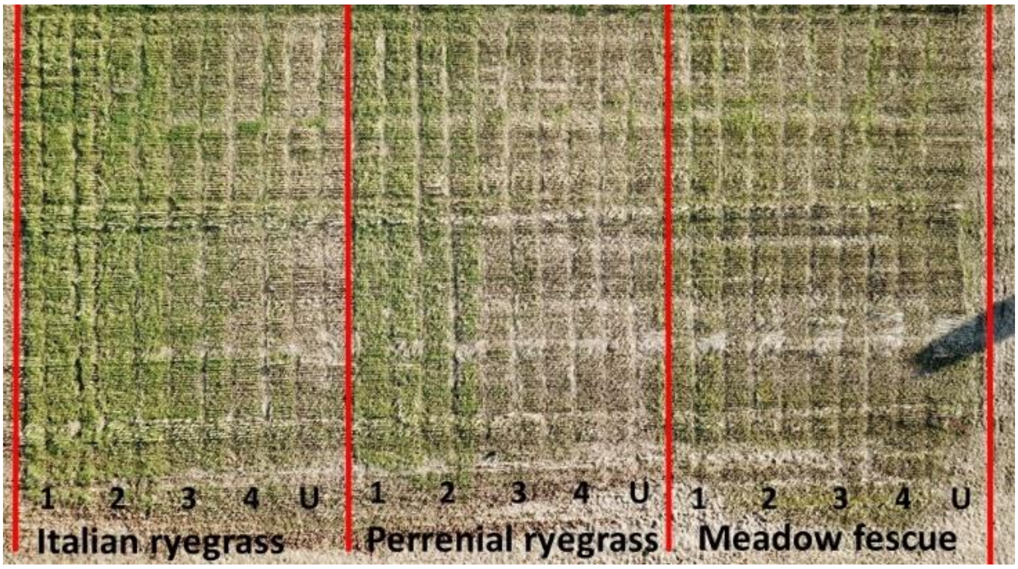

Figure 2. Drone photo of the cover crop establishment in the experimental field in 2019, with Italian ryegrass (**left**), perennial ryegrass (**middle**), and meadow fescue (**right**), and with sowing at the same time as the grain = 1, sowing at two, three, and four few weeks after the grain (=2, 3, and 4, respectively), and without cover crop (=U). The photo was taken shortly after threshing. The cover crops had another month and a half to grow in the autumn before winter but delaying the sowing time (=3 and 4) showed poor establishment and was not included in the analysis and not repeated in the 2020 trial.

The data were analyzed by using SPSS statistical software (© 2021 IBM (New York, NY, USA)) with two-way ANOVA tests, Duncan's multiple range tests of the means, and least significant differences (LSD) calculations. For common and scientific plant names, we applied GRIN-Global Taxonomy for Plants [26].

2.2. Interviews

Semi-structured interviews were done with 19 farmers or other persons that were involved in agriculture, and the persons were from Viken, Vestfold, and Telemark counties (Norway). The interviews were conducted with open-ended questions, 13 over the phone and 6 with farm visits. The responses were transcribed and analyzed by descriptive statistics. The number of respondents was too low for a more advanced quantitative analysis, but we rather looked for answers that could broaden the understanding of our field trial results. The persons in question were selected due to their experience, thus not randomly.

2.3. Literature Syntheses

We made two literature syntheses, one for carbon sequestration and one for the production and competition. The Web of Science Core Collection was used for literature searches. The facility includes around 12,000 international journals from all disciplines. We followed a systematic approach by combining search terms and recording the process. For soil carbon sequestration we applied the advanced search function and the following script TS = (soil organic carbon AND temperate climate OR Sweden OR Norway OR Denmark OR Finland OR Nordic countries) AND TI = (carbon AND cover crop OR cover crop). This gave a total of 42 hits (Figure S1). In addition, 6 more articles from other searches were added. The process resulted in 11 articles finally included in the qualitative synthesis; of these, 9 were included in the final calculations. The criteria for inclusion were papers with data from trials that were carried out over more than three years and in a climate that was relevant for Northern Europe. To calculate the annual carbon sequestration, we extracted information on the duration of the trials and the changes in the soil carbon content over those years. We transformed all the data to the same scale (g C kg^{-1} dry soil) before calculating the annual change as kg C ha^{-1} $year^{-1}$ within 0–20 cm soil depth. If bulk density was not provided, we applied 1.6 g cm^3 which gives 220,000 kg soil ha^{-1}. For production and competition, we replaced the word "soil organic carbon" with yield, biomass, or nitrogen. The process resulted in 12 articles that were included in our synthesis.

3. Results

3.1. Field Trials

We started the experiment in the first season (2019) with four different cover crop sowing times: from the same day as the grain to four weeks later. The establishment of cover crops was best by sowing at the same time as the grains. The biomass production of the cover crops was not measured this first season. A subjective assessment after the harvest showed that Italian ryegrass gave the best establishment, followed by perennial ryegrass and meadow fescue (Figure 2). The last two sowing times resulted in very poor establishment and were excluded in further analysis.

No clear grain yield reduction was found due to the cover crops. In 2019 and across the grain crops, Italian ryegrass that was sown at the same time as the grain or two weeks later resulted in, respectively, 97% and 98% of the grain yield compared to the control with no use of cover crop (Table 2) and the differences were not significant compared to the control. However, there was a tendency for yield reduction in spring wheat, with the lowest grain yields with 4380 ± 410 kg ha^{-1} on plots with Italian ryegrass that were sown on the same day as the grains compared to 4890 ± 174 kg ha^{-1} on plots with Italian ryegrass that were sown two weeks later, and 4910 ± 137 kg ha^{-1} on plots with no cover crop. Perennial ryegrass and meadow fescue gave the same grain yields as the control regardless of the sowing time.

In the second season (2020), we tried two different sowing times of the three cover crop species, and the biomass production was measured as well as grain yield and other parameters. We saw the same pattern as in 2020. Across the two grain crops, Italian ryegrass that was sown at the same time as the grain resulted in 93% of the grain yield compared to the control without a cover crop, while Italian ryegrass that was sown two weeks later resulted in 99% grain yield compared to the control. Perennial ryegrass and meadow fescue regardless of sowing time gave no yield reduction with grain yield values at 98–100% compared to the control.

The above-ground cover crop biomass was highest (991 kg DM ha^{-1}) for Italian ryegrass that was sown on the same day as the grain, followed by Italian ryegrass that was sown two weeks after the grain (461 kg DM ha^{-1}) and perennial ryegrass that was sown on the same day (336 kg DM ha^{-1}). Perennial ryegrass that was sown two weeks after the grain and meadow fescue that was sown on the same day as the grain yielded lower (336 and 322 kg DM ha^{-1}, respectively), and meadow fescue that was sown two weeks after the grain was at the bottom (300 kg DM ha^{-1}) (Table 2). The plant height of the cover crops in the late autumn followed the same pattern and showed significant differences (Table 2). The weed percentage in the late autumn was the highest on the control plots with no cover crops while Italian ryegrass as a cover crop that was sown at the same time as the grain had 83% less weeds than the control, and Italian ryegrass that was sown two weeks later had 55% less weeds than the control (Table 2). Also, perennial ryegrass and meadow fescue showed significant weed reductions compared to the control.

There was also more total nitrogen that was bound up in the biomass of the cover crops when sown at the same time as the grain compared to 1–2 weeks later, especially for Italian ryegrass. Italian ryegrass that was sown on the same date as the grain resulted in 16.6 ± 5.2 and 13.4 ± 4.8 kg N ha^{-1} bound up in the above ground biomass in late October in the cover crop biomass in the spring wheat and barley field, respectively. The numbers for Italian ryegrass that was sown two weeks later were 9.3 ± 0.6 and 3.9 ± 1.0, respectively.

Table 2. Grain yield in 2019 and 2020 (kg ha^{-1}) with different cover crop species and different sowing time, and above-ground dry matter (DM) biomass production, plant height of cover crops, and weed percentage in late autumn 2020 [A].

Treatment	Grain Yield 2019 (kg ha^{-1})	Grain Yield 2020 (kg ha^{-1})	Cover Crop Biomass (kg DM ha^{-1})	Cover Crop Plant Height (cm)	Weeds Late Autumn (%)
Main Crops					
Barley	6356	4355 a	301 b	18.9	2.9
Spring wheat	5679	3121 b	569 a	14.9	1.9
$LSD_{5\%}$	729 (ns)	1190 *	52 **	5.7 (ns)	2.0 (ns)
Cover crop and Sowing Time					
Italian ryegrass, same day	5707	3541	991 a	24.2 a	0.7 d
Italian ryegrass, two weeks later	5725	3736	461 b	14.8 bc	1.9 c
Perennial ryegrass, same day	6322	3816	336 bc	17.7 b	1.9 c
Perennial ryegrass, two weeks later	6705	3696	322 bc	14.8 bc	2.6 b
Meadow fescue, same day	5943	3770	300 bc	16.3 bc	2.9 b
Meadow fescue, two weeks later	5848	3819	203 c	13.5 c	2.8 b
Control (no cover crop)	5871	3788	-		4.2 a
$LSD_{5\%}$	1027 (ns)	232 (ns)	209 ***	2.8 ***	0.6 ***
CV%	12.3	5.2	40.0	13.7	21.2

[A] Same letter(s) within column represents a non-significant difference at 0.05 level of significance based on Duncan multiple range test. * significant at 5%; ** significant at 1%; *** significant at 0.1%, ns not significant. LSD5% is least significant difference at 5%.

In 2020, soil samples were also taken to examine the nitrate content in the soil in the autumn for each combination of cover crop and sowing time. No significant differences were found between the two sowing times of the cover crops and the different types of cover crops. However, there was a significant difference between cover crops and no cover crops (p = 0.02). On average, cover crops had 7.2 mg nitrate per 100 g of dry soil, while no cover crops had 8.3 mg nitrate per 100 g of dry soil.

3.2. Farmers' Perceptions

One thing that became clear in the interviews with the farmers was that almost everyone says the cover crops have improved soil structure. The economic aspect is also one of the respondents' main points.

More than half of the interviewed farmers say that they use cover crops based on a desire to practice reduced tillage/no-tillage. They say that they have experienced higher yields with the use of cover crops, with improved soil properties, faster water infiltration, and better root development.

Regarding the cultivation technique, the sowing time of cover crops varied from farm to farm and year to year. Around 25% of the farmers said they prefer to sow at the same time as the spring grain and highlight this as a safe and practical solution. The majority of the farmers said that they sow when the grain starts maturing, and to do this, they use a centrifugal spreader, typically used as a fertilizing machine. They argue that they do not risk competition with the main crop by this sowing method, but they need to ensure that the seeds are evenly spread, which is best obtained if the seeds have almost the same weight. The method also sets requirements for the weather on the day of dispersal, as it cannot blow too much, and the seeds need humidity to germinate. The last option is sowing immediately after harvest, but the season is often too short in Norway.

Half of the interviewed farmers, whom all run conventional farming, terminate the cover crop growth by spraying. They all pointed to the importance of selecting the right type of herbicide and timing; glyphosate is the herbicide that is used for this.

As reduced tillage is part of the motivation for many of the farmers that were interviewed, they need to find alternative ways to terminate the cover crop growth, especially if they are using perennial and biennial species. Such species can be sprayed the following spring and then harrowed before seeding. Italian and perennial ryegrass are mentioned as species for undersowing in almost all cases. Everyone has knowledge and experience with it; these plants are recognized for their expanded root systems and are easy to grow. For autumn sowing, oil radish is a popular plant as it is especially good at improving the soil structure. Italian ryegrass was also highlighted for autumn sowing. Legumes, such as vetches, are also very popular in autumn sowing, especially for those who grow organically and want nitrogen-fixing plants.

Only one out of the 19 interviewed persons believed that cover crops have a great potential in carbon sequestration. On the other hand, the same farmer did not see cover crops as necessary in a global climate measure. None of the farmers had climate and carbon sequestration as a main motivation to sow cover crops.

To sum up, most of the respondents believe that Norwegian soil can be utilized better and that using cover crops is a good agronomic tool to increase soil fertility. For undersowing methods, Italian ryegrass and perennial ryegrass are lifted up as good species and farmers have positive experiences with sowing at the same time as the grain. The termination of the growth, especially with the use of perennial ryegrass combined with reduced tillage/no-till, can be an issue and requires herbicides. Otherwise, farmers have experienced that the cover crop may show up again as weeds in the following years.

3.3. Literature Synthesis on Carbon Sequestration

Out of 40 identified studies on carbon sequestration, 9 were selected as relevant for a Scandinavian, temperate climate (Table 3). A summary of the literature review showed carbon sequestration in the range 250–500 kg C ha^{-1} year^{-1} but with large variations from study to study. The median value was at 264 kg C ha^{-1} year^{-1} and is perhaps better to use than the average value at 540 kg C ha^{-1} year^{-1}. More research is needed to clarify how much carbon the cover crops can contribute. Several factors will affect the result, where soil and climatic conditions are important but also the tillage system and the growing season's length; a short growing season gives less potential for carbon sequestration. Below we provide a summary of each of these studies chronologically.

Table 3. Summary of the literature synthesis with an overview of the studies with relevant data on quantifications of changes in soil organic carbon with the use of cover crops.

Study	Number of Years	Difference (g C kg^{-1})	Annual Change (kg SOC ha^{-1} year^{-1})	Details
Boselli et al. [27]	6	3.07	1127	North Italy
Chahal et al. [28] (trial A)	8	3.31	910	Canada
Chahal et al. [28] (trial B)	8	6.45	1774	Canada
Yang et al. [29]	13	0.75	127	Norway
Blombäck et al. [30]	7	0.18	57	Sweden
Thomsen & Christensen [31]	10	1.20	264	Denmark
Popelau et al. [32]	20	3.12	343	Sweden
Curtin et al. [33]	3	0.50	95	Canada
Mutegi et al. [34]	30	-	162	Denmark
Mean ± St.dev.	11.6 ± 8.4	2.3 ± 2.1	540 ± 598	
Median	8	2.1	264	

Boselli et al. [27]—Northern Italy: The study investigated the effect of the combination of no-tillage and cover crops on a silty clay soil under a temperate climate in Piacenza in northern Italy. The experiment lasted for six years. The cover crop that was used was a mixture of 55% rye, 25% winter vetch, 8% blood clover, 8% Italian ryegrass, and 4% fodder radish that was sown after harvesting the main crop. The results showed that using cover crops in no-till systems can increase the carbon content of the soil in a magnitude of 1127 kg C ha^{-1} $year^{-1}$. The fact that the combination of cover crops and no-tillage was looked at makes it hard to separate the effect of cover crops from the effect of tillage method.

Chahal et al. [28]—Canada: This study examined the effects of cover crops on carbon sequestration in two experiments (A and B) at the same area in Ontario, Canada. The climate in the area is temperate and humid (coastal). The crop rotation in the experiments was similar in A and B. It consisted of cereals and vegetables followed by a cover crop that was sown after the harvested main crop. The cover crop remained until the following spring. The results showed that the fields with cover crops had a significantly higher content of SOC than the control field without a cover crop. During the experimental period of over eight years, the cover crops had produced 4400–10,600 kg ha^{-1} more carbon than the control at location A and with even a more considerable difference at location B, where the cover crops produced 3700–18,600 kg ha^{-1} more than the control over those eight years.

Yang et al. [29]—Norway: The trial was conducted on clay soil in Southeast Norway and designed to examine the long-term effect of various crop rotations and where cover crops and fertilization practices were among the treatments that were included. The cover crop treatments were started in 1988, lasted for 13 years, and included grain with three different treatments: no cover crop, undersown ryegrass, and undersown clover. The cover crops were fertilized, and soil samples were taken from 0 to 10 and 10 to 25 cm soil depth in the autumn of 2001. The cover crops resulted in an increase in the soil's organic carbon content in the range of +200–300 kg C ha^{-1} $year^{-1}$ compared to no cover crop.

Blombäck et al. [30]—Sweden: This study simulated the effects of several years of use of cover crops on various parameters using the SOIL-N modeling tools. Over a simulation period of 35 years, it was found that without the use of cover crops, the relative carbon loss from the soil would be 5–7%, or 170–230 kg C ha^{-1} $year^{-1}$. By using cover crops, on the other hand, it would be possible to increase the organic carbon content by 0.6% compared to the initial level over a seven-year period, which equals a sequestration in the range of 57 kg C ha^{-1} $year^{-1}$. The modeling further showed that a net accumulation was very sensitive to the C/N ratio in the soil.

Thomsen & Christensen [31]—Denmark: This study investigated the long-term effects of different farming practices on the soil carbon content on sandy light clay soil at Askov experimental station in southern Denmark. Undersown perennial ryegrass as cover crop in grains was included as one of the treatments. Over the first ten-year period, the soil carbon content increased by 264 kg C ha^{-1} $year^{-1}$.

Popelau et al. [32]—Sweden: This study examined the effect of perennial ryegrass as a cover crop on the soil's content of organic carbon in two Swedish long-term trials in Mellby (Halland, Southwest Sweden). The Mellby I included four pairs of cover crops/non-cover crops, as well as different fertilization regimes for the cover crops over a period of 24 years. Spring barley, spring wheat, oats, spring oilseed rape (*Brassica napus* L.), and potatoes (*Solanum tuberosum* L.) were included as the main crops. In cereals and oilseed rape, the perennial ryegrass cover crop was sown in the spring, the same day as the main crop. In potato cultivation, rye was sown as a cover crop after harvest. In this experiment, the cover crops lasted over the winter and were terminated by ploughing in the spring. The Mellby II experiment examined the effect of undersown perennial ryegrass as a cover crop in grain. The main crops here were spring barley, oats, and spring wheat. The cover crop was sown in the spring and ended in the autumn, and the experiment lasted for 20 years. The results of the Swedish studies show that perennial ryegrass as a cover crop increased the soil carbon stock compared with no use of the cover crop. The effect varied but on average the cover crop resulted in an increase that corresponds to 343 kg C ha^{-1} $year^{-1}$, but here there are still large differences in the results.

Curtin et al. [33]—Canada: In Saskatchewan (Canada), it was examined how much soil carbon could be increased by using annual green manure legumes as an alternative to fallow in a crop rotation with «fallow-wheat-wheat». The experiment started in 1987 on a type of black soil in Canada. A total of three years before start-up, there was a fallow-wheat crop rotation on the soil with minimal fertilizer application. As many as nine crop rotations were included in the experiment, including "fallow-wheat-wheat" and "green manure-wheat-wheat". Tillage was kept to a minimum and the straw was cut high. The results showed that a three-year growth rotation where the fallow year has been replaced with legume-green manure only had a limited effect on the soil carbon content. This was explained by a rapid degradation of the legumes in the soil due to its low C/N ratio (in the range 12–13). Compared with fallow, the total organic carbon in the topsoil (0–7.5 cm) increased by 0.5 g kg^{-1}. However, at 7.5–15 cm soil depth, the total organic carbon decreased by 1.2 g kg^{-1}. On average, the increase was 95 kg C ha^{-1} year^{-1}.

Mutegi et al. [34]—Denmark: This study investigated the effect of using fodder radish as a cover crop for 3 years on carbon turnover in the soil/plant system in two field trials in Denmark. Based on 14C data from the experiment, they used modeling and estimated that over 30 years of continuous use of radish as a cover crop, 4900 kg C ha^{-1} can be stored in the soil, which may give an annual increase in the range of 162 kg C ha^{-1} year^{-1}.

3.4. Literature Synthesis on Cultivation and Competition

Our field trials were complemented with a targeted literature synthesis on earlier trials from Norway and the other Nordic countries. Here, we extracted information that was relevant for our field trial and focused on competition, biomass production, and N uptake in different species under field conditions. Below we provide a brief overview of the most relevant studies, and we present them chronologically. If nothing else is said, the cover crops were seeded at the same time as the grain and with normal seeding rates, which can be defined as 15–20 kg ryegrass ha^{-1} or equivalent.

Børresen & Eltun [35]: This study investigated undersown Italian ryegrass (25 kg ha^{-1}) and white clover (1 kg ha^{-1}) at two locations in Norway with different fertilization regimes. Italian ryegrass gave a 5–20% grain yield reduction compared to no use of a cover crops with the highest reduction at the lowest fertilization rates. The N uptake in the ryegrass was 10–15 kg N ha^{-1} and the reduction in the soil nitrate content in the late autumn was 19–43 kg N ha^{-1} compared to no use of a cover crop.

Lyngstad & Børresen [36]: This study also examined undersown Italian ryegrass in southeastern Norway and showed a 2–12% grain yield reduction compared to no use of a cover crop.

Andersen & Olsen [37]: Undersown Italian ryegrass and perennial ryegrass was compared in field trials in Denmark. Italian ryegrass produced 928 kg ha^{-1} and perennial ryegrass 800 kg ha^{-1} and the N uptake in the biomass was in the range of 15–16 kg N ha^{-1}. The cover crops reduced the soil nitrate content in the late autumn with 7–8 kg N ha^{-1} compared to no use of a cover crop.

Breland [38,39]: Undersown Italian ryegrass was examined under three different N application rates. The experiments were carried out in growth chambers and in fields in southeastern Norway. A 6–17% grain yield reduction was observed for Italian ryegrass compared to no use of a cover crop, and the highest reduction was found at the lowest fertilization rate. The N uptake in the ryegrass varied with fertilization from 17 to 55 kg N ha^{-1}. On average, the soil nitrate level was reduced by 38 kg N ha^{-1} with the use of a cover crop compared to no cover crop.

Ohlander et al. [20]: The competition between undersown cover crops and grain was investigated in fields trials in southern Sweden. Italian and perennial ryegrass as well as red clover were undersown at the same time as the grain, at grain root emergence, and at the 1-leaf and 3-leaf stages of the grain. Across the species 588, 468, 250, and 50 kg DM ha^{-1} were produced at the different sowing times. On average, Italian ryegrass and perennial ryegrass produced 452 and 291 DM kg ha^{-1}, respectively. Italian ryegrass that was sown at the same time as the grain reduced the grain yield by 6% and perennial ryegrass by 1%. Delaying the sowing reduced the competition.

Karlsson-Strese et al. [23]: Another study from mid-eastern and southern Sweden that examined the competition between undersown species and barley included a large number of undersown species. The seeding rate was 20 kg ha^{-1} for Italian ryegrass and 15 kg ha^{-1} for perennial ryegrass. A 5–10% yield reduction with the use of these grasses, and Italian ryegrass was among the species that had the greatest impact on the grain yield.

Lemola et al. [40]: Undersown Italian ryegrass was investigated under differ soil types in lysimeter trials in Finland. The use of cover crop, with the applied seeding rate of 10 kg ha^{-1}, reduced the grain yield by 0–6% compared to no cover crop, and with the highest reduction on clay soil. The N uptake in the ryegrass was in the range of 10–24 kg N ha^{-1} and the cover crop reduced the soil nitrate content in the late autumn by 3–16 kg N ha^{-1} compared to no use of cover crop.

Molteberg et al. [41]: Italian and perennial ryegrass were tested in field trials at different locations in Norway. A 4–7% yield reduction was measured with the use of Italian ryegrass and a 2–3% with the use of perennial ryegrass. The cover crop biomass production was in the range of 960–1170 kg DM ha^{-1} for Italian ryegrass and 810–880 kg TS ha^{-1} for perennial ryegrass. The cover crops reduced the soil nitrate content in the late autumn by 25–35 kg N ha^{-1} compared to no use of cover crop.

Känkänen and Eriksson [19]: This study investigated 17 undersown species with three seeding rates in spring barley. Competition, biomass production, and the effects on the soil nitrate content were measured in field trials in Finland. Italian ryegrass produced a shoot biomass of 1020–1660 kg DM ha^{-1} depending on seeding rates, and 16–23 kg N ha^{-1}. This cover crop decreased the soil nitrate content by 4 kg N ha^{-1} in the late autumn and there was no difference between the seeding rates. Italian ryegrass resulted in 7–17% yield reduction in barley depending on seeding rates. Meadow fescue produced a low biomass that did not compete with the grain.

Løes et al. [42]: A total of three years with repeated use of perennial ryegrass and white clover was investigated under organic grain production in Norway. Perennial ryegrass at the given seeding rate (10 kg ha^{-1}) gave no yield reduction in the grain, produced 760 kg DM ha^{-1} on average, and reduced the soil nitrate level in the soil by 20–25 kg N ha^{-1} compared to no use of cover crops.

Liu et al. [43]: This study was conducted on different sites in southern Sweden with undersown perennial ryegrass. Overall, no negative grain yield effects were found, and the repeated use of perennial ryegrass rather increased the yield, and the increase was 1–4%.

Aronsson et al. [9]: This study investigated the N uptake in undersown ryegrasses as cover crops on different sites in Sweden and Finland. The uptake was in the range of 7–38 kg N ha^{-1} and cover crops significantly reduced the soil nitrate content in autumn by 60% compared to no use of cover crop.

4. Discussion

Even though cover crops could provide numerous benefits in spring-sown grain production systems in Northern Europe, not many farmers benefit from the approach, as they overestimate the competing ability of the cover crops with the main crop and distress yield losses. Thus, this study aimed to investigate the benefits and challenges of cover crops. Cover crops can be grown during the growing season along with the main crop or between grains [18]; however, in areas where the growing period is short, the second approach is less common. Therefore, this study only tested cover crops that were sown together with spring grains. The cover crops that were assessed were Italian ryegrass, perennial ryegrass, and meadow fescue that were sown simultaneously with the main grain or a few weeks later.

Regarding cover crop establishment, our findings indicated that spring-sown cover crops provide decent establishment and cover the soil surface between the last harvest and the following spring grain (usually in late August) and to the next growing season (usually in late April). While no significant reduction in the yield of main grains was detected in our experiments, the highest biomass production was observed for Italian ryegrass. This is mainly because Italian ryegrass provides a quick and decent establishment; albeit Italian ryegrass can compete with the main grain when sown concurrently. Moreover, perennial ryegrass also seems to be a good alternative, with a proper establishment but without the same risk for competition. In contrast, the meadow fescue cover crop did not yield satisfactory results and is less favorable. Similar poor results for meadow fescue were detected by Känkänen and Eriksson [19], with the highest above-ground biomass yield in Italian ryegrass, and the lowest was obtained from meadow fescue at barley harvest. Our literature synthesis showed that Italian ryegrass that was sown at the same time as the grain may result in a yield reduction up to 15% (Figure 3). Only perennial ryegrass gave no yield reduction. In all these studies, except for one, cover crops were sown at the same time as the grain. Our experiments showed that delaying the sowing of the cover crops by one or two weeks after the grain sowing will reduce the competition. Ohlander et al. [20] also showed reduced competition with delaying the sowing but recommended not to delay the sowing more than a week, not to risk uneven main crop stands. From our trials, we learnt that delaying the sowing more than 2 weeks leads to poor establishment. An alternative strategy, but with the same effect, could be to sow at the same time as the grain but reduce the seed amount of the cover crop. This is especially relevant for Italian ryegrass. We do not have access to seeding rate data for all studies in Figure 3, but we believe that at least part of the variation among the studies can be explained by different seeding rates. Känkänen and Eriksson [19] showed less competition when using low (200 seeds $m^{-2} \approx 8$ kg ha^{-1}) compared to normal (400 seeds $m^{-2} \approx 16$ kg ha^{-1}) or high (800 seeds $m^{-2} \approx 32$ kg ha^{-1}) seeding rates. In our trials we used 15 kg ha^{-1} for both ryegrass species, which gave a good establishment and a modest grain yield reduction with Italian ryegrass. For perennial ryegrass, we got no yield reduction. Therefore, we see no reason for delaying the sowing time for perennial ryegrass or reducing the seeding rate further. On the other hand, for Italian ryegrass, a delay in sowing time or reduced seeding rates could be recommended. Kvist [44] recommended seeding rates at 6–12 kg ha^{-1} for undersown ryegrass, this to balance a proper establishment with little competition with the main crop. This fits well into our picture of the seeding rates.

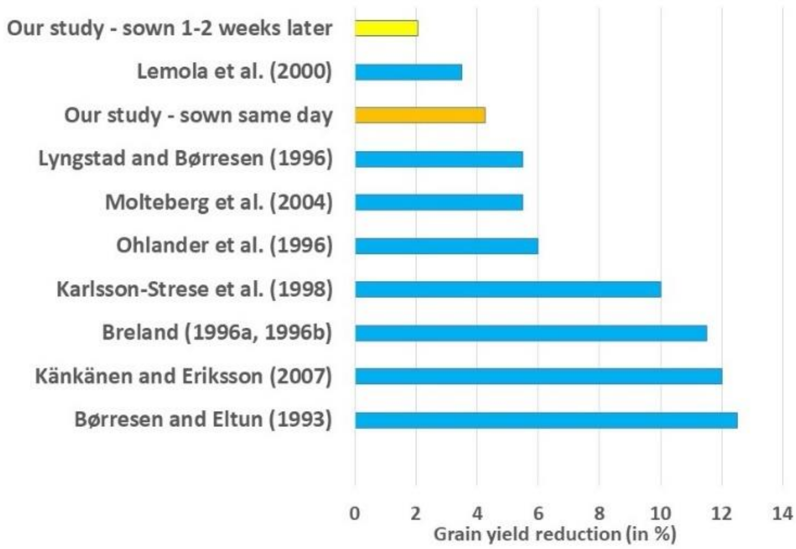

Figure 3. Grain yield reduction (in %) with the use of Italian ryegrass as the undersown cover crop. Our trials are compared to Lemola et al. [40], Lyngstad and Børresen [36], Molteberg et al. [41], Ohlander et al. [20], Karlsson-Strese et al. [23], Breland [38,39], Känkänen and Eriksson [19] and Børresen and Eltun [35]. Our trials are highlighted in orange = Italian ryegrass sown same day as the grain), and in yellow = Italian ryegrass sown 1–2 weeks later than the grain.

Cover crops have several environmental benefits; among other things, reduced soil erosion and nutrient losses during winter, elevated soil organic matter and carbon content, and several agronomic benefits for soil life and structure [8,45]. For instance, enhanced soil structure with high aggregate stability provides better air circulation and water infiltration. In this case, soil nitrifiers remain dominant over denitrifies, leading to fewer emissions and more accessible nitrogen for the plants. Also, cover crops simulate a natural grassland-like agroecosystem with a proper year-round soil surface cover. Grasslands are recognized for elevating carbon stock in the soil [46]. However, the amount of carbon that can be stocked through cover crops is influenced by various factors.

Regarding the soil carbon content, our literature review showed that cover crops supplement the soil carbon by a magnitude of 264 kg C ha^{-1} year^{-1}, despite significant variations between studies. Nevertheless, this is a smaller amount than what was reported in the worldwide review by Poeplau and Donin [19] and the long-term study with undersown ryegrass in Southern Sweden [32]. Moreover, there is a symmetry between increased carbon assimilation through cover crops and increased decomposition, where the net sequestration is zero. That said, in the conventional grain monoculture systems, it is taking much longer before an equilibrium is established, even with the cover crops. Generally, perennial cover crops increase the soil carbon stock more than annual cover crops [47]. Also, cover crop roots contribute to the accumulation of more soil organic matter than above-ground crop residues [48]. Wiesmeier et al. [49] assessed the carbon sequestration potential of grasslands and analyzed a dataset of 384 samples under arable land and 333 samples of permanent grassland in southeast Germany. The results indicated that the total SOC and N stocks in the soil depth of one meter were significantly higher in grasslands than in arable land, where the average SOC was 11.8 and 9 kg m$^{-2,}$ and N-storage was 0.92 and 0.66 kg m^{-2} in grassland and arable land, respectively. This was not a cover crop trial; however, there are certain similarities between grasslands and cover crops, both having active plant growth most of the season and both leaving little space for bare soil. The experiment indicates a more prominent organic carbon content in the covered soil than in exposed soil.

Another meta-analysis, including 95 studies, indicated that meadows generally had a positive effect on the soil carbon content, with a doubling effect of the carbon stock (+128%) over 100 years [50]. Similarly, afforestation of former arable land increased the soil carbon content less than meadows (+116%). In contrast, afforestation on meadows resulted in no net organic carbon sequestration than keeping the land as meadows.

Regarding the nitrogen content, our field trial results indicated a significantly lower nitrate level in soils with cover crops in late autumn than in soils without cover crops. A high nitrate level is considered a risk factor for nitrogen leaching [51]. The significance of using cover crops to preserve the nitrogen stand of the soil has been shown in several studies [9,19]. Hashemi et al. [52] observed that nitrate was accumulated in the cover crops while it leached to the environment in plots with no cover crops. Moreover, Sturite et al. [53] showed a higher N assimilation in Italian ryegrass than meadow fescue. Albeit, with the increased nitrogen uptake by the plants, the risk of losses through plants during winter increases, especially in species that are not surviving the winter. Karlsson-Strese et al. [23] indicated that delaying autumn incorporation of the cover crops decreased the N leaching risk, whereas Italian ryegrass was proven to be the most effective species at reducing soil nitrogen leaching (60%), followed by perennial ryegrass and Westerwold ryegrass (25%) [22]. In our trials we could not detect a similar difference between the species.

Concerning weeds, our results indicated fewer weeds with the use of undersown cover crops than no cover crops. In compliance with our findings, Gerhards [54] reduced weed density by 50% by sowing perennial ryegrass as a cover crop. Also, Cornelius and Bradley [55] showed a 40–80% reduction in the weed density where perennial ryegrass was used as a cover crop. Moreover, a US study showed that weeds' problems were significantly lower in cover cropping systems than in systems without cover crops [56]. The logic is that the frequent use of cover crops could compete with annual and perennial weeds for light and resources and inhibit their growth [57].

Nevertheless, perennial ryegrass is less competitive than other *Lolium* species, but the crop usually survives the winter in Scandinavia [32]. Therefore, a proper strategy for incorporating perennial ryegrass is required to prevent the cover crop from turning to a weed, as indicated by some of the farmers that we interviewed. For example, incorporation could be done in the late autumn to avoid N immobilization in the spring [58], but at the same time get the benefit of N leaching reduction [23].

5. Conclusions

The agricultural landscape in Northern Europe has changed from mixed farming to specialized farms with monoculture. Today, cover crops are an opportunity to diversify the spring-grain production system. We showed that Italian ryegrass, but also perennial ryegrass could work well as cover crops in barley and spring wheat. We raised four hypotheses. Our first hypothesis could partly be rejected based on our field trials, as undersown cover crops did not significantly reduce the grain yield in the year of sowing. However, our literature synthesis showed another picture. A 5–10% yield reduction was commonly found with the use of Italian ryegrass that was sown at the same time as the grain. We, therefore, recommend sowing Italian ryegrass one or two weeks after the main crop to be on the safe side and avoid competition, alternatively the amount of seeds should be reduced to 6–12 kg ha^{-1} for Italian ryegrass. Our second hypothesis was confirmed, as both our trials and the literature synthesis showed that the establishment, biomass production, and N uptake in the cover crop biomass was significantly affected by species. Not many studies have tested different sowing times. Our trials showed that Italian ryegrass that was sown at the same time as the grain produced a higher biomass than the other cover crops and delaying the sowing time reduced the production. N leaching potential, on the other hand, was not affected by species and sowing time but all the cover crops significantly reduced the potential compared to no use of cover crops. Our third hypothesis was hard to confirm, as the number of respondents was too low to draw conclusion, but we noted that farmers tend to overestimate the competing of undersown cover crops and rather choose to sow fast-growing annual species in autumn. The interviews showed that farmers highlight soil structure, rather than carbon sequestration, as their primary motivation. Our fourth hypothesis was confirmed, as the targeted literature synthesis showed a lower soil carbon sequestration than what was found in a worldwide meta-analysis. The synthesis showed a sequestration at 264 kg C ha^{-1} year^{-1}. If this is valid for undersown cover crops in Norway remains to see. We had a dry matter production in the cover crops up to 900 kg ha^{-1} year^{-1}, but only a fraction of this will remain in the soil as stable organic carbon content. Other trials have shown similar or higher biomass production. To sum up, we would say that our work is adding value to the research on cover crops. Our field trials were conducted in inland Norway, an area where little similar research has been made but is an important grain producing region in the country. We have documented that Italian ryegrass and perennial ryegrass give a decent cover crop establishment in barley and spring wheat, even though the biomass production is lower than what is found further south in Scandinavia. For Italian ryegrass, we recommend a one- or two-weeks delay in the sowing, but this is not needed for perennial ryegrass. Meadow fescue cannot be recommended; the establishment is too slow, and the plant survives the Norwegian winter, and so may cause a weed problem in the following seasons. Perennial ryegrass may also survive the winter in inland Norway, but it is less hardy than meadow fescue. Italian ryegrass does not survive the winter, which may cause nutrient losses during the winter. More research is needed to finetune the recommendations. There is also a need for long-term studies to better quantify the carbon sequestration under a Norwegian climate.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142013055/s1, Figure S1: PRISMA flow diagram of the current literature synthesis on carbon sequestration.

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