Carbon sequestration through agricultural practices

A review of international literature

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Colophon

This research was carried out by Wageningen UR and the Louis Bolk Instituut with subsidy from the Ministry of Agriculture, Nature and Food Quality (LNV), in the context of the Policy Support Program Slim Landgebruik (BO-53-106-015).

January, 2023

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Carbon sequestration through agricultural practices – a review of international literature

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Samenvatting

De Nederlandse agrarische sector heeft zich gecommitteerd aan het Klimaatakkoord van Parijs uit 2019. Een onderdeel daarvan is het doel om 0,5 Mton CO_2-equivalenten per jaar vast te leggen in minerale landbouwbodems met ingang van 2030. Dit vereist inzicht in de effecten van mogelijke landbouwmaatregelen om koolstof in de bodem vast te leggen. In het onderzoeksprogramma Slim Landgebruik worden 13 kansrijke landbouwkundige maatregelen om koolstof vast te leggen onderzocht met behulp van lange termijn experimenten (LTE's) en modelberekeningen. Dit heeft geleid tot voorlopige resultaten over de effectiviteit van de maatregelen en de CO_2 Bodem Tabel 2022 (Slier et al., 2022). Toch blijven er onzekerheden bestaan over de effectiviteit van de verschillende maatregelen wat betreft koolstofvastlegging door het beperkte aantal LTE's binnen Slim Landgebruik.

Een literatuuronderzoek is uitgevoerd om bij te dragen aan het begrip en de validatie van de 13 maatregelen om koolstof vast te leggen zoals deze worden onderzocht binnen Slim Landgebruik, aangezien niet alle maatregelen binnen Slim Landgebruik worden onderzocht door middel van LTE's. Artikelen zijn verzameld op twee ruimtelijke schalen: een mondiale schaal en een lokale schaal. Het literatuuronderzoek op mondiale schaal is uitgevoerd door specifiek te zoeken naar mondiale meta-analyses en literatuurstudies, waar mogelijk met een focus op gebieden met een gematigd klimaat. Bij het literatuuronderzoek op de lokale schaal is gezocht naar wetenschappelijke publicaties van veldexperimenten op locaties met een vergelijkbaar klimaat als Nederland waar vergelijkbaar agrarisch beheer wordt toegepast.

Uit de internationale literatuur blijkt dat er grote verschillen zijn in de potentie van de maatregelen om koolstof vast te leggen in de bodem en dat het eveneens verschilt in welke mate de effectiviteit van maatregelen op koolstofvastlegging onderbouwd zijn met onderzoek. De maatregelen waarvan werd vastgesteld dat ze de meeste koolstof vastleggen waren compost (0.62 - 2.1 t C ha^{-1} $jaar^{-1}$), meer permanent grasland (0.5 - 1.1 t C ha^{-1} $jaar^{-1}$), leeftijd grasland verhogen (0 - 1.8 t C ha^{-1} $jaar^{-1}$) en vaste mest (0.15 – 1.00 t C ha^{-1} $jaar^{-1}$). De maatregel vogelakkers had de minste potentie voor koolstofvastlegging (0.04 t C ha^{-1} $jaar^{-1}$). Maatregelen zoals compost, vaste mest en meer blijvend grasland worden uitgebreid bestudeerd in verschillende meerjarige veldexperimenten in West-Europa en de gevonden resultaten voor deze maatregelen hebben daarom een hogere mate van zekerheid. Sommige maatregelen zijn uniek voor de agrarische situatie in Nederland en/of nog slecht bestudeerd, waardoor er maar weinig relevante studies in deze literatuurstudie kunnen worden opgenomen. Dit is het geval voor meerjarige akkerranden, vogelakkers, mais-gras wisselteelt, agroforestry en het vergroten van het aandeel rustgewassen in de vruchtwisseling. De effectiviteit van alle maatregelen is onderhevig aan verschillende bronnen van variabiliteit, zoals het bodemtype, het initiële koolstofgehalte van de bodem, het eerdere bodembeheer en het lokale klimaat. Dit maakt het lastig om het effect van een maatregel in één waarde te vatten, en benadrukt het belang van modelstudies die deze variabiliteit in acht nemen bij de inschatting van koolstofvastlegging op landelijke schaal.

We raden het aan om nader (experimenteel) onderzoek te doen naar de maatregelen kruidenrijk grasland, groenbemesters, leeftijd grasland verhogen en agroforestry. Ook raden we aan om

onderzoek te doen naar de verwachte regionale effecten van bodemtype, initieel koolstofgehalte van de bodem, eerder bodembeheer en lokaal klimaat(verandering) op de potentie voor koolstofvastlegging in verschillende gebieden van Nederland.

Summary

The Dutch agricultural sector is committed to the Paris Climate Agreement of 2019. As part of this commitment, the Dutch agricultural sector aims to achieve a reduction of 0.5 Mt CO_2-equivalents per year by 2030 by sequestering carbon (C) in mineral agricultural soils. This requires insight into the effects of potential agricultural practices to sequester carbon in the soil. Within the Slim Landgebruik program, 13 promising carbon sequestration practices are being investigated using long-term field experiments (LTE's) and model calculations. This has led to provisional results regarding the effectiveness of carbon sequestration and the CO_2 Soil Table 2022 (Slier et al., 2022). Still, there remain uncertainties about the effectiveness of various carbon sequestration practices.

A literature review was conducted to contribute both to the understanding and validation of the effectiveness of the 13 carbon sequestration practices that are studied within the Slim Landgebruik program, considering that not all the practices are studies with LTE's. Literature was collected on two spatial scales: a global scale and a local scale. The literature review for the global scale was conducted by specifically searching for global meta-analyses and literature reviews, where possible with a focus on temperate areas. The literature review for the local scale was conducted by searching scientific publications of field experiments in sites with a similar climate to the Netherlands and with a similar agricultural management.

The range of carbon sequestration rates found in the international literature made clear that some practices have a higher potential to sequester carbon than others, and some practices are better substantiated with research than others. Carbon sequestration practices that were found to sequester the most carbon were compost (0.62 - 2.1 t C ha^{-1} $year^{-1}$), conversion to permanent grassland (0.5 - 1.1 t C ha^{-1} $year^{-1}$), extending grassland age (0 - 1.8 t C ha^{-1} $year^{-1}$), herb-rich grassland (0 - 1.8 t C ha^{-1} $year^{-1}$), and solid manure (0.15 – 1.00 t C ha^{-1} $year^{-1}$). The practice bird fields appears to have the lowest potential (0.04 t C ha^{-1} $year^{-1}$). Practices such as compost, solid manure and more permanent grassland are widely studied in various long-term field experiments conducted in western Europe, and therefore have a higher degree of certainty. Some practices are rather unique to the Dutch field conditions and/or still poorly studied, resulting in only few relevant studies to be included in this review. This is the case for perennial field margins, bird fields, crop rotation with maize and grass, agroforestry and increasing the share of cereals in the rotation. It became clear that the effectivity of all practices was subject to several sources of variability, such as the soil type, initial carbon content of the soil, previous management of the soil and the local climate. This complicates the establishment of a single value for the effect of a measure, and stresses the importance of modelling studies which take into account these sources of variability in the calculation of carbon sequestration at a national scale.

We recommend conducting further (experimental) research on herb-rich grassland, extending grassland age, cover crops and agroforestry in the Dutch context. Additionally, we recommend conducting research on the expected regional effects of soil type, initial carbon content, previous field management and local climate (change) on the potential for C sequestration in the different areas of the Netherlands.

1 Introduction

1.1 Background

The Dutch agricultural sector is committed to the Paris Climate Agreement of 2019. As part of this commitment, the Dutch agricultural sector aims to achieve a reduction of 0.5 Mt CO_2-equivalents per year by 2030 by sequestering carbon in the organic matter of mineral agricultural soils. This requires insight into the effects of potential agricultural practices to sequester carbon (C) in the soil. The practices that contribute to achieving the target for carbon sequestration must be in line with and contribute to the objective of the National Program for Agricultural Soils (Nationaal Programma Landbouwbodems, NPL) to sustainably manage all agricultural soils from 2030 onwards.

An important part of the NPL is the Slim Landgebruik (SL) research program. The SL program focuses among others on verifying the effectiveness of 13 agricultural practices for C sequestration. A number of these practices are being investigated using long-term field experiments (LTE's) and model calculations (Lesschen et al., 2021; Schepens et al., 2022). This has led to provisional results regarding the effectiveness of carbon sequestration and the CO_2 Soil Table 2022 (Slier et al., 2022). Still, there remain uncertainties about the effectiveness of some carbon sequestration practices, as there are only a limited number of LTE's available in the Netherlands, which are often of limited duration (**Fout! Verwijzingsbron niet gevonden.**, **Fout! Verwijzingsbron niet gevonden.**). Within Slim Landgebruik, there are no LTE's on bird fields, crop residues and conversion to permanent grassland. Besides, only few practices are studied with sufficient datapoints in space or time to find a significant effect or trend. Soil carbon stocks change very slowly, making it often impossible to measure a difference in soil carbon after running the experiment for a limited number of years. In addition, field experiments are commonly subject to several confounding factors which can create the need for the analysis of multiple experiments in order to find significant effects. An analysis of the most recent international findings with a special focus on research conducted in areas with similar climatological conditions will contribute to the verification and increase certainty of the effectiveness of the practices proposed for carbon sequestration in the SL program.

Table 1 Overview of the carbon sequestration rate with 95% confidence interval in the top soil (0-30cm) of the carbon practices studies within Slim Landgebruik in sandy soils (Schepens et al., 2022).

Practice	**Number of LTE's**	**CO_2 sequestration** (ton CO_2/ ha/ jr)	**95% confidence interval**	**p-waarde**
Change crop rotation	1	1.0	-3.9 , 5.9	0.59
Compost (per 3 ton OM)	1	5.7	-1.5 , 12.8	0.18
Slurry (per 3 ton OM)	2	1.6	-4.1 , 7.4	0.58
Cover crops	1	-1.0	-7.6 , 5.6	0.77
Perennial field margins	1	-16.4	-44.9 , 12.1	0.23
Non-inversion tillage	2	**-4.4**	**-8.3 , -0.6**	**0.02**
Extend grassland age	3	6.4	1.9 , 10.3	0.089

Maize-grass rotation	1	**6.5**	**2.5 , 10.5**	**0.004**
Herb-rich grassland	1	5.2	-2.9 , 13.3	0.18
Non-inversion tillage maize	1	0.0	-3.7 , 3.7	1.0

Table 2 Overview of the CO_2 sequestration rate with 95% confidence interval in the top soil (0-30cm) of the carbon practices studied within LTE's in clay soils (Schepens et al., 2022).

Practice	**Number of LTE's**	**CO_2 sequestration** (ton CO_2/ ha/ yr)	**95% confidence interval**	**p-value**
Change crop rotation	1	2.0	-0.7 , 4.8	0.12
Compost (per 3 ton OM)	3	**1.4**	**0.9 , 1.9**	**< 0.0001**
Solid manure (per 3 ton OM)	1	0.4	-0.5 , 1.2	0.31
Slurry (per 3 ton OM)	1	0.1	-2.6 , 2,8	0.96
Perennial field margins	1	**8.5**	**5.2 , 11.7**	**< 0.0001**
Non-inversion tillage	3	0.8	-0.2 , 1.7	0.10
Extend grassland age	3	**4.9**	**1.0 , 8.8**	**0.03**
Herb-rich grassland	1	-5.3	-17.1 , 6.4	0.43
Non-inversion tillage	1	**2.5**	**0.9, 4.2**	**0.03**

1.2 Objectives

This report synthesizes the current state of knowledge on the effectiveness of agricultural practices aimed to increase carbon sequestration. We focus on the practices that are described in the CO_2 Soil Table (Slier et al. 2022) and search for related international peer reviewed literature.

We aim to:

1. Determine the range of carbon sequestration rates (t C ha^{-1} $year^{-1}$) for each practice based on international findings of field experiments.
2. Concisely provide "global data" that include data from worldwide literature meta-analyses and reviews to get an estimate of the overall carbon sequestration rates based on many individual field experiments. Secondly, "local data" will be provided that include the output from specific studies in which the circumstances are comparable to Dutch conditions in terms of climate, soil type and agricultural practices considering this complies better with the context of the Slim Landgebruik practices.
3. Explain sources of variability in carbon sequestration for each practice.

This literature review contributes both to increased understanding of the effectiveness of carbon practices that are underrepresented in the Dutch LTE's, and to a lesser extend to the validation of the results from the practices which are well-represented in Dutch LTE's. In turn, this study contributes to the validation of the modelled results at national scale.

2 Methods

We carried out a literature search for each of the practices suggested by the CO_2 Soil Table (Slier et al. 2022) to increase soil carbon sequestration (hereafter "carbon practice"). The English translations for the Dutch carbon practices which are used for the scientific literature review are:

1. Cropping to grassland (Meer blijvend grasland)
2. Extending grassland age (Leeftijd grasland verhogen)
3. Maize-grass rotation (Wisselteelt mais-grasklaver)
4. Change in arable crop rotation (Aanpassen gewasrotatie)
5. Cover crops (Groenbemesters/vanggewassen)
6. Solid manure (Extra vaste mest)
7. Compost (Extra compost)
8. Crop residues (Gewasresten achterlaten)
9. Agroforestry (Agroforestry)
10. Bird fields (Vogelakkers)
11. Permanent field margins (Meerjarige akkerranden)
12. Non-inversion tillage (Niet-kerende grondbewerking)
13. Herb-rich grassland (Kruidenrijk grasland)

A short description of each carbon practice is included in the main text of the results section explaining the type of field studies gathered in the literature review for each practice aiming to come the closest to the defined Dutch C practices.

The literature search was carried out using Google Scholar and Web of Science search engines, and only peer review published papers were used. To cover the "global scale" we specifically searched for global meta-analyses and literature reviews which combine data from several field experiments and estimate an average carbon sequestration rate. Literature reviews and meta-analyses often collect data from experiments in different climatic zones. For our study we focussed on meta-analyses based on studies from temperate climates. For the "local scale" approach, we searched for scientific publications on field experiments in sites with a similar climate to the Netherlands and with a similar agricultural management. Relevant studies that were part of meta-analyses and literature reviews were used for the local scale search. Eventually, we searched for specific experiments reporting data on sandy and on clay soils since carbon sequestration rate is expected to vary between soil textures.

Relevant information from this literature review is summarized in the following tables:

1. Table 3 summarizes all carbon sequestration rates from our literature review from the global and local approach.
2. Appendix 1. In this table we made a comparison of the Dutch estimated carbon sequestration rates (modelled carbon sequestration rates and measured carbon sequestration rates from the SL LTEs in t C ha^{-1} $year^{-1}$) with the carbon sequestration rates gathered with our international literature review.
3. Appendix 2. This table lists the literature used in this review, grouped per carbon practice. For each article, the carbon sequestration, region of the study, number of experimental years, depth of the soil measurements, and the soil type is listed.

For some of the practices it was not possible to find data from the international literature because the carbon practice is very specific for Dutch agricultural type of management and is therefore not being tested in other countries. In those cases we either compared the Dutch carbon sequestration rate to similar carbon practices tested in other countries or we indicated that literature was not available.

3 Results & discussion

Table 3: Carbon sequestration rates for each carbon practice as found in global (temperate) meta-analyses and in local field experiments (t C ha^{-1} year^{-1}). For each practice, the results from global meta-analyses are given (global scale) and a range of C sequestration rate for local field experiments (local scale).

Carbon practice	Global (temperate) meta-analysis t C ha^{-1} yr^{-1}	Literature	Local field experiments t C ha^{-1} yr^{-1}	Literature
Cropping to grassland	1.01	Conant et al., 2001	0.5 - 1.1	Arrouays et al., 2001;Whitehead et al., 1975 Clement & Williams, 1964
	0.55	Minasny et al., 2017		
	0.13 ± 0.05	Lam et al., 2012		
Extending grassland age	1.1 ± 0.2	Klumpp & Fornara, 2018	0 - 1.8	Iepema et al., 2021; Hassink, 1994; Carolan & Fornara, 2016
Maize-grass rotation			0.11-0.7	Poulton et al., 2018*; Johnston et al., 2017*; Rios et al., 2022; Singh et al., 2005
Increasing share of rest crops			0.06 - 0.45	Götze et al., 2016; Grunwald et al., 2021 Triberti et al., 2016
Cover crops	0.5 ± 0.03	Jian et al., 2020	0.18 - 0.4	Schjönning et al., 2012; Thomsen and Christensen, 2004; Kahle et al., 2008; Constantino et al., 2010
	0.32 ± 0.08	Popleau & Don, 2015		
Solid manure	0.42 ± 0.11	Maillard & Angers, 2014	0.15 – 1.00	Körschens et al., 1994; Mercik et al., 1993 Powlson et al., 1994; Buysse et al., 2013
	0.52 ± 0.05	Han et al., 2016		
Compost	0.71 ± 0.4	Tiefenbacher et al., 2021	0.62 - 2.1	Poulton et al., 2018*; Arthur et al., 2011 Oldfield et al., 2018; Overesch et al., 2003
Crop residues	0.41 ± 0.04	Xu et al., 2019; Lessman et al., 2022	0.17 - 0.26	Poulton et al., 2018*
	0.38	Ranaivoson et al., 2017		
Agroforestry	0.21 ± 0.79	Mayer et al., 2022	0.033	Pardon et al., 2019
	0.3-0.9	Dexler et al., 2021		
Bird fields			0.04	Poulton et al., 2018*
Permanent field margins			0 - 0.52	Poulton et al., 2003*; Harbo et al., 2022
Non-inversion tillage	0.15 ± 0.04; 0	Haddaway et al., 2017 (0-30 cm; 0-150 cm)	0.68	Sun et al., 2011 (0-40 cm)
	0.22 ± 0.10	Meurer et al., 2018 (0-30 cm)		
	0.31	Angers & Eriksen-Hamel, 2008 (0-30 cm)		
Herb-rich grassland			0 - 1.8	De Deyn et al., 2011; Rutledge et al., 2017

* Experiments that are used for the calibration of the RothC model.

3.1 Cropping to grassland

Description

The practice 'cropping to grassland' describes the conversion of maize or temporary grassland (grassland that is renewed less than 5 years ago) to permanent grassland (grassland that is at least 5 years old). Because the Dutch term 'More permanent grassland' is generally not used in literature concerting field experiments, we used the term 'cropping to grassland'. Compared to cropland, permanent grasslands have a high supply of organic matter to the soil through root and leaf residues and the decomposition of the soil organic matter is low due to the low disturbance of the soil. For this practice, literature is gathered that reports the effects of converting cropland to pasture or grassland, regarding temporary grassland as an annual crop.

Literature

A meta-analysis on carbon sequestration potentials across the world by Minasny et al. (2017) reports various experiments and meta-analyses regarding conversion of cropland to permanent grassland, resulting in an average carbon sequestration rate of 0.55 t C ha^{-1} $year^{-1}$. Lam et al. (2013) studied improved agricultural management practices for carbon sequestration, such as mineral N application and improve pasture use, on Australian farms and showed that converting cropland to pastures was the most effective practice with a carbon sequestration rate of 0.13 ± 0.05 t C ha^{-1} $year^{-1}$ in the top 0-10 centimetres of the soil. Badgerey et al. (2014) compared the SOC stocks in the top 0-30 centimetres of the soil under cropped fields, temporary grasslands and permanent grasslands in Australia. There was no difference found between the temporary and permanent grasslands, but grasslands had higher carbon stocks than cropped fields. The difference in carbon sequestration rate was calculated to be 0.78 t C ha^{-1} $year^{-1}$. Within grasslands, the best indicator for SOC was the amount of bare soil in the sward, with less SOC in fields that were barer. On sandy soils in Western Australia, rotation trials showed no significant increase in SOC when temporary grassland was included in a crop rotation (Sanderman et al. 2010). Carbon stocks did increase when grassland was grown permanently, increasing with 0.30-0.60 t C ha^{-1} $year^{-1}$ in the top 0-15 centimetres.

The global meta-analysis by Conant et al. (2001) reviewed 23 studies on converting cultivated cropland into permanent grassland and determined the average carbon sequestration rate to be 1.01 t C ha^{-1} $year^{-1}$. This analysis includes studies from all around the world from which three studies are comparable to the Dutch circumstances based on climate and agricultural practices. At the Grassland Research Institute (Berkshire, England) a study on a sandy soil compared the conversion of plots from 100 years of continuous cropping to permanent grassland. After seventeen years, SOC was twice as high under permanent grassland plots than under plots that were continuously used for cropping (1.73 vs. 0.95 %SOC respectively), which comes down to a relative C sequestration rate of 0.8 t C ha^{-1} $year^{-1}$ (Whitehead et al., 1975). In a similar experiment Clement & Williams (1964) showed that grassland sequestered on average 0.9 t C ha^{-1} $year^{-1}$ over the first four years after sowing whereas reference plots with continuous cropping over the same period showed a reduction of 0.2 t C ha^{-1} $year^{-1}$, a difference of 1.1 t C ha^{-1} $year^{-1}$.

Another study conducted by Arrouays et al. (2002) in western Europe showed similar results. Arrouays et al. (2002) showed that conversion of cropped land used for cereal production to permanent grassland led to an increase of C sequestration of 0.49 ± 0.26 t C ha^{-1} $year^{-1}$ in the top 0-30 centimetres. It should be noted that maize had the lowest carbon sequestration among the crops included in this study, therefore the conversion from maize to permanent grassland might be higher than the 0.49 ± 0.26 t C ha^{-1} $year^{-1}$ found for going from cereal production to permanent grassland.

Discussion

Overall, these studies from across the world agree that converting cropland to grassland is generally an effective practice to sequester carbon in the soil (Table 3). However, high variation is found among long-term experiments. This variation can be explained by differences in the experimental length; crop rotation previous to the conversion; grassland management; soil conditions and/or climate.

Fields with an intensive crop rotation that are relatively depleted from carbon will achieve higher significant changes in soil carbon when converted to permanent grassland than fields with a higher initial carbon content. The net carbon flux to the soil is highest in young grasslands and lowers over time as the carbon stock reaches an equilibrium (Conant et al., 2001)(see also paragraph 3.2. Extending grassland age). Therefore, the carbon sequestration rate decreases with time after conversion to permanent grassland.

The rate of carbon sequestration in grasslands is also largely dependent on the productivity of the grassland and can be increased by enhancing grass biomass production. This can be achieved by using more productive grass species or higher fertilization. For instance, Conant et al. (2001) found that carbon sequestration could be enhanced with 0.3 t C ha^{-1} $year^{-1}$ through fertilization and up to 3.0 t C ha^{-1} $year^{-1}$ through changing the grassland species composition to include more productive species.

Mowing and grazing can also affect the carbon sequestration rate. In warm regions with low productivity, grazing generally leads to higher carbon sequestration as compared to mowing (Clement & Williams, 1964; Conant et al., 2001). However, in more productive conditions mowing likely leads to higher sequestration rates than grazing (Conant et al., 2001; Lorenz, 2018).

From the reviewed literature can be concluded that conversion of cropland to permanent grassland does effectively increase C sequestration (0.5-1.1 t C ha^{-1} $year^{-1}$), if managed properly (Table 1).

3.2 Extending grassland age

Description

Building on the previous practice 'cropping to grassland', this practice looks at increasing the age of grassland by preventing (early) renewal. By increasing the age of grassland and thus increasing the time between ploughing, the soil remains undisturbed for longer periods and can potentially accumulate more carbon in between grassland renewals.

No studies were found that compare the carbon stocks in fields that are renewed with a fixed frequency for many decades. Often, the history of a field is not known in such detail and grassland renewal varies over time depending on irregular disturbances such as droughts. Therefore, the included studies in this literature search compare the SOC stocks under grasslands with varying ages (years since renewal) and determine the amount of carbon sequestered as permanent grassland ages.

Literature

In a literature review performed by Klumpp and Fornara (2018), that involved data from 50 literature studies including over 400 study sites across the world, it was found that grasslands sequester on average 0.7 ± 0.16 t C ha^{-1} $year^{-1}$. They found a large variability in C sequestration rate among continents, mainly due to differences in climate, vegetation type and grassland management.

Carbon sequestration in European studies was determined to be 1.1 ± 0.2 t C ha^{-1} $year^{-1}$. This is the average sequestration in grasslands, hence rates might be higher or lower depending on previous management and the time since sward renewal.

Soil carbon sequestration rates in permanent grassland tend to decrease over time when no management changes occur (Klumpp and Fornara, 2018). For instance, in an experimental study on permanent grassland age in marine clay soils in the north of the Netherlands, Iepema et al. (2022) found that topsoil C stocks (0-10cm) in young grasslands (5-15 years since sward renewal) increased on average 3.0 t C ha^{-1} $year^{-1}$ whereas in the old grasslands (20+ years since sward renewal) the increase was on average 1.6 t C ha^{-1} $year^{-1}$. Carbon stocks were 11 t ha^{-1} higher (62 t C ha^{-1} as compared to 51 t C ha^{-1}) in the old grasslands, which clearly shows grasslands to act as a carbon sink as they age. Even after 30 years since sward renewal, carbon saturation had not been reached. Similarly, Hassink (1994) found a significant difference on SOC between young (1-3 years) and old (10 years) grasslands in a sandy area in the south of the Netherlands. This difference showed that grasslands sequester an average of 1.8 t C ha^{-1} $year^{-1}$ as they age from 2 to 10 years old.

In a similar experiment in Northern Ireland no differences were found in carbon stocks among grasslands of different ages (ranging from less than two to more than seventeen years since the last grassland renewal) (Carolan & Fornara, 2016). After re-seeding, CO_2 fluxes from the soil slightly increased. These increased fluxes did not affect the soil carbon stock, likely due to respiration being caused mainly by the old plant biomass that is brought into the soil when ploughing that enhances the pool of labile organic carbon and breaks down relatively rapidly. Carolan & Fornara (2016) argue that the SOC stock was more influenced by changes in the soil bulk density than by the disturbance associated to renewal of the sward, probably because reseeding events in their study were very infrequent. Soils with a lower bulk density were able to contain more soil carbon.

Discussion

Most studies agree that extending the age of permanent grassland leads to an increase of carbon stored in the soil. The older a grassland, the more carbon is stored in its soil. These carbon sequestration rates vary due to differences in crop productivity, fertilization rates and the mowing or grazing regime (similar to cropping to pasture; paragraph 3.1.) (Table 1). From this limited amount of studies, it appears that the carbon sequestration rates are highest in young grasslands and level off. Therefore, the marginal effect of increasing the periods between renewal on soil carbon is most likely highest on relatively young grasslands. In grasslands that have not been renewed in decades, the carbon content increases with a slower rate and extending the time between renewals likely has a smaller effect on the carbon sequestration rate. All the studies report on the effect of grassland age on carbon sequestration within one period between grassland renewals, hence the effect of the sward renewal itself is not included. Whether long-term changes in the grassland renewal regime leads to carbon sequestration could therefore not be determined from these studies.

3.3 Maize-grass rotation

Description

The practice ‘maize-grass rotation’ within Slim Landgebruik project is also described as the ’60-20-20’ practice, as the land use on a farm is divided into 60% permanent grassland, and 20% 3-year grass-clover in rotation with 20% 3-year maize. The effect of conversion of cropland to grassland is already described in section 3.1**Fout! Verwijzingsbron niet gevonden.**, and in this section we focus on the effect of converting a rotation of continuous maize to a rotation with 3-year grass-clover followed by 3-year maize. However, in international literature there are no meta-analyses or individual studies available which exactly match the description of a grass-clover in a 3-year rotation with maize. In this section we focussed therefore on individual studies which assess the effect of including grassland for more than one year in arable rotations, which are also called arable-ley rotations.

Literature

Poulton et al. (2018) summarize results earlier reported by Johnston (1973) and Johnston et al. (2009) from two arable-ley experiments that took place on a silty clay soil (18-27% clay) in England. In the first 37 years of a 3-year grass ley with a 3-year arable rotation, an increase of 0.07 t C ha^{-1} yr^{-1} was found. In the next 20 years of the experiment (3-year grass/clover with 3-year arable) an increase of 0.31 t C ha^{-1} yr^{-1} was reported. Before the start of the experiment the soil was under long-term arable use. In the same experimental set-up on a different site which had been permanent grassland, a loss of carbon (-0.61 t C ha^{-1} yr^{-1}) was reported in the first 39 years. In the next 20 years the carbon content increased again with 0.18 t C ha^{-1} yr^{-1}.

Johnston et al. (2017) measured C sequestration rates of ley-arable rotations (3 year grass or grass-clover and 2 years arable cropping) compared to continuous arable cropping over a 62 year period. In the arable-ley rotations, the carbon sequestration rate was between 0.11 and 0.33 t C ha^{-1} $year^{-1}$ in the first 30 years, and between 0.01 and 0.16 t C ha^{-1} $year^{-1}$ in the second 30 years after the start of the experiment. In the continuous arable rotation the carbon sequestration was positive in the first 30 years (0.06 t C ha^{-1} $year^{-1}$), but negative in the second 30 year (-0.09 t C t C ha^{-1} $year^{-1}$) after the start of the experiment. The experiment was located on a sandy soil in England which was under long-term arable management before the start of the experiment.

Rios et al. (2022) compared the effect of different crop rotations on SOC in a 8-year experiment. The rotations include continuous silage maize; different 3-year rotations with 1 or 2 year grass-clover ley; and permanent grassland. At regular N fertilization with slurry, the continuous silage maize treatment as well as the treatment with 1 year grass-clover had a negative SOC rate (-0.6 t and -0.2 t C ha^{-1} $year^{-1}$ respectively). Rotations with 2 years grass-clover had a slightly positive C sequestration rate (0.1 t C ha^{-1} $year^{-1}$), but not as high as the permanent grassland (1,1 t C ha^{-1} $year^{-1}$). This experiment was performed on a sandy soil in Northern Germany.

Singh et al. (2005) report a C sequestration rate of respectively 0.21 and 0.36 t C ha^{-1} $year^{-1}$ in a 4-2 and 2-4 arable-ley rotation, as compared to a loss of -0.08 t C ha^{-1} $year^{-1}$ in a continuous arable rotation. This is based on a 37 year experiment on a sandy soil in the south of Norway.

Van Eekeren et al. (2018) measured the SOM content in a field experiment after 35+ years of permanent arable cropping, permanent grassland and grass-arable rotations (3 year grass rotated with 3 year arable). The SOM content in the grass-arable rotations was significantly higher compared to the continuous arable rotation, although not as high as in the permanent grassland. SOC and the C sequestration rate are however not reported. The experiment was performed on a sandy soil in Belgium.

Discussion

All studies agree that carbon sequestration rates increase in the order arable rotation, grass- or grass-clover in an arable rotations, grassland. If the period with grass or grass-clover in an arable rotation is longer, the sequestration rate will be higher. Whether the rotation with grass in an arable rotation increases the carbon stocks is highly dependent on the crop history of the field (permanent grass- or arable cropping). Considering the carbon practice maize-grass rotation of Slim Landgebruik assumes a field history of continuous maize, the carbon sequestration rate will likely be positive (0.11-0.7 t C ha^{-1} $year^{-1}$)(Table 1). Although these studies included different arable crops than maize, it can be expected that the results will be similar in crop rotation with maize and grass.

3.4 Change in arable crop rotation

Description

The type of crops grown in arable crop rotations may have a large influence on the carbon in- and outputs to the soil. Therefore, the crop rotation may affect carbon sequestration rates. In Dutch arable farming it is common to use crop rotations with a large share of root crops such as potatoes, onions and sugar beets. Cereals, grasses and legumes such as clover and alfalfa, do not need as much tillage activities as root-crops leave relatively more crop residues to the soil. This literature search includes studies that compare crop rotations with varying shares of cereals in the crop rotations as compared to more intensive crops (sugar beets, silage maize).

Literature

In Europe there are few studies published that test the effect of including more cereals in the crop rotation. Götze et al. (2016) compared a monoculture of sugar beets to a rotation with sugar beets and winter wheat in central-east Germany. Crop residues of the wheat crop were removed each year. After maintaining the rotation treatments for over forty years, in 2010 and 2012 the carbon stocks in the top 0-30 centimetres were measured. On average, SOC stock in the sugar beet – winter wheat rotation was higher than under the monoculture of sugar beets. The carbon sequestration rate was calculated to be 0.06 t C ha^{-1} $year^{-1}$ higher in the rotation with winter wheat. This difference was however not significant. Soil carbon stocks appeared to vary greatly between the two sampling years, making it difficult to compare rotation treatments.

Another field experiment of thirteen years in central Germany with sugar beet rotations found that the carbon sequestration rate was 0.31 t C ha^{-1} $year^{-1}$ higher in the top 0-20 centimetres of the soil with a rotation of sugar beet – winter wheat – winter wheat compared to a rotation of sugar beet – winter wheat – silage maize (Grunwald et al., 2021). Despite the similarity with the Götze et al. (2016) experiment, Grunwald et al., (2021) found a much higher value for the carbon sequestration rate. In the experiment of Grunwald et al. (2021), crop residues of the winter wheat were left on the field whereas they were removed in the experiment of Götze et al. (2016). This could explain part of the difference in carbon sequestration rates found.

On a sandy soil in the north-east of Italy, Triberti et al. (2016) conducted a similar crop rotation experiment in which, among others, the crop rotation sugar beet – winter wheat and a monoculture of winter wheat were compared in regard to soil carbon stocks. Crop rotation significantly affected the carbon sequestration rate: the winter wheat monoculture sequestered 0.45 t ha^{-1} $year^{-1}$ more carbon in the top 0-40 centimetres than the sugar beet – winter wheat rotation.

Discussion

The carbon sequestration rate achieved with increasing the share of rest crops is likely dependent on the crop that winter wheat replaces in the rotation. Our literature search shows experiments in which different crops are exchanged with winter wheat. In Grunwald et al. (2021) one year of silage maize was exchanged for winter wheat, whereas in Götze et al. (2016) and Triberti et al. (2016) sugar beet was exchanged for winter wheat. No studies were found that exchanged potatoes with cereals. On average, less crop residues remain on the field after growing potatoes than after growing sugar beets, hence carbon sequestration is likely similar or lower. The carbon sequestration rates found by Götze et al. (2016) and by Triberti et al. (2016) differ however greatly. In both experiments, wheat crop residues were removed from the field. Fertilization might explain some of the variation: Götze et al. (2016) does not specify the amount of nutrients applied, but the fertilization rate in Triberti et al. (2016) was rather high. A well fertilized soil can lead to higher crop productivity and therefore to higher carbon sequestration rates.
Overall, the studies indicate that exchanging more intensive crops with winter wheat leads to an increased carbon sequestration rate (0.06-0.45 t C ha^{-1} $year^{-1}$), but this is dependent on the type of crop that is being exchanged and the crop management (Table 1). Unfortunately, no meta-analyses are found for this carbon practice. This is presumably due to the fact that many crop rotations in many countries have already a high share of cereals, and a further increase of the amount of cereals would reduce crop diversity. For the Dutch context, however, the share

of cereals in the crop rotation is rather low in many regions, and therefore an increase would can be considered as a carbon practice.

3.5 Cover crops

Description

Cover crops are crops that are sown between periods of main crop production. They can provide multiple soil, agricultural production, and environmental benefits (Blanco-Canqui et al., 2015). It is known that the growth of cover crops can increase SOC stocks due to the extra addition of organic matter into the soil, which results in higher SOC accumulation (Jian et al., 2020, Poeplau & Don, 2015). In this study we consider global meta-analyses and individual field studies in Europe that test the effect of monocultures and mixtures of cover crops versus fallow on soil carbon sequestration. We summarize the effect of cover crops on carbon sequestration rate under temperate European climate conditions.

Literature

Recently, Lessmann et al. (2022) published a literature review on the effects of several carbon practices in which data from published global meta-analyses was collected and used to determine carbon sequestration rates in different climatic regions. Lessmann et al. (2022) determined that adding cover crops into the rotation can increase soil carbon with a rate that varies between 0.32 and 0.5 t C ha^{-1} $year^{-1}$. These numbers are based on the results from two global meta-analyses on the effect of cover crops on soil carbon accumulation for temperate regions (Jian et al., 2020, Poeplau & Don, 2015). One main difference between these two meta-analyses is the average study length that varies from 4 years in Jian et al. (2020) up to 12 years in Poeplau and Don (2015).

The meta-analysis by Poeplau and Don (2015) showed that time since introduction of cover crops in crop rotation was linearly correlated with the SOC stock within a depth layer of (on average) 22 cm. From the 30 studies that are included in this study only 3 investigated the effects of cover crops on SOC stocks below the ploughing layer which reflects a gap of knowledge on carbon dynamics in the subsoil. From the 139 plots included in the meta-analysis, 13 plots showed SOC stock depletion after introducing cover crop and 8 showed an increase of carbon of 2.0 t ha^{-1} $year^{-1}$. Poeplau and Don (2015) suggest that the high variation in carbon sequestration rates within cover crop experiments may be explained by: (1) priming; addition of rapidly decomposable plant material leads to microbial community growth and enough energy becomes available to break up more stable compounds of SOC as compared to the cover crop treatment (Fontaine et al., 2004, Poeplau & Don, 2015). (2) spatial heterogeneity of SOC at sampling sites and the monitoring of SOC stocks can make it difficult to detect small changes on SOC stocks.

The meta-analysis from Jian et al. (2020) distinguishes between carbon sequestration rate in sandy and clay soils globally and showed a higher carbon sequestration rate in clay soils than sandy soils (0.81 ± 0.16 vs 0.44 ± 0.05 t C ha^{-1} $year^{-1}$). This is explained by the fact that fine-textured clay soils provide physical protection to SOC, because clay and silt-sized particles are more likely to form stable aggregates that can protect SOC against microbial decomposition (Jian et al., 2020). Also, this meta-analysis showed that soil carbon stock changes after cover crops had a significant positive correlation with annual temperature and precipitation and negative with latitude. This can be explained by the fact that warmer temperatures and higher precipitation is often related to higher plant productivity. This positive correlation suggest that the rate of carbon accumulation from higher plant productivity and input under warmer temperatures and higher precipitation can exceed the decomposition rates.

When looking into specific European field experiments with similar conditions to the Netherlands, we find that the effect of adding cover crops to crop rotation on SOC stocks varies between 0.18 to 0.4 t C ha^{-1} $year^{-1}$. These values are similar to the values found in meta-analyses for temperate climates. In Denmark, Schjønning et al. (2012) studied the effect of growing cover crops every second year on SOC stocks in a field experiment located in a sandy loam soil. The experiment lasted for 12 years and samples were collected in the soil 6-13 centimetres layer. The results showed an increase on carbon sequestration rates by cover crops of 0.4 t C ha^{-1} $year^{-1}$. Similarly, another Danish experiment tested the effect of adding perennial ryegrass during 10 years and showed an increase of SOC of around 0.22 t C ha^{-1} $year^{-1}$ (Thomsen & Christensen, 2004). Accordingly, a field study in Germany showed that including cover crops increases the carbon sequestration rate with 0.15 t C ha^{-1} $year^{-1}$ (Kahle & Schulz, 1994). Finally, in a field experiment in France it was found that after 17 years of growing cover crops every year or every two years (white mustard, Italian ryegrass, radish or winter cereal) resulted in an increase of the SOC stock with a carbon sequestration rate of 0.25 t C ha^{-1} $year^{-1}$ (Constantin *et al.*, 2010).

Discussion

Overall, using cover crops is an effective practice to increase SOC stocks, however variability is high (Table 1). The advantage of cover crops as compared to other carbon practices is that this carbon practice does not intervene with the main crop that is grown (Poeplau & Don, 2015). Furthermore, growing cover crops can provide other ecosystem services such as improved nutrient efficiency and a reduction of erosion (Poeplau & Don, 2015).

Variation among experiments at the local scale can be strongly influenced by the initial carbon stock at the beginning of the experiment. Soils with high SOC content will be able to sequester less additional carbon than soils with lower SOC. In fact, Jian et al. (2020) showed that SOC stock change under cover crops is negatively correlated with total soil carbon content. Higher temperatures and increased precipitation are often related with higher plant productivity which increases the carbon returned to the soil and therefore the rate of soil carbon sequestration.

In general cover crop experiments show a strong correlation between the carbon input of cover crops and the sequestered carbon in the soil. Constantin *et al.* (2010) showed that every ton of added carbon to the field via cover crop biomass can lead to an increase of 0.28 t C ha^{-1} $year^{-1}$ of sequestered carbon in the soil. The potential of this measure is therefore very dependent on the amount of biomass that was manage to form, hence the growing period should be as long as possible to reach the highest carbon input to the soil. Cover crops is a very broad term and cover crop practises vary greatly throughout the world, making it difficult to translate the results from this literature review back to the Netherlands. The effects of the growing period and climatic conditions on carbon sequestration rates should be studies further and quantified in future research. This in order to make better estimations of the effects cover crops grown within the Dutch context have on carbon sequestration.

3.6 Solid manure

Description

Solid manure has a relatively high content of organic material as compared to mineral fertilizer or liquid manure, due to the fact that manure is being mixed with litter such as straw. Adding solid manure to the soil can therefore increase the soil carbon content. In this literature study, there was a focus on including studies that applied realistic amounts of manure (15-35 t ha-1 year-1). There was no focus on a certain type of solid manure. Additionally, when the information was available, carbon sequestration rates were calculated back to the amount of carbon sequestration that was achieved for every ton of applied carbon.

Literature

Lessmann et al. (2022) gathered data from various global meta-analyses on the effect of fertilizer treatments on soil carbon sequestration. From these meta-analyses we selected two studies that determined the effect of manure addition in temperate regions (Han et al., 2016; Maillard & Angers, 2014). Maillard & Angers (2014) evaluated 130 observations from 49 sites across the world and found a linear relationship between the manure input and the change in SOC. Comparing fields that receive manure with fields that receive mineral fertilizer, an average sequestration rate of 0.42 t C ha^{-1} year^{-1} was observed. For every t manure-C ha^{-1} that was brought into the field, 0.12 t C ha^{-1} was sequestered. The carbon sequestration rate did not change with the type of manures or the type of soils, but there was an indication that C sequestration may be higher for cattle manure than pig or poultry manure.

Similar results were found in the meta-analysis by Han et al. (2016) when comparing fields that received mineral fertilizer and manure with fields that received no fertilization. The carbon sequestration rate was 0.52 ± 0.05 t C ha^{-1} year^{-1}, which is equal to 0.10-0.13 t C ha^{-1} for every t C ha^{-1} that was applied with the manure. No distinction between soil types or manure types were made.

From a more local approach similar to the climate and management in the Netherlands, we found the meta-analysis conducted by Körschens et al. (1998) that tested the effects of fertilization strategies on the soil nutrient balance and gives an overview of the manure dosages and carbon sequestration rates of several European long-term fertilizer experiments. In this meta-analysis they determined the carbon sequestration rates for manure application to be: 0.21 t C ha^{-1} year^{-1} in central Germany with a fresh weight dosage of 15 t ha^{-1} year^{-1} (Körschens et al. 1994), 0.20 t C ha^{-1} year^{-1} in central Poland with a fresh weight dosage of 20 t ha^{-1} year^{-1} (Mercik et al., 1993) and 0.24 t C ha^{-1} year^{-1} in south-east England with a fresh weight dosage of 35 t ha^{-1} year^{-1} (Powlson et al. 1994). Calculating this back to the carbon sequestered relative to the carbon input through the manure results in 0.22 t C ha^{-1} in central Germany, 0.10 t C ha^{-1} in central Poland and 0.07 t C ha^{-1} in south-east England (Körschens et al., 1994; Mercik et al., 1993; Powlson et al. 1994). Additionally, another field experiment in Belgium found a similar increase of soil carbon sequestration. On a silty soil, 44 t farmyard manure ha^{-1} was applied every 3 or 4 years, leading to a significant increase of soil carbon over time (Buysse et al., 2013). Over a 50-year timespan, carbon was sequestered at an average rate of 0.15 t C ha^{-1} $year^{-1}$. For every t C ha^{-1} added, 0.10 t C ha^{-1} was sequestered.

These values are the average rates at which carbon was sequestered over several decades. In reality, the rates are high at first and level off over time as the carbon stocks reach a new equilibrium. Poulton et al. (2018) describes the various experiments with solid manure that have been performed at Rothamsted (England). In the Broadbalk experiment (clay loam) and the Hoosfield experiment (silty clay loam), 35 t farmyard manure ha^{-1} $year^{-1}$ was applied for more than a hundred years. The carbon sequestration levels off over time in both experiments. In the Broadbalk experiment, the carbon sequestration rate over the first 20 years is 1.00 t C ha^{-1} $year^{-1}$ and only 0.10 t C ha^{-1} $year^{-1}$ in the final 100-120 years of the experiment. The sequestration rate in Hoosfield is 0.69 t C ha^{-1} $year^{-1}$ in the first 20 years and decreased to 0.06 t C ha^{-1} $year^{-1}$ in the final 140-160 years of the experiment. The same pattern was also found in the Woburn Market Garden experiment. The field also received on average 35 t manure ha^{-1} $year^{-1}$, but on a shorter period of 25 years. The average carbon sequestration rate throughout these 25 years was 0.85 t C ha^{-1} $year^{-1}$, of which the sequestration rate over the first 9 years of the experiment was on average 1.59 t C ha^{-1} $year^{-1}$.

In the Woburn Organic Manuring experiment, also described by Poulton et al. (2018), the effect of different manure dosages (10, 25 and 50 t ha^{-1} $year^{-1}$) was studied on a sandy loam soil that received 50 t ha^{-1} $year^{-1}$ in an earlier stage of the experiment. Carbon sequestration rates showed to increase with the amount of manure applied: 1.23 t C ha^{-1} $year^{-1}$ when 50 t ha^{-1} $year^{-1}$ was applied, 0.46 t C ha^{-1} $year^{-1}$ when 25 t ha^{-1} $year^{-1}$ was applied and a negative rate of -0.03 t C ha^{-1} $year^{-1}$ when the application rate was 10 t ha^{-1} $year^{-1}$. The negative sequestration rate for the low manure dosage is likely caused by the high dosage that the field received in the earlier stage of the experiment, resulting in the field moving to a new lower equilibrium of the carbon stock.

Discussion

Carbon sequestration rates are highly dependent on the manure dosage and generally increase from tropical to cooler temperate regions, which is attributed to the slower decomposition of organic matter in cooler soils (Han et al., 2016; Maillard & Angers, 2014). Most studies discussed previously found a carbon sequestration rate of approximately 0.07 to 0.22 t C ha^{-1} for every t C ha^{-1} that was added to the field in the first few decades since the application of manure has started. With fresh weight dosages of 13-35 t ha^{-1} $year^{-1}$ farmyard manure, the carbon sequestration rates ranged between 0.15-1.00 t C ha^{-1} $year^{-1}$ (Table 1). Some variation can likely be explained by initial soil conditions, soil type, manure type or additional mineral fertilizer usage. Carbon sequestration due to manure application was found to be higher on clay soils than on sandy soils, and higher when additional mineral fertilizer was applied as compared to when only farmyard manure was used (Gross et al., 2021).

3.7 Compost

Description

Similar to solid manure, compost has a high content of organic matter compared to mineral fertilizers or slurry, making the application of compost an effective practice for sequestering carbon. There are many types of compost, but in this literature study we focus on vegetable compost and garden waste compost in dosages comparable to the average Dutch practice (15-20 t compost ha^{-1} year^{-1}).

Literature

The meta-analysis by Tiefenbacher et al. (2021) analysed the results of six studies on compost amendment and determined the potential for carbon sequestration to be 0.71 ± 0.4 t C ha^{-1} year^{-1} in the top 0-20/30 centimetres of the soil, depending on the application rate. Soils were found to sequester 0.12, 0.56 and 1.0 t C ha^{-1} year^{-1} with annual compost amendments of 8, 14 and 20 t ha^{-1}, respectively.

Poulton et al. (2018) reports the findings of several field experiments located in England in which the effectiveness of carbon sequestration practices were studied. Experiments with annual compost amendments were conducted in Woburn on a sandy loam soil. In the Woburn Market Garden experiment annual amendments of approximately 35 t ha^{-1} year^{-1} of vegetable compost were added during 25 years. In the first 9 years since the start of the experiment there is a carbon sequestration rate of 2.1 t C ha^{-1} year^{-1} in the top 0-23 centimetres. In the subsequent nine years, sequestration rates decreased to 1.03 t C ha^{-1} year^{-1}, followed by 0.2 t C ha^{-1} year^{-1} in the last seven years of the experiment. This clearly shows how the carbon sequestration levels off as the soil reaches saturation. Another experiment at the same site in Woburn with annual amendments of vegetable compost (40 t compost ha^{-1} year^{-1}) resulted in a carbon sequestration rate in the top 0-23 centimetres of the soil of 1.41 t C ha^{-1} year^{-1} over the first ten years since starting the experiment. This significantly lower sequestration rate is likely due to the higher initial carbon stocks in the latter experiment (38.8 t C ha^{-1} vs. 31.1 t C ha^{-1} in the Woburn Market Garden experiment).

Arthur et al. (2011) describes an experiment on a loamy sandy soil in Belgium with different types of compost. Over a time period of 10 years, annual amendments of 30 m^3 ha^{-1} vegetable compost and garden waste compost both were measured to lead to a carbon sequestration rate of 0.6 t C ha^{-1} year^{-1}.

Two similar field trials on sandy soils were conducted by Overesch et al. (2004) in the western part of Germany; Wildehausen and Listrup. In both trails, three treatments were compared: two treatments with a different compost application rate and a control treatment with no compost amendments. In Wildehausen, the carbon sequestration rate was determined to be 1.1 t C ha^{-1} year^{-1} with an application rate of 32.1 m^3 ha^{-1} year^{-1} compost. In Listrup, the carbon sequestration rate was determined to be 0.19 and 2.1 t C ha^{-1} year^{-1} when compost amendments were respectively 30 and 60 m^3 ha^{-1} year^{-1}. Per t C applied on the field with compost, this resulted on average in 0.25 t C sequestered in the soil. In both experiments, it was found that for the higher application rates, a relatively larger share of the amended carbon was sequestered in the soil.

Discussion

Within the previously discussed experiments that applied compost dosages ranging between 30 and 40 t ha^{-1} $year^{-1}$, the reported carbon sequestration rates vary between 0.19 to 2.1 t C ha^{-1} $year^{-1}$ (Table 1). Many studies do not report the type- and the carbon content of the applied compost. There are various types of compost that differ in composition and will have varying effects on the soil carbon content when applied in the same amount. It is likely that the variation in carbon sequestration rates between the different long-term experiments is partly due to the different dosages and carbon contents of the composts used. In addition, the initial soil carbon content and previous management history of the field also influence the achieved carbon sequestration rate (Poulton et al., 2018). When a field has a long history of compost amendments, it is likely that the effect of adding more compost on the soil carbon content has levelled off and is a lot lower than when the same amount of compost is added on a field that did not receive any compost in the past decades.

3.8 Crop residues

Description

Crop residues that remain on the field after the crop is harvested form a significant input of fresh organic material that may positively affect the SOC content, as well as other soil ecosystem services such as soil fertility and crop yield (Lehtinen et al., 2014, Lessmann et al., 2022, Ranaivoson et al., 2017) (Liu *et al.*, 2014). Within Slim Landgebruik, research focusses specifically on the effect of leaving behind and incorporating residues of cereal crops. In this study we provide information on the effect of leaving crop residues on the field on carbon sequestration rates, with a focus on cereal residues.

Literature

The literature review by Lehtinen et al. (2014) reports an average increase in SOC content of 7% ± 1.39% comparing 84 study cases in Europe. In this study the experimental duration and soil texture explained most of the variation in the effect of leaving crop residues on SOC content. Data from clay soils and from LTE's of more than 20 years showed an higher increase on SOC content. However, despite the known effect of climate on carbon cycling, the impact of crop residues on SOC content was not influenced by the environmental zone.

Accordingly, the global meta-analysis by Xu et al. (2019) showed that leaving corn stove residues can increase SOC stocks in 0.41 ± 0.02 t C ha^{-1} $year^{-1}$. Most of the data from this study was located in the US in a temperate region that it is comparable in climate with temperate Europe. Also, similar results are found in the global meta-analysis by Ranaivoson et al. (2017) that includes data from 110 study cases worldwide and carbon sequestration rates from temperate and tropical zones. On average, temperate regions showed an increase of 0.38 t C ha^{-1} $year^{-1}$ with 4 to 5 t ha^{-1} of residues (Ranaivoson *et al.*, 2017). This rate was calculated in the top 20 centimetres of the soil, and the experimental length varied between 3 and 28 years. Similar to Lehtinen et al. (2014), soil texture was the main factor explaining the variability of results for the same amount of added residue, with generally higher SOC stocks in clay soils than in sandy soils.

At a local scale, Poulton et al. (2018) reported the effect of incorporating wheat straw on SOC stocks in both sandy and clay soils. They use data from two experiments in the United Kingdom: The Rothamsted experiment on clay soil and the Woburn LTE on sandy soil. During the first 12 years of the Rothamsted LTE, straw was incorporated at an average annual rate of 3 t ha^{-1} and the rate of increase of carbon in the soil was 0.26 ± 0.108 t C ha^{-1} $year^{-1}$). In the Woburn experiment, when straw was incorporated at 3.77 t ha^{-1} $year^{-1}$ every 2 year, there was an increase of carbon of 0.17 t C ha^{-1} $year^{-1}$. Similarly, in Denmark Thomsen and Christensen (2004) showed that a sandy soil retained 14% of the carbon content in straw residue that had been added during three years from spring barley.

Discussion

In general we observe that the incorporation of crop residues increases SOC sequestration (Table 1). Under the same amount of added residues, soil texture is the main factor controlling variation on sequestration rates, with higher sequestration rates in clay soils compared to sandy soils.

Besides an increase in SOC content, crop residues also provide other benefits to the system such as decrease soil water evaporation, increase soil water infiltration and increase nutrient availabilities (Ranaivoson *et al.*, 2017). However, adding crop residues may in some situations result in a net production of CO_2. Straw residues have a high C:N ratio, which results in relatively low N_2O emissions. The amount of added residue correlates with N_2O emissions, as well as the water filled pore space. Therefore in order to guarantee that under addition of crop residues the field acts as a sink of carbon, rather than as a source of carbon, soil properties and quantity and quality of the residues needs to be connected with the crop residue management (Ranaivoson *et al.*, 2017).

3.9 Agroforestry

Description

Agroforestry is the cultivation of perennial woody species (usually trees) in combination with grassland or arable crops. This includes alley cropping (trees included in arable systems), silvopasture (trees in grassland) and food forests (cultivation of diverse edible plants mimicking a natural ecosystem with different layers). Lesschen et al. (2021) already performed a literature study on carbon sequestration by agroforestry. They found a total average sequestration of 4.19; 3.26 and 4.75 in respectively alley cropping, silvopasture and food forests, of which respectively 1.22; -0.59 and 1.30 in soil carbon. The literature below is additional to the literature already presented by Lesschen et al. (2021).

Literature

Mayer et al. (2022) performed a meta-analysis on SOC in alley cropping, hedgerows, and silvopastoral systems, where the sequestration rate is determined from the difference between control- and agroforestry sites. They report on average 0.21 ± 0.79 t C ha^{-1} $year^{-1}$ in the 0-20 centimetres layer, and 0.15 ± 0.26 t C ha^{-1} $year^{-1}$ in the 20-40 centimetres layer. In the topsoil layer (0-20 centimetres) they find highest carbon sequestration rates for hedgerows (0.32 ± 0.26 t C ha^{-1} $year^{-1}$), followed by alley cropping systems (0.26 ± 1.15 t C ha^{-1} $year^{-1}$); and a slight SOC loss in silvopastoral systems (-0.17 ± 0.50 t C ha^{-1} $year^{-1}$). High sequestration rates in hedgerow- and alley cropping systems can be explained by the fact that these systems mostly have cropland as control sites. In contrast, silovpastoral systems usually have grassland as control sites with a higher initial carbon content. Planting of trees in grassland may even lead to a loss of carbon caused by disturbance of the (permanent) grass sod. The high standard error in Mayer et al. (2022) indicates that the differences between regions and different systems cause a high variation in carbon sequestration. Within the data of this study, climatic factors were of minor importance compared to soil texture and management. Clay content was positively related with SOC stocks in the subsoil (20-40 cm). The included studies lack a common methodological approach for sampling: the distance from tree rows varied between 0.4 and 12 m distance, and the sampling was performed on either set intervals, by random distribution, grid sampling or sometimes no information was provided. From the presented data it is not clear whether the found sequestration rates apply to the area of the whole system, or just to the area under under the trees or hedges. This meta-analysis includes studies from Asia (3), Europe (41) and North America (17), with an average clay content of 22% and an average duration of 28 years of agroforestry.

Drexler et al. (2021) performed a meta-analysis on carbon sequestration specifically in hedgerow biomass and soil in temperate regions (Canada, France, UK, Greece, Germany, Canada and Belgium). They find a soil carbon sequestration rate of 0.9 and 0.3 t C ha^{-1} $year^{-1}$ respectively over 20 or 50 years establishment of the hedgerows. Furthermore they find an additional 4.3 and 1.7 t C ha^{-1} $year^{-1}$ in the hedgerow biomass over respectively 20 or 50 years of establishment. This clearly shows that additional carbon sequestration will level off after the initial phase of high sequestration rates during the establishment of an agroforestry system. In addition to systematic differences, variation in the length of the experiments can also partly explain differences found between carbon sequestration rates in different individual studies. Drexler et a. (2021) did not identify an effect of soil texture or climate on SOC storage due to the limited dataset. Just as Mayer et al. (2022), these authors report that a lack of standardized sampling procedures (both in depth and distance from the hedgerow) have caused heterogeneity in the outputs of the meta-analysis. Sampling depth ranged from 5-60 cm, and in some studies samples were taken within the hedgerow, whereas in others the samples were taken next to the hedgerow. It also not clearly reported whether the reported SOC rates apply to the whole area with hedgerows or just the area under the hedgerow.

Only one study from a region similar to the Netherlands was found (additional to the individual studies used by Lesschen et al. (2021)). Pardon et al. (2019) report on the introduction of walnut trees in an arable system in Belgium and finds an additional soil carbon sequestration rate of 0.033 t C ha^{-1} $year^{-1}$ over a period of 72 years. The fact that this value is rather low compared to the other studies can be explained by the low density of trees per hectare and the long establishment period. It is likely that the rate would be higher in the first years of establishment, and that a higher tree density would increase the rate per hectare as well.

Discussion

The values found by Mayer et al. (2022) for alley cropping and silvopastoral systems are in the same range as the values for soil carbon under agroforestry in Lesschen et al. (2021). This is not the case for de value found by Pardon et al. (2019), but this can easily be explained by duration of the experiment and tree density. The positive effect of hedgerows is clearly shown by Mayer et al. (2022) as well as Drexler et al. (2021). However, hedgerows do not correspond well with the definition of agroforestry in Slim Landgebruik (namely alley cropping, silvopasture and food forests).

From these studies it becomes clear that agroforestry and hedgerows can contribute positively to carbon sequestration in the soil as well as above- and belowground biomass (Table 1). Only in the case of the implementation of trees on permanent grassland (silvopasture), carbon might be lost due to the disturbance of the grass sod. It can however be expected that the carbon stock will recover after the initial phase.

Since agroforestry systems are inherently heterogeneous, the spatial design and depth of sampling of soil carbon can strongly affect the found effects, which complicates interpretation and comparison of the results between studies. Moreover, the amount and rate of soil carbon sequestration is highly dependent on the type of system (row width, tree species, etc.), the length of the establishment period and factors such as climate and soil type. Within temperate climates, annual mean temperature was not observed to affect SOC sequestration rates, whereas the rates were positively correlated with the clay content. Generally, a higher carbon sequestration rate can be expected at a higher tree density and in the first phase after establishment of the trees.

3.10 Bird fields

Description

In Slim Landgebruik bird fields are defined as perennial (3-4 years) forage crops with strips of natural vegetation. The forage crops usually consist of red clover on sandy soil and lucerne on clay soils, which covers 70% of the surface area and is mown 3 or 4 times each year. The natural strips consist of mixtures of grasses, cereals and herbs which cover around 30% of the surface area. In the literature there are no studies available which exactly match this description, but we include a comparable study that tested the effect of including lucerne on the crop rotation. The practice assumes a history of arable cropping prior to applying the perennial bird fields.

Literature

Poulton et al. (2018) report the results of two long-term experiments (37 years) with 3-year lucerne in rotation with 3-year arable crops on clay soils in England. An increase of 0.04 t C ha^{-1} $year^{-1}$ was found on a site with a history of continuous arable management. On a site that had previously been permanent grassland, there was a loss of -0.63 t C ha^{-1} $year^{-1}$ under lucerne-arable rotation.

No other studies were found that assess the effect of bird-fields (or comparable rotations) on carbon sequestration rates in regions similar to the Netherlands.

Discussion

Very little is known about the effects of this practice on carbon sequestration. What becomes clear from Poulton et al. (2018) is that perennial lucerne can increase carbon sequestration, but that the effect is dependent on its previous management. According to this study, perennial lucerne in rotation with arable crops can increase carbon sequestration when the field was previously used for arable cropping. The effect that was found was however only limited (0.04 t C ha^{-1} year $^{-1}$). The effect of the strips with natural vegetation is not known yet.

3.11 Permanent field margins

Description

Permanent field margins are strips along the boundary of a field designed to support biodiversity and reduce runoff of nutrients and pesticides to the surface water. These margins are usually sown with a grass-wild flower seed mixture (dominated by grass species) and are maintained for multiple years. The margins receive no fertilization. Most margins are mown yearly with the cuttings being removed to supress vegetation succession and maintain the less competitive herbs and flowers.

This study collects literature that compares carbon stocks under cropped field with herbaceous field margins or arable land that is left uncultivated for a long time. Field margins that contain hedgerows, shrubs or trees were not included.

Literature

D'Acunto et al. (2014) sampled five perennial herbaceous field margins and five cropped field margins in eastern Argentina to determine whether there are differences in accumulated carbon. Carbon stocks did not differ between the two margin treatments, indicating there were no differences in carbon sequestration rates.

In south-central England, different types of perennial field margins were sown on a clay loam soil (Bullock et al., 2021). After three years, SOC was measured in the field margins as well as in adjacent cropped fields. The SOC content was 0.7% higher under the field margins, but this was not a significant difference. A longer duration time might have led to significant changes in SOC as three years is quite short to detect changes in SOC.

In an experiment on Rothamsted Farm, UK, plots were left uncultivated since 1881 to study the accumulation of carbon and nitrogen in the soil (Poulton et al., 2003). Carbon stocks were measured twice, after 83 years and 118 years. In plots on which saplings of shrubs and trees were removed to maintain the herbaceous grassland vegetation, carbon stocks in the top 0-23 centimetres increased with 43 t C ha^{-1} in the first 83 years after cultivation. On average, the carbon sequestration rate was therefore 0.52 t C ha^{-1} $year^{-1}$. Carbon stocks increased with 13 t C ha^{-1} over the second period, meaning a lower carbon sequestration rate of 0.37 t C ha^{-1} $year^{-1}$. This could mean that the increase in soil carbon stocks is levelling off.

Throughout north and eastern Germany, covering a variety of soil types and climatic conditions, 23 flower margins were sampled for aboveground and belowground biomass (Harbo et al., 2022). Among these flower margins were both annual and perennial margins, ranging in age between 2 and 10 years. The annual margins were mulched, tilled and reseeded every year on the same location. The perennial margins were seeded once and left untouched afterwards. Margins received no fertilizer and were not harvested. Due to the relatively short age of the flower margin treatments, no SOC was measured considering the effects of the treatments on the SOC was likely too small to be detectable. Instead, the aboveground and belowground biomass data was used to model the potential carbon sequestration rate using the RothC model. The model determined that flower margins sequester on average 0.49 ± 0.36 t C ha^{-1} $year^{-1}$, which was positively correlated to both aboveground and belowground biomass production. A negative correlation was found between plant species richness in the margin and the carbon sequestration rate. The grass species in these flower margins are much more productive than the herbs. When margins become more dominated by the grass species, plant species richness decreases but biomass production increases hence the carbon sequestration rate is expected to become higher. Though this carbon sequestration rate is based on modelling and not directly measured in the field, it can give an indication of sequestration in field margins managed similarly as in the Netherlands.

Discussion

The number of long-term experiments that study the effect of permanent field margins on carbon sequestration is very limited. In the studies of Poulton et al. (2003) and Bullock et al. (2021), carbon stocks did increase within the field margins, however, the duration of the latter study was rather short and the effect not significant. In a way, the effect of permanent field margins on carbon sequestration can be expected to be similar to that of permanent agricultural grassland (paragraph 3.1). Both are sown with mainly grass type species and maintained for many years without disturbing the soil, enabling carbon from roots and plant residues to accumulate in the soil over a relatively long time. However, productivity in field margins is lower, considering that field margins are not fertilized, mown much less frequent than the average agricultural grassland and consist of more flowers and less productive grass species. Hence, carbon sequestration is expected to be lower under field margins than under permanent grassland. Accordingly, this report shows a carbon sequestration rate of 0-0.52 t C ha^{-1} $year^{-1}$ on field margins (Poulton et al. 2003), while the carbon sequestration rate from converting cropland to grassland (paragraph 3.1) range from 0.5 to 1.1 t C ha^{-1} $year^{-1}$ (Table 1).

3.12 Non-inversion tillage

Description

The loss of carbon in agricultural soils has often been assigned to deep tillage or ploughing of the soils. In the last decade, conservation and regenerative agriculture recommends using less intensive tillage or non-inversion tillage to increase SOC content and improve soil health. However the effect of non-inversion tillage on SOC stocks is many times under discussion and field studies in temperate regions show opposing results. Lesschen et al. (2021) already performed a literature study on carbon sequestration by non-inversion tillage, to which the studies provided below are additional. In this study we summarize the conclusions from the most recent published literature reviews and give indications on the effect of non-inversion tillage on soil carbon sequestration rate in Europe.

Literature

It is often discussed that non-inversion tillage redistributes the organic matter in the soil profile rather than increasing overall carbon sequestration. The review carried out by Lesschen et al., (2021) showed that while there was a significant increase of carbon concentration in the upper layer (0-30 cm), carbon content in deeper soil layers decreased. Over the whole soil profile (0-150 cm) they reported no evidence of increased carbon sequestration. Similar results were found in the global meta-analyses by Baker et al. (2007) and Haddaway et al. (2017). Baker et al. (2007) showed a redistribution of the carbon in the soil profile with higher soil carbon concentration in the upper layers after application of reduced tillage and higher soil carbon concentration in the deeper layers after application of conventional ploughing. Similarly, Haddaway et al. (2017) did not find an increase on SOC under non tillage when the full soil profile was considered. Nevertheless, it is important to consider that the amount of data from the first 0 to 30 cm is much higher than from deeper layers. For instance, in Haddaway et al. (2017), only 19% of the data were from a depth below the first 30 centimetres.

The review of meta-analysis by Lessmann et al. (2021) looked at the effects of non-inversion tillage on SOC sequestration rates in the upper layer (0-30 centimetres) finding a positive effect that varied from 0.07 to 0.31 t C ha^{-1} $year^{-1}$ in the temperate climatic zone (Angers & Eriksen-Hamel, 2008, Haddaway *et al.*, 2017, Meurer *et al.*, 2018). The meta-analyses by Haddaway *et al.* (2017) and Meurer et al., (2018) in the boreo-temperate area estimated an increase of 0.15 ± 0.04 t C ha^{-1} yr^{-1} and 0.24 ± 0.11 t C ha^{-1} yr^{-1} respectively in the top 0-30 centimetres. In both analyses, the SOC storage capacity decreased significantly when considering the 0-60 centimetres profile. Similarly, Angers and Eriksen-Hamel (2008) showed a carbon sequestration rate of 0.31 t C ha^{-1} yr^{-1} in the 0-30 centimetres layer in non-inversion tillage compared to full inversion tillage, that contrasted with greater SOC content just below the average depth of ploughing (26-35 centimetres) in the full inversion tillage.

Discussion

The amount of carbon in the soil is distributed differently depending on the tillage practice: while soils under non-inversion tillage have a higher SOC stock in top layers, conventional tillage soils show higher SOC stock in layers below the tilled layer. In agreement with Lesschen et al., (2021); Baker et al. (2007) and Haddaway et al. (2017) conclude that there is no evidence of an increase in C sequestration over the whole soil profile. Nevertheless, less soil disturbance can increase carbon coming from the microbial carbon biomass (Cotrufo *et al.*, 2013), which is shown to be essential to enhance stable SOC stocks.
When moving from conventional tillage to non-inversion tillage it is also important to consider that applying non-inversion tillage may increase N_2O emissions under certain conditions mainly related with soil water content and soil texture (Huang *et al.*, 2018, Mei *et al.*, 2018, Shakoor *et al.*, 2021, van Kessel *et al.*, 2013).

3.13 Herb-rich grassland

Description

Herb-rich grasslands are grassland enriched with various species of herbs and leguminous plants. The greater diversity in species can result in a more stable biomass production, considering there are more chances that a species will thrive under varying conditions. Due to the greater diversity of species and deeper rooting of herbs, the carbon supply to the soil can be higher and the microclimate for the soil life better, which could lead to higher carbon sequestration rates. In this literature search, all kinds of studies on biodiverse grasslands are included, ranging from studies on natural grassland to those on productive perennial ryegrass grasslands comparable to the Dutch conventional grassland system.

Literature

In the Wageningen Biodiversity experiment, the effect of increasing species in a mixture on soil carbon content was studied by Cong et al. (2014) on a sandy soil. The species pool consisted of four grass species (*Agrostis capillaris L.*, *Anthoxanthum odoratum L.*, *Festuca rubra L.*, and *Holcus lanatus L.*) and four forbs (*Centaurea jacea L.*, *Leucanthemum vulgare Lamk*., *Plantago lanceolata L.*, and *Rumex acetosa L.*), which were sown in different combinations ranging from monocultures to a mixture of all eight species. Results show an increase of the SOC of 0.08 t C ha^{-1} year^{-1} in the top 15 centimetres of the soil with every doubling of the number of species present in the mixture.

A similar experiment was set up in Jena (Germany), on a soil gradient from sandy loam to silty clay with 60 species that are typical to central European semi-natural low productive grasslands. In the top 30 centimetres of the soil, SOC increased with 0.14 t C ha^{-1} year^{-1} for every doubling of the number of species in the mixture (Steinbeiss et al., 2008; Lange et al., 2015).

In an experiment in Minnesota, USA, the carbon stocks in plots on ex-agricultural land with different mixtures ranging from one to sixteen species were studied (Yang et al., 2019; Fornara & Tilman, 2008). Over a time period of 22 years, the average additional carbon sequestration rate when the number of species in a mixture was doubled was measured to be 0.1 t C ha^{-1} year^{-1} in the top 0-60 centimetres. This rate was however not fixed throughout the experimental duration because of higher rates as the experiment progressed.

The circumstances in these three experiments focus on natural grasslands. Agricultural grasslands are much more productive and exposed to disturbances such as grazing and fertilization. On a clay loam soil in south-central England (perennial ryegrass) grasslands and grasslands enriched with herbs that were grazed by cattle or sheep were compared in a three-year experiment (Bullock et al., 2021). At the end of the experiment, the measured carbon stocks in the top 0-15 centimetres appeared to be higher in de forb rich grasslands, but this difference was not significant. The duration time of the experiment might have been too short to detect differences.

Another experiment on grazed grasslands was conducted by Rutledge et al. (2017) in New Zealand. Fields with perennial ryegrass were tilled and resown with either a perennial ryegrass and white clover mixture or a more diverse mixture consisting mainly of perennial ryegrass but enhanced with other grasses, legumes and herbs. Net ecosystem carbon balances were calculated for three years based on measured carbon fluxes and showed that both treatments had a net loss of carbon to the environment, caused by the high carbon losses to the atmosphere due to the recent grassland renewal. Although it was still a net carbon source, the herb-rich grassland had a higher carbon balance (0.85 t C ha^{-1} $year^{-1}$) than the ryegrass pasture.

Skinner et al. (2016) compared a two-species grass white clover mixture with a five-species mixture in an experiment of nine years which was set up on grazed grasslands in Pennsylvania. The average carbon sequestration rate over the entire 0-100 centimetres soil layer appeared to be more than 1 t C ha^{-1} $year^{-1}$ higher in the five-species mixture as compared to the two-species mixture. However, this difference was not found to be significant.

In an experiment in the north of the UK, the effect of grassland enrichment with seed mixtures on carbon sequestration was studied in fertilized grassland consisting of perennial ryegrass-and crested dog's-tail (*Cynosurus cristatus*) (De Deyn et al., 2011). The experiment was conducted in a randomized block design with treatments with or without seed addition and with or without mineral fertilization. Carbon stocks were measured to be higher in the plots that were enhanced with seed mixtures, but there was no significant correlation found between plant species diversity and carbon stocks. The increase in carbon stocks in the plots that were enhanced with seed mixtures could mostly be attributed to the presence of red clover (*Trifolium pratense*). In the plots with red clover, carbon losses from the soil through microbial and root respiration was reduced hence more carbon was maintained in the soil. Of all treatments, the highest carbon sequestration rates were found in the enhanced grasslands with red clover that did not receive any mineral fertilizer. In comparison to the control grasslands without mineral fertilizer, the enhanced grassland with red clover sequestered an additional 1.8 t C ha^{-1} $year^{-1}$. When mineral fertilizer was applied, the effects of seed addition were not significant.

Discussion

Most reviewed studies showed that more biodiverse grasslands sequestered or maintained more carbon than grasslands with fewer species. The species and grassland systems included in most studies are however less productive compared to the agricultural grasslands and herb-rich agricultural grasslands in the Netherlands. Fertilization rates were low (Bullock et al., 2021; Yang et al., 2019; Rutledge et al., 2017) or no fertilizer was applied at all (Cong et al., 2014; Steinbeiss et al., 2008; Skinner et al., 2016). Hence, productivity was probably lower than in Dutch agricultural grasslands. Only the studies described by Bullock et al. (2021), Rutledge et al. (2017) and De Deyn et al. (2011) included perennial ryegrass (*Lolium perenne*), the most commonly grown species in Dutch agricultural grasslands. This first study did not find a significant increase in the carbon sequestration rate, though this could also be explained by the relatively short experimental duration of three years. The second study found large differences between the perennial ryegrass and more enhanced mixtures, but measurements were only taken in the first few years after sward renewal when the soil is still rather disrupted. The latter study by De Deyn et al. (2011) did find a large effect caused mainly by the addition of red clover, but this effect was only significant when fertilization was brought to zero. This effect was probably due to red clover affecting both soil nutrient cycling (mainly through N-fixation) and soil physical properties which together enhance the retention of newly fixed and residing C.

None of these studies align completely with the Dutch context of the Slim Landgebruik definition of the carbon practice herb-rich grassland, but do give valuable insights. These studies show that the practice of adding more species to the grassland may but does not necessarily lead to an increase of carbon sequestration (0 – 1.8 t C ha^{-1} $year^{-1}$)(Table 1). It is important to consider not only plant species richness but more importantly the key species that are added to the grassland and how they affect the quantity and quality of roots and root exudates. Increasing the species richness will not lead to an increase of the carbon sequestration rate if the added species reduce the sward productivity greatly.

4 Discussion and conclusions

Carbon sequestration rates

We used scientific literature to provide data on the effect of carbon measures on carbon sequestration. For the carbon measures that are still lacking or limited within the LTE's in Slim Landgebruik program we found positive effects in the local approach: crop residues (0.17-0.26 t C ha^{-1} $year^{-1}$), herb-rich grassland (0-1.8 t C ha^{-1} $year^{-1}$), conversion to permanent grassland (0.5-1.1 t C ha^{-1} $year^{-1}$) and bird fields (0.04 t C ha^{-1} $year^{-1}$). These numbers are in line with the values found in the global approach. The other measures are better represented within the Dutch LTE's, and with this study we increase the certainty on the effect of these measures on C sequestration by substantiating them with international literature. For most practices, the carbon sequestration rates from this study comply with the findings of the Slim Landgebruik program (Appendix 1). Considering the local approach, carbon practices that were found to sequester the highest amount carbon were compost (0.62 - 2.1 t C ha^{-1} $year^{-1}$), conversion from cropping to grassland (0.5 - 1.1 t C ha^{-1} $year^{-1}$), extending grassland age (0 - 1.8 t C ha^{-1} $year^{-1}$), and solid manure (0.15 – 1.00 t C ha^{-1} $year^{-1}$). This complied well with the global meta-analyses of these practices, which also showed a high potential (except for herb-rich grassland from which so far, no meta-analysis are available).

Within Slim Landgebruik, the grassland practices cropping to grassland, extending grassland age and maize-grass rotation are regarded among the most effective practices, as these are the practices that apply organic amendments such as compost or solid manure (Appendix 1). For the practice extending grassland age, the results found in the Slim Landgebruik LTE's were a bit higher on sandy soils compared to the literature review. Grassland productivity is relatively high in the Netherlands, which could explain the higher carbon sequestration rate. In the Slim Landgebruik LTE's, the practice maize-grass rotation was found to be the most effective practice, whereas from the international literature it appears to have less potential. This practice how it was studied in other sides in Europe did however not fully comply with how the practice is applied in the Netherlands. In most studies, an arable rotation was implemented with multiple arable crops instead of solely maize. This could be the cause that led to a lower effect on the carbon stocks when periods of grass (clover) were added to the rotation.

Practices in which organic amendments are applied on the field (compost and solid manure) were found to have lower carbon sequestration rate in the Slim Landgebruik LTE's than in the literature review. Agricultural soils in the Netherlands have generally a relatively high organic matter content and the effects of applying organic amendments could therefore be lower than in the local scale study sites that were included in the literature review. In the Slim Landgebruik LTE on cover crops, negative sequestration rates were found, contrary to what was expected. This literature review concluded cover crops to have positive sequestration rates based on multiple meta-analyses and individual studies. It is therefore likely that cover crops do lead to a moderate increase in carbon stored in the soil, but these effects are very dependent on the type of cover crop, growing period and years the practice is applied. The Slim Landgebruik LTE on cover crops was likely to short of duration to detect a reliable effect.

Agroforestry and herb-rich grassland were measured in LTE's in Slim Landgebruik although the timeframe experiments was relatively too short to draw definite conclusions. The effects of bird fields were not yet studied within a LTE in Slim Landgebruik. Among these practices, herb-rich grassland appears to be the most promising, whereas the bird fields were found to lead to a very low (0.04 t C ha^{-1} $year^{-1}$) carbon sequestration rate.

In terms of overall potential based on available hectares on which the practice can be applied, the four practices that were found to have the highest potential per hectare (compost, conversion from cropping to grassland, extending grassland age and solid manure) appear to be the most effective on a nationwide scale as well, considering they are found to have high carbon sequestration rates and are applicable in a large area (Slier et al., 2022).

Available literature

There was a large variety in the number of literature studies available on each carbon sequestration practice, which affects the extent to which the carbon sequestration rate of each practice can be quantified. Some practices studied within Slim Landgebruik are practices that are also widely implemented in other parts of the world and their effectiveness regarding carbon sequestration is often researched thoroughly. This is the case for the use of solid manure, compost and non-inversion tillage. The effects of converting cropland to grassland has also been frequently studied. Scientific literature on practices that are unique to the Dutch or western European circumstances are scarcer. The carbon sequestration rates for perennial field margins, bird fields and crop rotation with maize and grass, given in Table 1, are based on only one or very few studies. Additionally, the effects of changing the crop rotation are not very well known and do not fully align to Dutch conditions with rotations that consist mainly of root crops. Therefore, the rates for these carbon practices have a larger uncertainty than the rates for practices that are supported by many studies.

Difficulty to detect changes on SOC content

The changes in SOC are relatively small compared to the carbon stock of the soil and occur slowly. This makes changes in the soil carbon stock difficult to detect. According to Smith et al. (2004), changes in SOC content may not be detectable until at least 7 to 10 years, depending on the relative change in carbon inputs and soil characteristics. The effect of a practice can only be detected within a few years if the carbon sequestration rate is very high. In various studies included in this literature review, no significant effects were measured within a few years of monitoring where an effect of the practice was expected. This could be due to a combination of a moderate carbon sequestration rate and a relatively short experiment duration, leaving the positive effects on carbon sequestration unnoticed.

Factors causing variability

From the literature it became clear that the effectivity of all the practices was subject to several sources of variability, namely the soil type, initial carbon content of the soil, previous management of the soil and the local climate.

- <u>(1): Soil type:</u> The amount of carbon which can be sequestered when applying a certain practice is largely determined by the soil type. SOC is greatly associated with the finer clay particles, which give the clay soil regions of the Netherlands a higher potential to sequester carbon than the sandy regions (Jarecki & Lal, 2003). In this literature review, for several practices differences in the carbon sequestration rate were found between sandy and clay soils, with sequestration rates being higher on the clay soils.

- (2): Initial carbon content: Soils with a low initial carbon content can sequester more carbon with the same effort than soils that are already high in carbon content (Minasny et al., 2017). The initial carbon content is partly determined by previous management (see next section) and climatic conditions. Soils in the Netherlands and western Europe are relatively high in SOC content, hence sequestering more carbon requires a fair amount of effort.
- (3): Previous field management: The history of the field regarding the crop rotation, manure amendments and tillage methods can strongly impact sequestration rates. For instance, if a field has received compost for the last few decades, the effect of adding more compost will have a less significant effect than when the same amount of compost is applied on a field that received no compost in the recent past. We also saw the effect of previous management clearly in field experiments which have been managed as permanent grassland, causing a loss of carbon in the initial years of the implementation of a carbon practice, thereby implying a negative effect of a carbon practice (Poulton et al., 2018). In contrast, in the same experiments with a history of arable management, the practices showed an increase in carbon sequestration.
- (4): Local climate: In general, the SOC content in Europe tends to decrease from north to south due to the soil temperature. The decomposition of organic matter in the soil is lower under low temperatures, resulting in less SOC being lost to the atmosphere due to soil respiration (Freibauer et al., 2004; Minasny et al., 2017). Contrarily, crop productivity can be higher in warmer climates (provided that rainfall is not limiting), resulting in higher carbon inputs into the soil. For practices that are highly dependent on crop growth such as cover crops and crop residues, the increased biomass production in warmer weather can outweigh the increased carbon losses through decomposition in the soil. Practices with external organic inputs (solid manure, compost) may however be more effective in cooler climates.

  In the current changing climate, soils in the Netherlands will become warmer, leading to increased soil respiration and carbon fluxes to the atmosphere. In addition, increased weather extremes may lead to more crop failures and lower inputs of fresh plant material to the soil. A warming climate may however also lead to a longer growing season and higher crop production, leading to increased organic inputs. The overall effect of climate change on the 13 practices in Slim Landgebruik is however not yet researched within the program.

The above-mentioned factors complicate the establishment of a single value for the effect of a measure, which stresses the importance of modelling studies which consider these sources of variability in the calculation of carbon sequestration at a national scale.

Recommendations

Based on the results from the literature study, we suggest the follow-up research on the following topics:

- Regarding the LTE's in Slim Landgebruik we recommend conducting more research on extending grassland age, herb-rich grassland, improved crop rotation and cover crops due to their high potential in terms of sequestration and implementation (1), deficit of data in Dutch conditions (2) and/or inconsistencies in the LTE data (3). Perennial field margins may be of interest due to the legal situation in the Netherlands implying a strong increase in the amount of field margins in the future. Agroforestry has a high potential of sequestration per hectare, but the number of hectares in the Netherlands are expected to remain limited and further research is therefore not of the highest priority. For bird fields little is known in literature and a clear definition is still lacking, however the acreage is likely very low and therefore the measure is of low priority in future research.

- A comparison of the results from this literature study with the results of the Dutch LTE's (Schepens et al., 2022) and the modelled Roth C results (Lesschen et al., 2021), to see if these comply and how differences might be explained. This will lead to increased certainty of the effect of the carbon measures, both on field- and national scale.
- As this literature review has shown that for some measures the rate of carbon sequestration is expected to decrease on the long term, a study on the expected duration of the effect of the carbon measures is required to make better long-term predictions.
- A study on the (regional) effects of soil type, initial carbon content, previous field management and local climate (change) on the potential for C sequestration in the different areas of the Netherlands.

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Appendix 1 – Comparison table

The carbon sequestration rates as found in global meta-analyses and local long-term experiments compared to the modelled sequestration rates (Lesschen et al., 2021) and the sequestration rates found in the SL LTE's (Schepens et al., 2022).

	Mean global	**Local European**	**Sand**		**Clay**	
Carbon practice	t C ha^{-1} yr^{-1}	t C ha^{-1} yr^{-1}	RothC t C ha^{-1} yr^{-1}	LTE t C ha^{-1} yr^{-1}	RothC t C ha^{-1} yr^{-1}	LTE t C ha^{-1} yr^{-1}
Cropping to grassland	1.01	0.5 - 1.1	0.71		0.50	
Extending grassland age	1.1 ± 0.2	0 - 1.6		1.75		1.34
Maize-grass rotation		0.11-0.7	0.58	1.77	0.46	
Change in arable crop rotation		0.06 - 0.45	0.52	0.27	0.54	0.55
Cover crops	0.5 ± 0.03 0.32 ± 0.08	0.18 - 0.4	0.63	-0.27	0.51	
Solid manure	0.42 ± 0.11	0.15 - 0.24 0.07 - 0.22 (t C applied^{-1})	0.015		0.015	0.11
Compost	0.71 ± 0.4	0.62 - 2.1	0.022	1.56	0.025	0.38
Crop residues	0.41 ± 0.04 0.38	0.17 -0.26	0.21		0.45	
Agroforestry	0.21 ± 0.79 0.3-0.9	0.033				
Bird fields		0.04				
Permanent field margins		0 – 0.52	0.14	-4.5	0.21	2.3
Non-inversion tillage	0.07 ± 0.02 0.22 ± 0.10 0.31					
Herb-rich grassland		0 - 1.8		1.42		-1.45

Appendix 2 – Literature with details

Region	Reference	Meta-analysis	Carbon sequestr. (t C ha^{-1} yr^{-1})	Details	LTE duration (years)	Depth (m)	Soil type
Cropping to grassland							
Global	Conant et al., 2001	Yes	1.01			0-0.30	
Global	Minasny et al., 2017	Yes	0.55				
Australia	Badgery et al., 2014	No	0.78			0-0.30	Sandy loam
Australia	Lam et al., 2012	Yes	0.13 ± 0.05				
Australia	Sanderman et al., 2010	No	0.30-0.60			0-0.15	Sandy loam
England	Clement et al., 1964	No	1.1		6	0-0.15	
England	Whitehead et al., 1975	No	0.8		17	0-0.30	Loamy sand
France	Arrouays et al., 2002	No	0.49 ± 0.26		20		
Extending grassland age							
Global	Klumpp & Fornara, 2018	Yes	1.1 ± 0.2				
Europe	Klumpp & Fornara, 2018	Yes	0.7 ± 0.16				
Ireland	Carolan & Fornara, 2016	No	0			0-0.20	Clay-loam
Netherlands	Hassink, 1994	No	1.8			0-0.10	Sand
Netherlands	Hassink, 1994	No	1,4			0-0.10	Loam
Netherlands	Iepema et al., 2021	No	3.0	Young		0-0.10	Clay
Netherlands	Iepema et al., 2021	No	1.6	Old		0-0.10	Clay
Maize-grass rotation							
England	Poulton et al., 2018	No	0.07	After long-term arable	37	0-0.25	Silty clay
England	Poulton et al., 2018	No	-0.61	After long-term grass	39	0-0.25	Silty clay
England	Johnston et al., 2017	No	0.33	With N fert.	30	0-0.25	Sand
England	Johnston et al., 2017	No	0.11	With clover	30	0-0.25	Sand
Germany	Rios et al., 2022	No	0.10	1/3 ley	8	0-0.30	Sand
Germany	Rios et al., 2022	No	0.21	2/3 ley	8	0-0.30	Sand
Norway	Singh & Lal, 2005	No	0.21	1/3 ley	8	0-0.30	Sand
Norway	Singh & Lal, 2005	No	0.36	2/3 ley	8	0-0.30	Sand
Change in arable crop rotation							
Global	West & Post, 2002	Yes	0.52 ± 0.05	Avg. rotation with wheat	20	0-0.20	
Global	West & Post, 2002	Yes	0.15 ± 0.01	Avg. rotation	25	0.0-22	
Germany	Götze et al., 2016	No	0.06	SB, SB-WW	40	0-0.30	Silty loam
Germany	Grünwald et al., 2021	No	0.31	SB-WW-WW, SB-WW-SM	13	0-0.20	Silty loam
Italy	Triberti et al., 2016	No	0.45	WW, SB-WW	17	0-0.40	Silty loam

Region	Reference		Carbon sequestr.	Details	LTE duration	Depth	Soil type

		Meta-analysis	(t C ha^{-1} yr^{-1})		(years)	(m)	
Cover crops							
Global	Jian et al., 2020	Yes	0.5 ± 0.03	Average	5	0-0.30	
Global	Jian et al., 2020	Yes	0.44 ± 0.05	Sand	5	0-0.30	
Global	Jian et al., 2020	Yes	0.81 ± 0.16	Clay	5	0-0.30	
Global	Poeplau & Don, 2015	Yes	0.32 ± 0.08		12	0-0.22	
Denmark	Schjönning et al., 2012	No	0.4		12	0-0.25	Sandy loam
Denmark	Thomsen & Christensen, 2004	No	0.2		10	0-0.20	Sandy loam
France	Constantin et al., 2010	No	0.25		16	0-0.90	
Germany	Kahle & Schulz, 1994	No	0.15		12	0-0.20	Loamy sand
Compost							
Global	Tiefenbacher et al., 2021	Yes	0.71 ± 0.40		20	0-0.25	
Belgium	Arthur et al., 2011	No	0.62	30 m^3 $year^{-1}$	10	0-0.15	Loamy sand
England	Poulton et al., 2018	No	2.1	35 t $year^{-1}$, year 0-9	9	0-0.23	Sandy loam
England	Poulton et al., 2018	No	1.03	35 t $year^{-1}$, year 9-18	9	0-0.23	Sandy loam
England	Poulton et al., 2018	No	0.2	35 t $year^{-1}$, year 18-25	7	0-0.23	Sandy loam
England	Poulton et al., 2018	No	1.41	40 t $year^{-1}$	10	0-0.23	Sandy loam
Germany	Overesch et al., 2004	No	1.1	32.5 t $year^{-1}$	7	0-0.15	Sand
Germany	Overesch et al., 2004	No	0.19	30 t $year^{-1}$	10	0-0.15	Sand
Germany	Overesch et al., 2004	No	2.1	60 t $year^{-1}$	10	0-0.15	Sand
Solid manure							
Global	Han et al., 2016	Yes	0.52 ± 0.05	Manure + mineral fert. Vs. no fert.	26	0-0.20	
Global	Maillard & Angers, 2014	Yes	0.42 ± 0.11	Manure vs. mineral fert.	28	0-0.26	
Global	Maillard & Angers, 2014		0.53 ± 0.14	Manure vs. no fert.	26	0-0.26	
Belgium	Buysse et al., 2013	No		12,5 t $year^{-1}$	50	0-0.25	Silt
England	Powlson et al., 1998	No	0.24	35 t FYM $year^{-1}$	27	0-0.23	Silty clay loam
England	Poulton et al., 2018	No	0.85	35 t FYM $year^{-1}$	25 (0-25)	0-0.23	Sandy loam
England	Poulton et al., 2018	No	1.59	35 t FYM $year^{-1}$	9 (0-9)	0-0.23	Sandy loam
England	Poulton et al., 2018	No	0.36	45 t FYM $year^{-1}$	9 (9-18)	0-0.23	Sandy loam
England	Poulton et al., 2018	No	0.51	25 t FYM $year^{-1}$	7 (18-25)	0-0.23	Sandy loam
England	Poulton et al., 2018	No	1.00	35 t FYM $year^{-1}$	20 (0-20)	0-0.23	Clay loam
England	Poulton et al., 2018	No	0.10	35 t FYM $year^{-1}$	20 (101-120)	0-0.23	Clay loam
England	Poulton et al., 2018	No	0.69	35 t FYM $year^{-1}$	20 (0-20)	0-0.23	Silty clay loam
England	Poulton et al., 2018	No	0.06	35 t FYM $year^{-1}$	20 (141-160)	0-0.23	Silty clay loam
England	Poulton et al., 2018	No	-0.03 ± 0.12	10 t FYM $year^{-1}$	10	0-0.23	Sandy loam
England	Poulton et al., 2018	No	0.46 ± 0.10	25 t FYM $year^{-1}$	10	0-0.23	Sandy loam
England	Poulton et al., 2018	No	1.23 ± 0.23	50 t FYM $year^{-1}$	6	0-0.23	Sandy loam
England	Poulton et al., 2018	No					
Germany	Körschens et al., 1998	No	0.21	15 t FYM $year^{-1}$	18	0-0.30	Silty loam

Poland	Mercik et al., 1993	No	0.20	20 t FYM year^{-1}	27		Sandy loam

Region	**Reference**	**Meta-analy-sis**	**Carbon sequestr.** (tont C ha^{-1} yr^{-1})	**Details**	**LTE duration** (years)	**Depth** (m)	**Soil type**
Crop residues							
Global	Xu et al., 2019	Yes	0.41 ± 0.04		10	0-0.30	
Global	Lehtinen et al., 2014	Yes	7±1.39% SOC		10	0-0.30	
Global	Ranaivoson et al., 2017	Yes	0.38		3-28	0-0.20	
England	Poulton et al., 2018	No	0.26 ± 0.11	3 t straw year^{-1}	12	0-0.23	Clay loam
England	Poulton et al., 2018	No	0.17	3,77 t straw every 2nd year	18	0-0.20	Sandy loam
Denmark	Thomsen & Christensen, 2004	No	0.25 (14% of input C)	4 t straw year^{-1}	18	0-0.20	Sandy loam
Agroforestry							
Global	Mayer et al., 2022	Yes	0.21 ± 0.79	Avg. system	28	0-0.20	
Global	Mayer et al., 2022	Yes	0.15 ± 0.26	Avg. system	28	0.2-0.4	
Global	Mayer et al., 2022	Yes	0.32 ± 0.26	Hedgerow	28	0-0.20	
Global	Mayer et al., 2022	Yes	0.26 ± 1.15	Alley cropping	28	0-0.20	
Global	Mayer et al., 2022	Yes	-0.17 ± 0.50	Silvopastoral	28	0-0.20	
Global	Dexter et al., 2021	Yes	0.9	20-year old			
Global	Dexter et al., 2021	Yes	0.3	50-year old			
Belgium	Pardon et al., 2019	No	0.033	Walnut	72		
Bird fields							
England	Poulton et al., 2018	No	0.04	After arable	50+	0-0.23	Clay loam
England	Poulton et al., 2018	No	-0.63	After grassland	50+	0-0.23	Clay loam
Permanent field margins							
Argentina	D'Acunto et al., 2015	No	0			0-0.15	
England	Bullock et al., 2021	No	0,7% SOC*		3	0-0.15	Clay loam
England	Poulton et al., 2003	No	0.52	Uncultivated vs. cultivated	83 (0-83)	0-0.23	Silty clay loam
England	Poulton et al., 2003	No	0.37	Uncultivated vs. cultivated	35 (83-118)	0-0.23	Silty clay loam
Germany	Harbo et al., 2022	No	0.49 ± 0.36	Both annual & perennial		0-0.30	
Non-inversion tillage							
Global	Angers & Eriksen-Hamel, 2008	Yes	0.31	NT – HT	16	0-0.30	
Global	Haddaway et al., 2017	Yes	0.15 ± 0.04	NT - HT	18	0-0.30	
Global	Haddaway et al., 2017	Yes	0	NT - HT	18	0-1.50	
Global	Meurer et al., 2018	Yes	0.24 ± 0.11	NT - HT	18	0-0.30	
Scotland	Sun et al., 2011	No	0.68	NT – HT	5	0-0.40	Sandy loam
Herb-rich grassland							
England	Bullock et al., 2021	No	0	PR, PR+herbs	3	0-0.15	Clay loam
England	De Deyn et al., 2011	No	1.8	PR, PR+RC	16	0-0.10	
Germany	Lange et al., 2015	No	0.14	Doubling species		0-0.30	Sandy loam
Netherlands	Cong et al., 2014	No	0.08	Doubling species		0-0.15	Sand
New-Zeeland	Rutledge et al., 2017	No	0.85	PR+C, PR+herbs	3	0-1.0	Silty loam

USA	Skinner et al., 2016	No	1.0*	2-spec, 5-spec		0-1.0	Silty clay loam
USA	Yang et al., 2019	No	0.1	Doubling species	22	0-0.60	