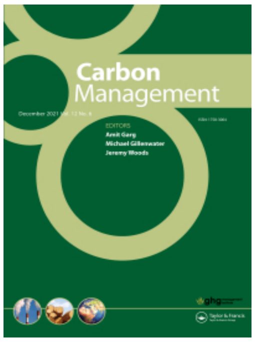

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The role of transaction costs for the optimal supply of carbon sequestration from cover crops in Denmark

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ABSTRACT

Climate change suggests the use of carbon dioxide removal technologies, such as soil carbon sequestration in agriculture, to complement mitigation efforts. However, there could be challenges with implementing sequestration measures due to transaction costs, such as farm expenses for research, information, and planning. The purpose of this study is to investigate how transaction costs affect the cost-effective supply of carbon sequestration from cover crops in Denmark. We develop a model of the optimal adoption of cover crops, accounting for farm spatial heterogeneity and potentially nonlinear transaction costs to adoption. In the presence of transaction costs and at a carbon price of 220 €/tCO2e (suggested as an appropriate level of a CO2e tax for Danish agriculture) increased cover crop cultivation will only offset 15.4 tCO2e per year, corresponding to 0.002% of the Danish agricultural emissions reduction target. Assuming zero transaction costs overestimates the annual sequestration supply at the given price by 13,030 tCO2e. Total abatement and transaction costs for cover cropping are on average 78 € per ha and transaction costs can represent up to 90% of total costs for low carbon prices. Transaction costs also alter the cost-effective distribution of carbon sequestration across space and farm size groups.

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Agriculture; carbon sequestration; cost-effectiveness; cover crops; transaction costs

Introduction

To mitigate the effects of climate change, the use of carbon dioxide (CO_2) removal technologies (CDRs), including soil carbon sequestration in agriculture, may be a viable approach [1,2]. By promoting the removal of CO_2 from the atmosphere, such nature-based sequestration measures not only help to offset ongoing emissions [3] but also aid in restoring and preserving carbon sinks [4]. The global technical potential of carbon sequestration in agriculture is estimated to be between 1.2 and 3.1 billion tons of carbon per year [5], and in the European Union, agricultural soils are estimated to sequester up to 16 to 19 Mt C per year [6].

Implementing agriculture carbon sequestration measures has associated costs. First, there are direct mitigation (or cultivation) costs, such as extra expenses for farm operations, supplies, and land opportunity costs. Second, there are transaction costs, i.e. market-related costs and additional costs borne by stakeholders to acquire necessary information [7,8]. For carbon sequestration to be a cost-effective strategy for climate change mitigation, it is a requirement that the sum of mitigation and transaction costs is not too high relative to the total carbon uptake [9,10].

In most studies modelling carbon sequestration in the land use sector, transaction costs are assumed to be zero. Estimates from the land use sector, however, suggest that transaction costs are between 20% and 80% of the total cost of measures [11–15]. This share is higher than the transaction costs reported for climate mitigation measures in other sectors. For example, transaction costs are 10 to 20% of the total costs for climate projects in the Danish energy sector [16][1]. Therefore, accounting for transaction costs is crucial for comparing environmental policies [17,18] and for understanding whether carbon

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sequestration can be a cost-effective climate mitigation strategy.

Transaction costs are examined in economic literature concerned with environmentally optimal outcomes. Abler [19] analytically shows that transaction costs affect the optimal level of production and thus also have consequences for farm level emissions. In a case study of the emissions from the textile industry in Flanders, Rousseau and Proost [20] provide empirical proof that transaction costs can alter the relative cost-effectiveness of climate measures. Ofei-Mensah and Bennett [21] further support this conclusion in a comparative analysis of GHG emission reduction instruments in Australia.

There are many empirical studies assessing the cost-effectiveness of agricultural carbon sequestration, while abstracting from transaction costs. Notable works are Antle et al. [22], Bamière et al. [23,24]. These studies combine ecological and economic data to derive abatement cost curves of carbon sequestration, the first on the United States of America and the remaining two on France. In contrast, transaction costs are indirectly captured in valuation studies estimating the willingness to accept (WTA) for farmers for carbon enhancing sequestration techniques, for example, Pautsch et al. [25] and Zandersen et al. [26]. Both papers use econometric approaches to examine farmers' hypothetical adoption of reduced tillage, with emphasis placed on farm heterogeneity as a determinant of the adoption decision. However, these studies do not distinguish transaction costs from other costs such as equipment purchases and loss in profits. Hence, they are unable to inform on the specific role of transaction costs in implementing carbon sequestration practices.

The purpose of this paper is to investigate how transaction costs might affect the cost-effective supply of carbon sequestration from cover crops in Denmark. We develop a spatially disaggregated optimization model that highlights the trade-offs between the societal benefits of sequestration and the abatement and transaction costs. We estimate the supply of carbon for a range of carbon prices, and account for structural farm heterogeneity. The model is applied empirically, considering the expansion of cover crops as the possible carbon sequestration measure in Denmark. Three questions are of interest: first, what is the cost-effective supply of carbon sequestration with additional cover cropping in Denmark under different carbon prices; second, how is that supply affected by the presence of transaction costs; and third, what is the optimal allocation of cover crop production across different Danish farms for a given carbon price.

Cover crops[2] are widely suggested as a low-cost option for enhancing carbon sequestration on agricultural land. They are non-commercial crops grown in rotation between regular cash crop production periods or under or in-between main crops in rotation. They serve multiple functions within farming, such as preventing nutrient leaching and soil erosion, conserving of soil moisture, increasing microbial activity in the soil and, the focus of this study, promoting higher carbon sequestration [27,28]. When compared to bare soil (i.e. no cover crops) under typical management conditions, cover crops are estimated to increase soil organic carbon (SOC) stocks by 12% on average for experiments with a mean duration of 6 years [29]. Further, if cover crops were introduced globally, the resulting carbon sequestration is estimated to compensate up to 8% of the direct annual agricultural GHG emissions [30].

There are several reasons to study cover cropping in Denmark. First, Denmark has a notable dominance of agricultural land [31].[3] As the Danish government plans to cut carbon emissions from agriculture by 7.1 million tons by 2030 [32], policies aimed at increasing agricultural carbon sequestration will play a significant part in Denmark's upcoming climate goals (The Danish Council on Climate Change, 2023). Given the prominent role of agriculture in many other countries, understanding how transaction costs affect the implementation of a Danish carbon sequestration practice is thus interesting to scientists and policymakers. Cover crops, specifically, are listed in the report from the Danish Council on Climate Change as one the measures expected to lead to future agricultural emission reductions in Denmark. Secondly, there already exists a subsidy for cover cropping in Denmark, the targeted catch crop scheme. The subsidy aims to reduce nutrient leaching in selected coastal catchments, and is part of the political agreement on the Food and Agricultural Package of December 2015 [33]. Finally, cover cropping has comparatively low costs in relation to other measures. For example, agroforestry and grasslands in crop rotations require machinery and general equipment, making cultivation costs high [24].

To the best of our knowledge, no previous study has empirically estimated the optimal supply of carbon sequestration in the agricultural sector accounting for transaction costs. In doing that, our study offers insights on the tradeoff between mitigation and transaction costs and thus contributes to the design and understanding of carbon sequestration policies.

The remainder of this paper is organized as follows: section 'theoretical model' presents the theoretical model. Section 'data' describes the data used for empirically applying the model, and section 'results' brings the results and sensitivity analysis. Section 'discussion and concluding remarks' presents policy implications of the findings and conclusions.

Theoretical model

We develop a static optimization model of carbon sequestration. The model balances the societal benefits of sequestration and the farm level cultivation and transaction costs from additional cover cropping. This section describes the equations forming the regulator's decision problem and the optimal solution.

Carbon sequestration

We assume that there are m_i farms of different types $i = 1, \ldots, n$, in a country, with the type being determined by a combination of structural farm characteristics, including soil type and production orientation, see Taghizadeh-Toosi & Olesen [31]. The carbon sequestration generated with cover cropping is assumed to be a function of the area allocated for cover crops, A_i, measured in hectares. Cultivating cover crops contributes to total carbon sequestration, S_i, in farm i, as depicted in Equation (1):

$$S_i = s_i A_i^{\alpha}, \tag{1}$$

where the parameter s_i is a coefficient expressing the annual increase in the SOC stock in tons of carbon dioxide equivalents (tCO_2e), due to cover cropping on the first hectare of land. The sequestration provided by cover crops is expected to vary, conditional on factors like water [34], climate, and soil conditions [31]. To account for varying sequestration potential on a given farm we introduce the exponent α, with $0 < \alpha \leq 1$, implying potentially decreasing marginal returns when the cover crop area is expanded.

Cultivation costs

Cultivating cover crops generates extra farm expenses, including costs for seed, sowing, and new machinery or technology. We focus on under-sown cover crops, which are crops grown under already established main spring crops, a cover cropping technique traditionally used in northern Europe [35–37]. The only direct expenses for under-sown cover crops are those for seed and sowing.[4] It can be noted that we disregard potential effects on the production of main crops, as recent literature indicates cover crops may have negligeable effects on yield [31,35,38–40]. We assume that cultivation costs are linear in the amount of land devoted to cover crops:

$$C_i = c_i A_i. \tag{2}$$

In Equation (2), the variable C_i is the total cultivation costs of adopting cover crops on farm i. The parameter c_i is the per hectare cultivation costs, assumed to vary by farm.

Transaction costs

The implementation of cover crops in the farm is assumed to lead to private transaction costs for farmers due to the time spent on research, information acquisition [7,8], and planning [41] necessary for the adoption of the practice. For example, farmers must spend time on paperwork and eventual crop inspections and may need to additionally hire auxiliary services for negotiation, contracting, and certification, so that they may receive governmental compensation for the cultivation of the crops.

Following the empirical [11,42], analytical [43,44], and theoretical [45] literature, transaction costs are assumed to be a function of total farm sequestration S_i. The motivation for having output formulated transaction costs is that identifying and establishing carbon sequestration is costly. Increasing levels of mitigation effort should raise transaction costs, everything else equal [43]. Further, it is reasonable to believe that farmers with more productive land (i.e. that have higher per hectare sequestration) have higher transaction costs due to their increased opportunity costs of time, which is consistent with our approach. We define transaction costs (T_i) as:

$$T_i = k S_i^{\beta}. \tag{3}$$

In Equation (3), k is a scaling factor. The exponent $\beta > 0$ is introduced to account for potential non-linearity between carbon sequestration and transaction costs. It can be interpreted as the elasticity of the function. Although economies of scale might occur in transactions, farmers can be expected to have an increasing opportunity cost of time spent on planning and administration. We therefore do not make any initial assumptions about the convexity or concavity of Equation (3)[5], thereby following the set up in Stavins [45].

Benefits of carbon sequestration

We assume that sowing of cover crops in a farm type i generates a benefit b for society for each tCO_2e sequestered by the crops. The parameter b expresses the constant marginal gain of sequestration.[6] Further, we disregard other cover cropping benefits, such as fertilization effects and the mitigation of nutrient leaching, which could vary in relation to the farm type.

The social planner's objective function

The social planner maximizes the net benefits of implementing cover crops in all farms in the country, W. The regulator's problem is given by:

$$\max_{A_i} \ W = \sum_i m_i(bS_i - C_i - T_i) = \sum_i m_i(bs_iA_i^{\alpha} - c_iA_i - ks_i{}^{\beta} \ A_i{}^{\alpha\beta}) \quad \text{s.t.} -A_i \leq 0 \ \text{and} \ A_i - \overline{A}_i \leq 0. \tag{4}$$

The term $\overline{A_i}$ is maximum number of hectares that can potentially be allocated for cover crops in a farm type i due to land availability. The Lagrangian function is given by Equation (5):

$$\mathcal{L} = \sum_i \left[m_ibs_iA_i^{\propto} - m_ic_iA_i - m_iks_i{}^{\beta} \ A_i{}^{\alpha\beta} - \lambda_i(A_i - \overline{A}_i)\right]. \tag{5}$$

The term λ_i, with $\lambda_i \geq 0$, is the Lagrange multiplier associated with the capacity constraint.The Karush Kuhn Tucker (KKT) equations give the necessary conditions for finding a solution to this problem. The stationary condition for this problem is:

$$\frac{\delta\mathcal{L}}{\delta A_i} = m_i \ bs_i\alpha \ A_i^{\alpha-1} - m_ic_i \ - m_iks_i^{\beta}\alpha\beta \ A_i^{\alpha\beta-1} - \lambda_i = 0. \tag{6}$$

and the slackness condition is:

$$\lambda_i(A_i - \overline{A}_i) = 0 \tag{7}$$

Equation (6) illustrates that in an interior optimum, the marginal benefit $(bs_i\alpha \ A_i^{\alpha-1})$ should equal the sum of marginal cultivation (c_i) and marginal transaction costs $\left(ks_i^{\beta}\alpha\beta \ A_i^{\alpha\beta-1}\right)$. In a world of zero transaction costs, the optimal A_i is bigger and found for the point where marginal benefits equal marginal cultivation costs. Equation (7) shows that either the capacity restriction is exactly binding, implying that $A_i^* = \overline{A}_i$ (i.e. cover crops are implemented in all available area in farm and $\lambda_i > 0$, or the optimal area allocated for cover crops is obtained from Equation (6), and we will have that $0 \leq A_i^* < \overline{A}_i$, and $\lambda_i = 0$.

Equations (6) and (7) will only be sufficient for A_i^* to be a global optimum when the objective function is concave in A_i. This will hold if the parameter β is sufficiently small compared to the parameter α. If this is not the case, Equations (6) and (7) still apply, however, they will not be sufficient for ensuring that the optimal solution is also a global optimum.

Data

In this section, we describe the data used in the empirical application of our model. All our data is in 2023-year value, calculated by inflating values with the Danish consumer price index (CPI) available at Statistics Denmark [46]. When converting monetary values to Euro, we used average exchange rates from 2023 [47]. All parameter values used in the benchmark model can be found in Table A1, Appendix A.

Farm types

We use data from Statistics Denmark [50] for the number of farms of different types (m_i), with type i determined by the location, the farm's size category, and the output produced. We consider farms in five different regions in Denmark: Capital Region (*Hovedstaden*), Southern Denmark (*Syddanmark*), Zealand (*Sjælland*), Central Jutland (*Midtjylland*) and North Jutland (*Nordjylland*), which together cover the whole country. Additionally, we divide the farms into five size categories: tiny (0.1 to 19.9 hectares), small (20 to 49.9 hectares), medium (50 to 124.9 hectares), big (125 to 249.9 hectares) and large (250 hectares or over). Finally, farms are categorized based on the main production orientation: pig, cattle, and plant. In total, there are 75 farm types, see Table A2 in Appendix A.

Carbon sequestration

For the per hectare sequestration coefficient s_i we use values estimated by Taghizadeh-Toosi and Olesen [31]. The authors report the average yearly increase in SOC stock following 26 years under typical management conditions, considering cover cropping relative to the comparable bare soil management treatment, for mineral well drained soils differentiated across three soil types (sand, sandy-loam or loam) and farm production orientation (plant, pig or cattle)[7]. The authors report coefficients for two sampling sites in Denmark. We use the average of the two sites to get a unique coefficient for each combination of soil type and production type. We associate these values with each of our farm types according to the production orientation of the farm and soil types in the region where the farm is located. For the latter we use a national map of topsoil [51] and the soil classification scheme from Madsen et al. [52] to calculate the soil composition for each Danish region in terms of the percentage area of each soil type. Thereafter, we calculate a spatially weighted average of the coefficients for different soil types in Taghizadeh-Toosi and Olesen [31]. The result is a unique s_i for each farm production orientation (pig, plant, or cattle) in each Danish region[8], see Table A2 in Appendix A. This calculation shows that cover crops tend to result in higher carbon sequestration in plant farms and in farms located in regions with higher concentration of sandy soils. Finally, we arbitrarily assume that the exponent β in the sequestration equation is equal to 0.9.

Area available for cover crop cultivation

To find the available agricultural area for cover crops per farm type, we calculate the remaining potential for cover cropping in Denmark, using data from Statistics Denmark [49] on the area currently dedicated for the cultivation of spring crops[9] in each Danish region (about 572,699.00 hectares in total) and subtracting from that the number of hectares already dedicated to the planting of cover crops, estimated to be 475,000 hectares or approximately 20% of Denmark's agricultural land [36]. We assume that the area currently dedicated to cover crops is exactly equal to 20% of the total agricultural area in each region and for each farm type. Table 1 presents the remaining potential for cover crops in percent of the agricultural area in each region. As observed, Zealand and the Capital Region have the highest and lowest estimated potential for cover crop cultivation in relation to total agricultural area, respectively. The value of $\overline{A_i}$, per farm type, is listed in Table A2 in Appendix A.

Cultivation and transaction costs

For the parameter c_i, the per hectare cultivation cost, we make use of the estimated cost for cover crop establishment, i.e. the costs for seeds and sowing in Denmark as reported in Hasler et al. [48] and Konrad et al. [53]. Following the mentioned references, we assume a uniform per hectare cost for all costs equal to 30 €/ha.We have additionally not found empirical data on private transaction costs faced by farmers for cover cropping in Denmark. Instead, we calibrate the parameters of the transaction cost function using data from two different studies. First, Phan et al. [42] estimate transaction costs for establishing carbon sequestration projects, using results from a survey with forestry project developers. The econometric estimates from their paper are used to find the elasticity of marginal transaction costs with respect to sequestration, β. Phan et al.'s [42] data pertains to projects carried out in Latin America, Asia and Africa, where transaction costs can be expected to be lower than in Denmark due to the lower opportunity cost of time resulting from lower income levels. We therefore calibrate the function to better fit the Danish agricultural context using results in Mettepenningen et al. [14], showing that european farmers' reported costs for labor hours, operation, and administration, for agri-environmental schemes are 54.23 €/ha[10] on average[11]. The calibration procedure led to setting the parameter k equal to 159[12], and β is equal to 1, i.e. there is a proportional relationship between sequestration output and transaction costs. Details can be found in Appendix B. Given this choice of data for calibration, the empirical transaction cost function reflects costs for labor, operation, and administration of environmental support, faced by the landowners. The relevance of our combined mitigation and transaction costs is checked by calculating the total per hectare costs of cover cropping, i.e. including both cost types using the parameter values described above. The average area potentially

Table 1. Remaining potential for cover crop cultivation in Denmark.

Region	Area available for cover cropping, in % of total agricultural area	Area available for cover cropping, in hectares
Capital Region	0.03	21.83
Zealand	6.14	25,383.02
Southern Denmark	4.35	29,235.61
Central Jutland	4.70	34,176.48
North Jutland	2.14	8,883.01

Note: Calculations based on data from Nielsen et al. [37] and Statistics Denmark [54].

available for cultivating cover crops equals 3.62 hectares (see Table A2 in Appendix A), and the average sequestration provided by cover crops is 0.33 tCO_2e per hectare (as calculated from Taghizadeh-Toosi & Olesen [31]). Given these numbers, the average total costs per hectare for cover cropping will be approximately €75.52. This is less than the estimated average WTA of 225.76 €/ha for catch-crop contracts in Denmark [54]. However, it is within the range of WTA estimates for sequestration measures considered in Zandersen et al. [26], where it is suggested that between 21 and 103 €/ha is necessary for Danish farmers to engage in conservation or reduced tillage. Thus, our cost functions are reasonable in comparison to these studies, while still being conservative.

Monetary benefits

Some studies use economy wide modelling approaches for estimating the value of carbon emission reductions using, for example, integrated assessment models (IAMs) that simulate atmospheric CO_2e concentration, impacts, and resulting reductions in gross domestic production output [55]. Pindyck [56], however, criticizes such methods due to lack of complete theoretical and empirical grounding, suggesting using the ratio of the present value of lost GDP from an extreme outcome to the total emission reduction needed to avert that outcome. However, Pindyck [56] relies on a survey of experts and finds a large variation in values.

Another frequently used approach is to set the marginal benefit of reductions in CO_2e equal to carbon prices applied in actual policies. This is typically motivated by an assumption that governments strive for economically optimal carbon sequestration policies, hence equating the marginal cost and the marginal benefit.[13] One option would be to apply prices from the European Emission Trading Scheme (EU ETS). However, the EU ETS covers only emissions from the manufacturing and energy sectors and aviation [57], not including the agricultural sector. A more plausible value of the carbon price in the Danish agricultural sector context is the agricultural carbon tax rate recommended by the Danish Climate Council [58], equaling 220 €/tCO_2e. The same report also analyses the impact of a tax of around 100 €/tCO_2e, which is the level more recently suggested by the Danish Expert Group for a Green Tax Reform [59].[14]

Considering the above, we use a range of values between 0 and 500 €/tCO_2e in different scenario simulations. This is motivated by our desire to observe the effect of varying prices on the resulting carbon output. When conducting comparative and sensitivity analysis, we use a baseline price of 220 €/tCO_2e, equal to the tax level recommended by the Danish Climate Council.

Results

The model was solved using non-linear programming (NLP) in the software GAMS [60] using a CONOPT4 solver. We estimate the model for a range of carbon prices between 0 and 500 €/tCO_2e. The results are organized as follows: First, we present the results with our benchmark parameter values (following the numbers presented in Table A2 in Appendix A), considering two alternative scenarios: with and without transaction costs. Following that, we conduct sensitivity analysis with respect to parameter assumptions.

Benchmark results

Figure 1 brings the optimal total carbon sequestration (in 1,000 tCO_2e) resulting from the expansion of cover crops in Denmark under varying carbon prices. The graph depicts the sequestration outcome for the scenarios with and without transaction costs. The vertical black dotted line marks the level of the proposed agricultural carbon tax, i.e. when the carbon price equals 220 €/tCO2e.

As expected, assuming zero transaction costs leads to higher carbon sequestration for most carbon prices considered, with a notable difference, of approximately 13,000 tCO_2e, being observed in the range of the recommended agricultural carbon tax. For low carbon prices (<40 €/tCO_2e), farms do not implement cover cropping, and sequestration is zero regardless of whether there are transaction costs or not. Without transaction costs, a carbon price of at least 40 €/tCO_2e is necessary. When transaction costs are accounted for, the minimum carbon price for cover cropping is more than four times higher (180 €/tCO_2e). For high carbon prices (>400 €/tCO_2e), there is again convergence in the carbon sequestration with and without transaction costs. This is because most farms have met their capacity constraint for cover cropping. The maximum carbon sequestration that can be provided is 15,300 tCO_2e/yr, found when the carbon price is >500 €/tCO_2e.

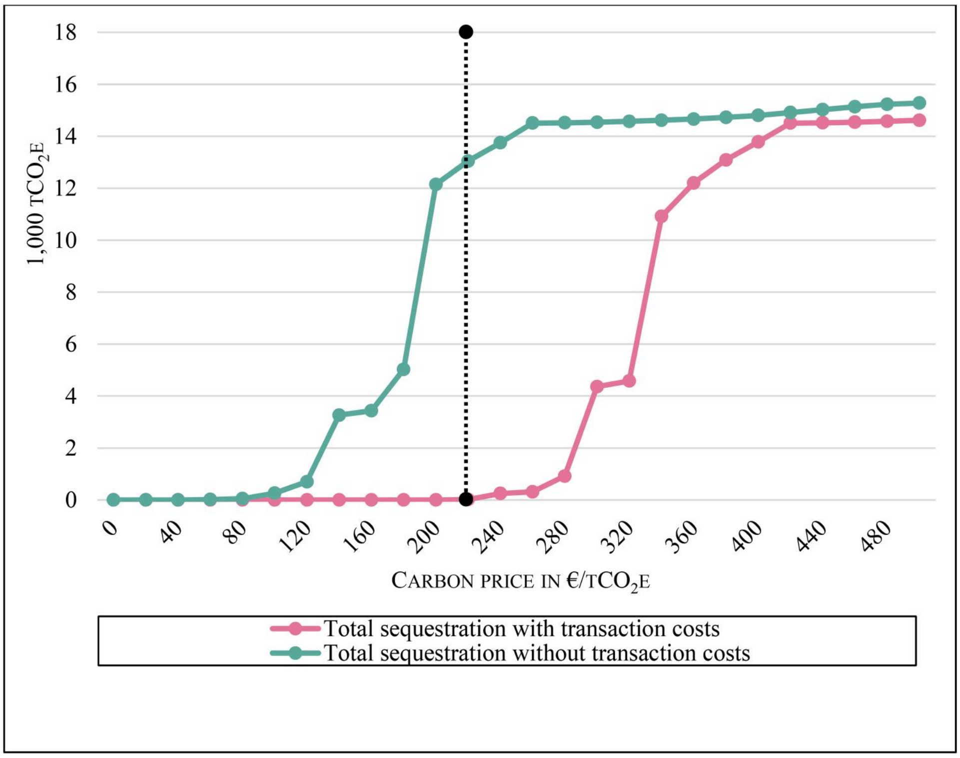

Figure 1. Carbon sequestration output (in 1,000 tCO2e) provided by expanding cover crops in Denmark under different carbon prices. Note: the black dotted line illustrates the agricultural carbon tax price scenario.

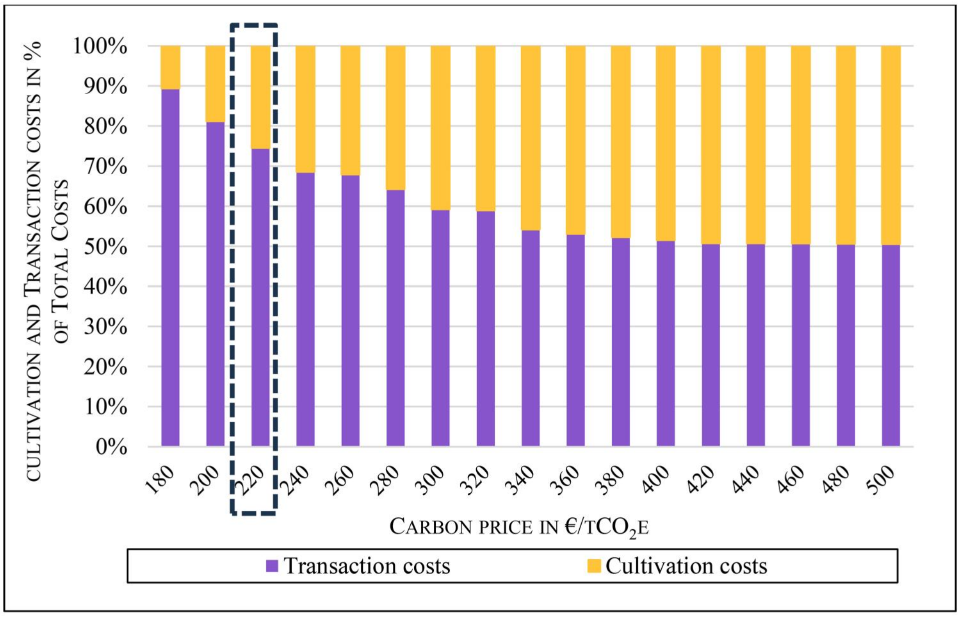

Figure 2. Percentage distribution of abatement and transaction costs in relation to total costs for cover cropping in Denmark, under different carbon prices. Note: the black dotted square illustrates the agricultural carbon tax price scenario.

Figure 2 illustrates how transaction and cultivation costs vary in relation to the total costs of cover cropping for the different carbon prices. The dotted square again highlights the agricultural carbon tax level. As observed in the figure, transaction costs represent between 90% and 50% of total costs, depending on the carbon price that applies. A decrease in the share of transaction costs as the carbon price increases is expected. For high carbon prices, farms that are only able to achieve comparatively low carbon sequestration per hectare will also have an incentive to engage in cover cropping. Thus, there will be more area allocated for cover crops but there will not be a proportional increase in sequestration levels, causing cultivation costs to grow more than the increase in transaction costs. At the agricultural carbon tax price, transaction costs are 74.5% of the

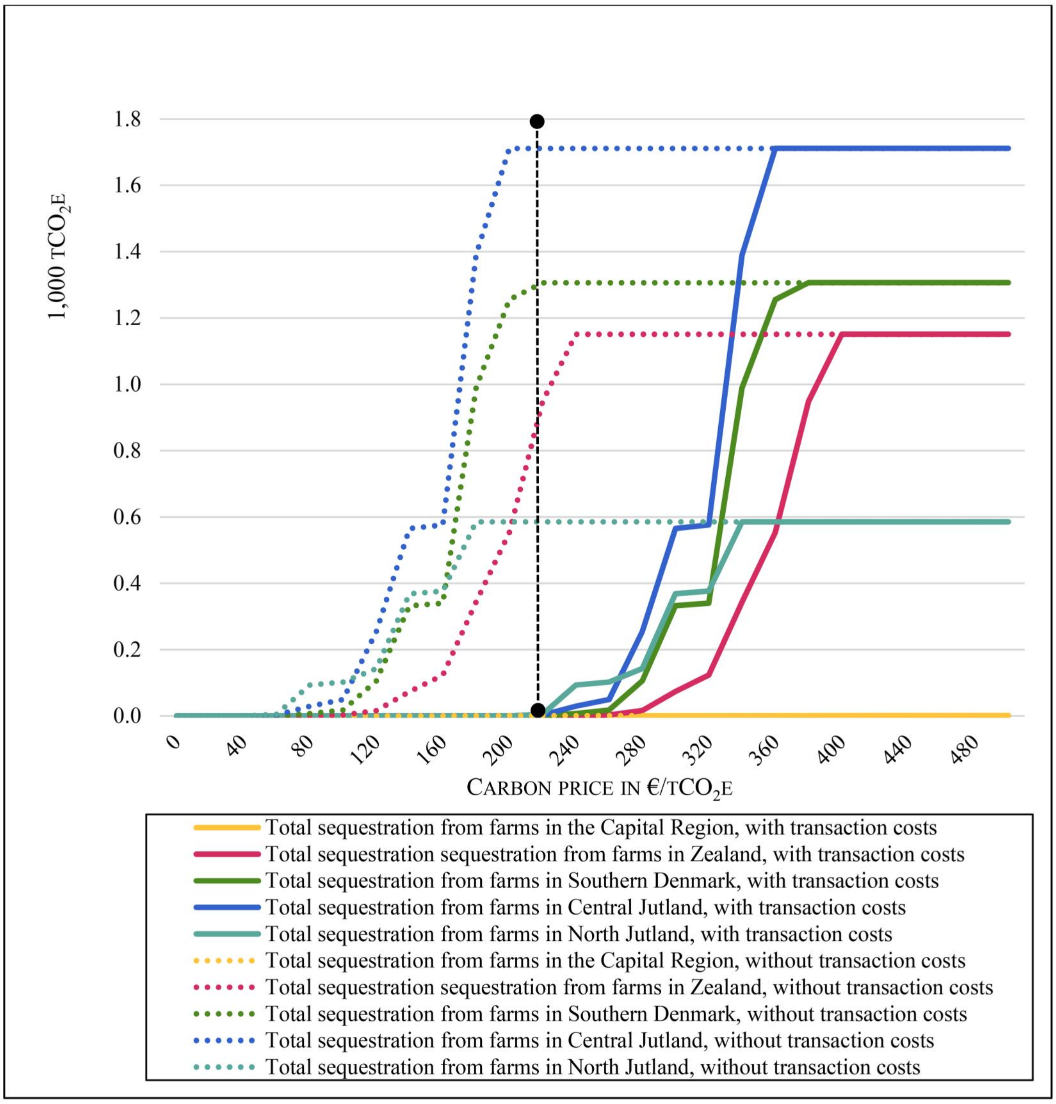

Figure 3. Optimal carbon sequestration output (in 1,000 tCO2e) from cover crops across farm location types under different carbon prices. Note: the black dotted line illustrates the agricultural carbon tax price scenario.

total costs. At high carbon prices, similar shares of transaction and cultivation costs are observed.

Figure 3 illustrates the carbon sequestration provided by cover crops under different carbon price scenarios, with (solid lines) and without (hashed lines) transaction costs in the model, for each region. Again, the agricultural carbon tax price is highlighted with a black dotted line. The pattern observed in the figure is driven by a combination of land availability, transaction costs, and per hectare sequestration coefficients. For example, farms in the Capital Region have the lowest land availability for cover cropping out of all the regions, and low per hectare sequestration coefficients (see Table A2 in Appendix A). Thus, the model allocates little cover cropping in this region regardless of whether transaction costs are considered or not, and the carbon sequestration output remains low in the region for all carbon prices. North Jutland farms have higher sequestration of cover cropping at low carbon prices in scenarios both with and without transaction costs, due to the prevalence of sandy soils and the high number of production farm types associated with high per hectare sequestration existing the region, see Table A2 in Appendix A, and thus causes more areas to be allocated for cover cropping at low carbon prices. However, as the more productive farms in North Jutland, i.e. that sequester more carbon at fewer hectares, reach their land availability constraint (reflected in the plateaus in the teal-colored graph), the carbon sequestration output from other regions increases more rapidly, surpassing that of North Jutland. Transaction costs increase the carbon price necessary for all available land to engage in cover cropping, making all the curves shift right in comparison with the non-transaction costs scenario.

The spatial distribution of cover crops under the agricultural tax carbon price scenario can be seen in Figure 4. The maps depict the area allocated for cover crops, in percentage of the area estimated

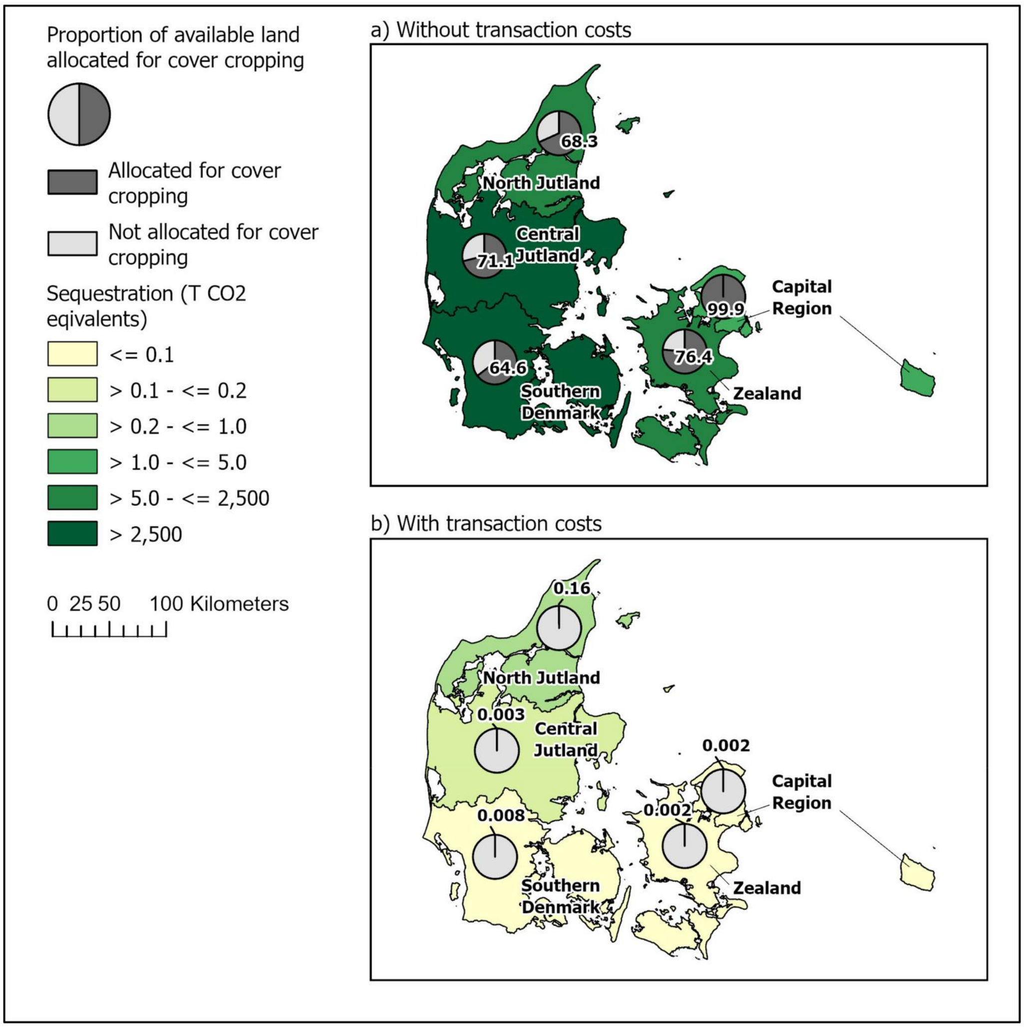

Figure 4. Optimal allocation of cover crops under the agricultural carbon tax scenario (sequestration in tCO2e and portion of land allocated for cover cropping in percent relative to area estimated as available for cover crops), for different danish regions, with zero (a) and positive (b) transaction costs.

to be available for cover cropping, for scenarios without (a) and with (b) transaction costs. The colors in each region represent the amount of carbon sequestration under each model, in tCO_2e. Without transaction costs, the highest carbon sequestration output comes from farms in Central Jutland (24,303 tCO_2e), followed by Southern Denmark (5,366.74 tCO_2e), Zealand (2,254.3 tCO_2e), North Jutland (1,700 tCO_2e) and finally the Capital Region (4.03 tCO_2e). With transaction costs the Capital Region remains the location with lowest output (sequestering $<$0.0001 tCO_2e). However, the highest output comes instead North Jutland (0.38 tCO_2e), followed by Central Jutland (0.128 tCO_2e), Southern Denmark (0.031 tCO_2e) and Zealand (0.002 tCO_2e). Transaction costs, thus, change the cost-effective spatial distribution of carbon sequestration. Further, the percentage of area allocated for cover cropping, for all regions, decreases from an average 76.06% to 0.04% of available cover cropping area, when accounting for transaction costs.

Figure 5 is a graph analogue to Figure 3, but for farm product orientations instead of farm locations. As before, results are reported with and without transaction costs. Plant farms provide the highest total carbon sequestration and cattle farms the lowest, regardless of whether transaction costs are considered and what is the carbon price that applies. This is a direct result of the per hectare carbon sequestration coefficients, that are the highest for plant farms and the lowest for cattle farms regardless of farm location. Transaction costs, however, visibly shift the supply curve for each farm type. At the agricultural carbon tax level, without transaction costs, the sequestration output is 10,560 tCO_2e from plant farms, 2,286.01 tCO_2e from pig farms and 241 tCO_2e from cattle farms. Also, without transaction costs, a carbon price of around 240 €/tCO_2e is enough to incentivize cover cropping on all available pig farms area, as indicated by the plateau in the pink dotted curve after that level. When transaction costs are introduced, the agricultural tax carbon price yields only 0.535 tCO_2e from plant

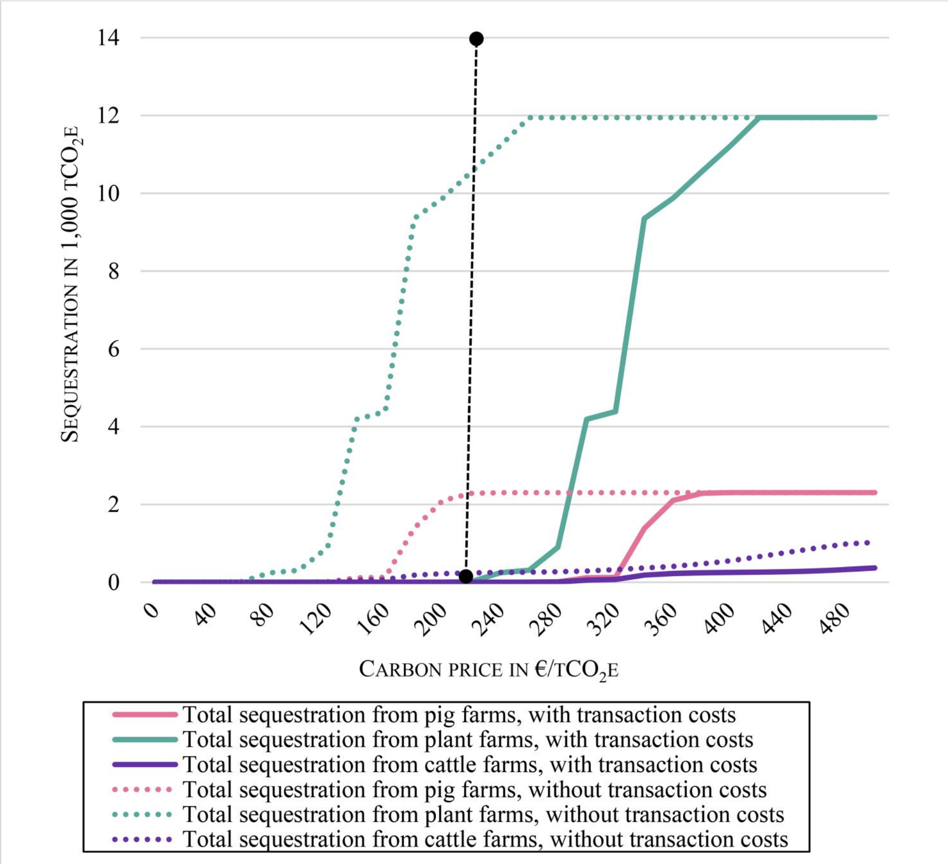

Figure 5. Optimal carbon sequestration output (in 1,000 tCO2e) from cover cropping across farm product orientation under different carbon prices. Note: the black dotted line illustrates the agricultural carbon tax price scenario.

farms, 0.005 tCO_2e from pig farms and 0.001 tCO_2e in cattle farms. The needed price level for all available pig farms area to engage in cover cropping (400 €/tCO_2e) is more than 1.5 times higher than in the scenario without transaction costs. Similarly, the carbon price level necessary for all plant farms to engage in additional cover cropping increases from 260 €/tCO_2e to 420 €/tCO_2e when transaction costs are considered.

Figure 6 reports the carbon sequestration output for different carbon prices across the farm size categories. As before, outputs are reported with (solid lines) and without (hashed lines) transaction costs, and the agricultural carbon tax price is highlighted. As intuitively expected, the total carbon sequestration mostly follows farm size, with large and tiny farms providing the highest and lowest total sequestration output, respectively, in most carbon price scenarios. The inclusion of transaction costs will again change the relative distribution of sequestration across farms at a given carbon price. For example, for the agricultural tax level and without transaction costs, the ranking of the farms from highest to lowest sequestration output is: large (5,588 tCO_2e), medium (2,681 tCO_2e), big (2,643 tCO_2e), small (1,274.72 tCO_2e), and tiny (900 tCO_2e). With transaction costs, for the same carbon price, tiny farms are instead the type with highest total sequestration output (0.24 tCO_2e), followed by small (0.11 tCO_2e), medium (0.11 tCO_2e), large (0.035 tCO_2e) and finally big (0.043 tCO_2e). Both the models with and without transaction costs initially allocate more cover cropping to tiny farms, because there is a high share of plant farms within the tiny category (and therefore a high per hectare sequestration coefficient for many tiny farms). A sharp increase in the allocation to other farm categories (e.g. big and large farms) is only observed when all the available area from tiny farms is used for cover crops. As transaction costs shift the plateaus indicating the end of land availability for each farm category to the right, the relative supply of cost-effective carbon sequestration is thus changed at a fixed carbon price, in the same logic as explained for farm locations.

Sensitivity analysis

In this section, we perform sensitivity tests, with the aim of understanding how assumptions made about model parameters impact the sequestration supply in the model with transaction costs. First, in Table 2 we present the percentage change in the total sequestration supplied for a 10% upward and downward

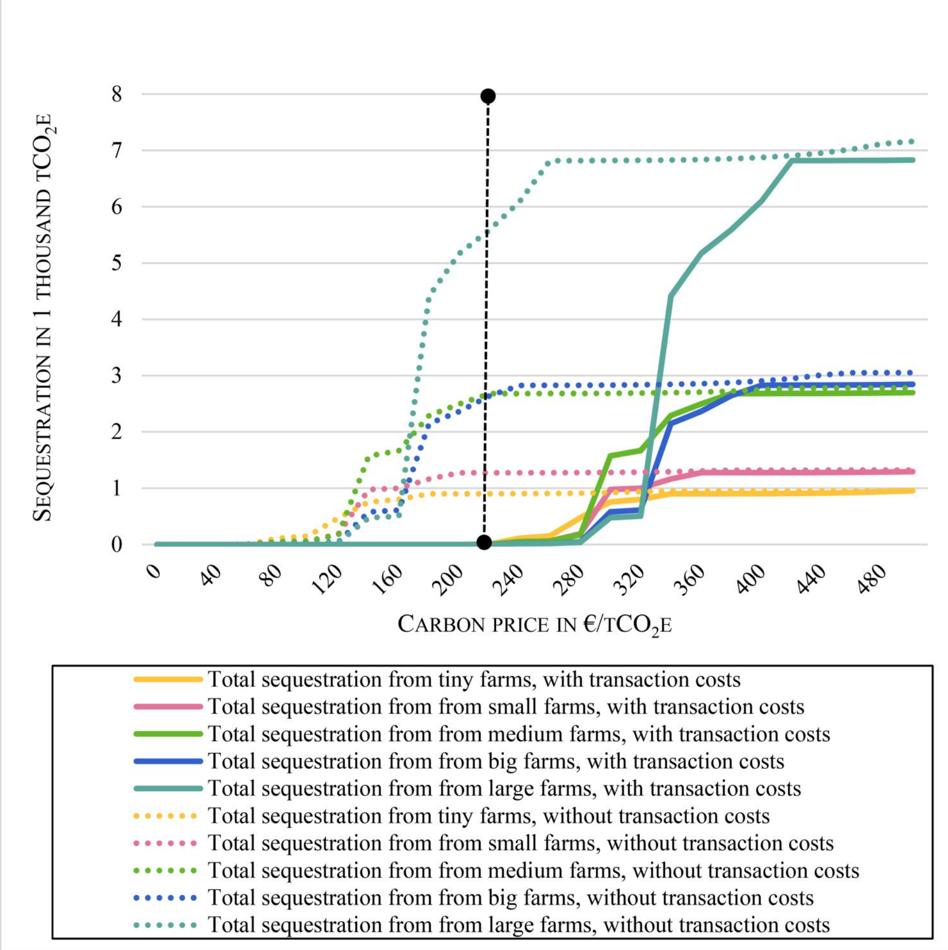

Figure 6. Optimal carbon sequestration output (in 1,000 tCO2e) from cover crops across farm size category types under different carbon prices. *Note:* the black dotted line illustrates the agricultural carbon tax price scenario.

Table 2. Percentage change in the sequestration output when parameters are decreased or increased by 10% relative to baseline values (using agricultural tax carbon price scenario of 220 €/tCO$_2$e), model with transaction costs.

Parameter	10% increase	10% decrease
Scale parameter o transaction cost function (k)	−92.5 %	630.8%
Sequestration coefficient (s_i)	225.1%	−85.5%
Exponent in sequestration function (α)	−99.8%	1,090.1%
Per hectare cultivation cost (c)	−98.5 %	167.0%
Per hectare cultivation cost (c_i) of tiny farms	−67.2%	72.0%
Per hectare cultivation cost (c_i) of small farms	< 1.0% change	24.3%
Per hectare cultivation cost (c_i) of medium farms	−52.8%	49.4%
Per hectare cultivation cost (c_i) of big farms	−19.6%	14.8%
Per hectare cultivation cost (c_i) of large farms	−54.0%	20.8%

change in each parameter relative to baseline values and at a carbon price of 220 €/tCO$_2$e. The table reports the values for all parameters, except for the transaction cost elasticity parameter β, investigated in further detail next. We further considered an increase or decrease in cultivation costs separately for each farm size category. The motivation for this sensitivity test is that cultivation costs could differ systematically across farm size group due to potential economies of scale, investment needs, and variations in the opportunity cost of labour time. Thus, this test considers the impact of non-uniform per hectare cultivation costs in the model.

The results from the table indicate that the model is sensitive to assumptions about all parameters used, as a 10% change leads to a more than 10% change in the resulting sequestration. Notably, decreasing the per hectare sequestration output α by 10% leads to the biggest change in output, of 1,090%, i.e. a sequestration output that is around 12 times larger compared to the baseline. While intuitively one might expect that a decrease in α would result in lower overall sequestration, a lower α also decreases transaction costs. For low carbon prices, the reduction in the benefits of sequestration due to a reduction in α is small, while the reduction in transaction costs is large, which explains this outcome.

Further, the sensitivity analysis shows that the impact on the total sequestration of an increase in cultivation costs for a particular farm size category is largely proportional to the category's share of cover crop area in optimum, as can be expected. Under the proposed carbon tax, the strongest sequestration response to changes in cultivation costs is for tiny farms, suggesting that more detailed information on the costs incurred by tiny farms would be valuable for policy makers.

The reason for the overall high effects of all coefficients in Table 2 is that we examine a critical range of the supply around the suggested carbon price, where area allocation for cover cropping is low. When checking at a higher carbon price the sequestration output, the model is less sensitive, particularly to changes in the per hectare cultivation cost c_i and the transaction cost scale parameter k. Further, for higher carbon prices higher α values lead to increases in sequestration output, and *vice versa*, given the larger resulting impact on sequestration benefits. Results for a sensitivity check with a carbon price of 400 €/tCO2e are available in Table A3 in Appendix A.

Next, we look closer at the elasticity parameter β. In Figure 7, we illustrate the impact of varying β up and down by 10%, indicating a convex and concave transaction cost function, respectively. As observed in the figure, the sequestration output follows the same S-shape for all levels of β, with low carbon output at low carbon prices, rapid increases at medium prices, and stabilization at high prices due to decreasing land availability for cover cropping. The varying assumptions on scale effects in transaction costs influence the slope of the sequestration output function. At the agricultural carbon tax price, convex transaction costs yield an output 30 times higher than linear transaction costs. The convex transaction cost function yields the highest sequestration output under low carbon prices, but the lowest under higher prices. The former is explained by an increase in β implying a reduction in transaction costs for $S_i<1$, while for $S_i>1$, transaction costs increase, and then at a more rapid rate. In all cases with transaction costs, sequestration remains notably smaller compared to the non-transaction cost model.

Discussion and concluding remarks

In this paper, a spatial economic model of cover crop implementation is developed and applied in Denmark, showcasing the trade-offs between societal carbon sequestration benefits and farm-level cultivation and transaction costs. We find that in the presence of transaction costs, and at a carbon price of 220 €/tCO_2e, only 15.4 tCO_2e can be sequestered annually *via* additional cover cropping in Denmark. Assuming zero transaction costs overestimates the sequestration output by 13,030 tCO_2e for the same carbon price. Transaction costs also change the optimal allocation of sequestration across space and farm size, but do not affect the

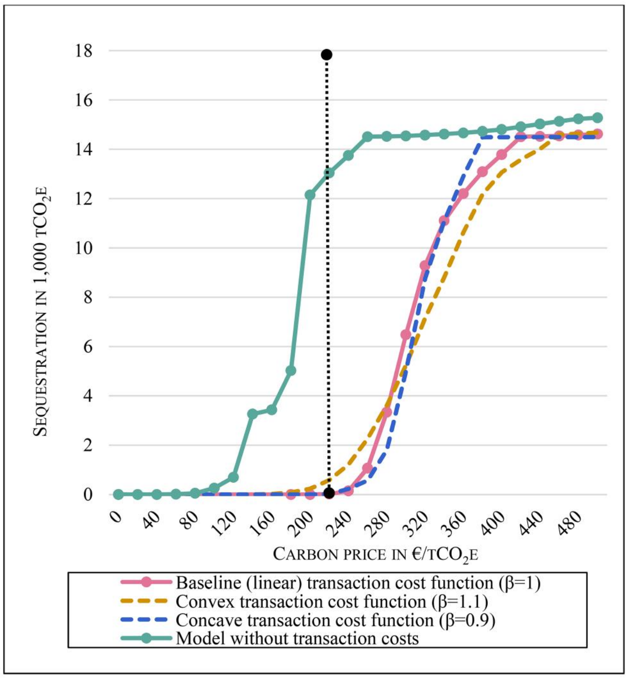

Figure 7. Carbon sequestration output (in 1,000 tCO_2e) for linear, convex, concave, and zero, transaction costs and under different carbon prices. Note: the black dotted line illustrates the agricultural carbon tax price scenario.

allocation across farms with different product orientation. Plant and cattle farms provide the highest and lowest output, respectively, for all carbon prices, independently of the size of transaction costs. This occurs because the production orientation is a key determinant of sequestration per hectare.

Our paper adds to the literature on transaction costs in climate policies by examining their impact on the supply of agricultural carbon sequestration. In doing that, we find empirical evidence that the farm level distribution supply of carbon sequestration from cover cropping shifts when transaction costs are introduced, as similarly observed for mitigation initiatives in other sectors. This effect aligns with previous findings that soil type and location are significant determinants of adoption rates for conservation tillage [25,26]. Taken together, the evidence we bring points to farm heterogeneity as a relevant factor for deriving the least-cost path allocation of carbon sequestration across farmers. Further, our model converses with Bamière et al. [24] estimates, that previously found around 0.8 tCO_2e/ha could be annually sequestered through cover crops in France, when assuming zero transaction costs. The value reported by to Bamière et al. [24] is about 1.5 times higher than the yearly carbon sequestration we find when applying our model in the presence of transaction costs under the agricultural carbon tax price. As our modelling approach accounts for farm heterogeneity in transaction costs, our analysis thus bridges a gap between mitigation cost-based analyses, such as those by Bamière et al. [24], and stated preference studies generally, which often show discrepancies in conclusions about the required level of economic incentives for carbon sequestration.

We estimate that total (i.e. abatement plus transaction) costs of expanding cover crops in Denmark are 213.4€/tCO_2e, under a carbon price of 220 €/tCO_2e. Marginal costs for reducing fossil fuels use within the agricultural sector and elsewhere are typically higher: The study by Zandersen et al. [26] finds that Danish farmer's marginal abatement costs for energy savings from, e.g. lower tractor use from adopting reduced tillage would be 580 to 3,700 €/tCO_2e, and the marginal abatement costs for decarbonization in the fossil fuel sector in Denmark is 474 to 622 €/ tCO_2e [61], all in 2023 year value. Thus, even when farmers' transaction costs are accounted for, our model suggests that agricultural sequestration is cost-effective for climate mitigation in Denmark.

There are limitations to our approach. First, public transaction costs faced by policymakers in incentivizing carbon sequestration are not considered. Some regulations may be inexpensive for farmers but costly for the public to implement, or *vice versa,* but data on public transaction costs is limited. This is an interesting topic to be explored by future research. Further, we do not consider the potential role of socio-demographic differences between farmers for farm heterogeneity in transaction costs, while such characteristics have been shown to matter for transaction costs as well as adoption rates [62–64]. For example, higher educational levels can reduce farmer's transaction costs [65]. However, there is no data available that allows us to associate our farm types with such characteristics. Secondly, we assume that transaction costs are variable. There could be also fixed transaction costs, such as discussed with reference to agri-environmental schemes by Falconer et al. [66], Abler [19] and Ducos et al. [65]. In addition, the transaction costs estimates used in this study do not provide context-specific evidence from Danish conditions, and, hence, results should be interpreted with caution.Also, we do not consider the potential benefits of cover crops in terms of the impact on soil quality, where cover crops may enhance soil microbial activity and increase the availability of nutrients [67], thereby reducing the need for fertilization, diminishing weed biomass, mitigating soil compaction and tillage demands, and enhancing the management of soil moisture [68], all of which could increase farming revenues. Finally, the results from the sensitivity analysis highlight that our model needs calibration for applicability in other contexts, where different parameter values are expected. For example, the cultivation cost parameter c and the sequestration coefficient s_i are specified for cover cropping in Denmark. Therefore, calibration of those parameters is necessary for application outside of Denmark or when considering other sequestration measures. In addition, the availability of differentiated cost data for different farm types could increase the robustness of the results.

Our study has relevant policy implications. The results highlights that a carbon price of at least 180 €/tCO_2e may be necessary to expand cover crops in Denmark, when taking transaction costs into account. This is significantly higher than most existing carbon prices as discussed in session 3.5, including the carbon tax currently analyzed in Denmark [58,59]. However, it is lower than the agricultural carbon tax recommended by the Danish Climate

Council. Still, we find that the achieved sequestration under the recommended tax would be small. Considering the Danish agricultural emissions target requires an average yearly reduction in emissions by 0.79 million tCO_2e [32], our results suggest that only 0.002% of the reduction could be met with cover cropping under a carbon price of 220 €/tCO_2e, when transaction costs are considered. The adoption might be increased through governmental efforts to reduce farmer's transaction costs, for example by disseminating information about cover crop benefits and management practices [69].

Future research on transaction costs and carbon sequestration policy could extend the analysis to a larger number of sequestration measures, thus allowing for a comparative analysis on the role of transaction cost differences for the cost-effectiveness of different sequestration measures. Moreover, it could be relevant to account for time dynamics of carbon sequestration, due to carbon stock decay and release of emissions from the crops and time dynamics of transaction costs, related to potential fixed costs as well as learning-by-doing effects. Learning-by-doing implies that transaction costs tend to decrease in time with growing experience in agri-environmental schemes [66]. Finally, our study shows that assumptions on scale effects in transaction cost functions visibly alter the sequestration output curve. Thus, more empirical assessments should strive to provide accurate values for transaction costs in agricultural sequestration, for higher accuracy in cost-effective assessments. This can be done with primary data collection from farmers and other stakeholders involved in the implementation of sequestration projects, as well as systematic reviews aggregating values from existing literature. Direct measurements of administrative, monitoring, and compliance costs, as well as farmer-specific costs for adopting different practices, would be valuable for enhanced cost-effectiveness comparisons across different sequestration measures.

Notes

1. This is the range estimated for the Free-of-Charge Energy Audit (FCEA) program in Denmark.
2. Cover crops are also known as forage crops, green manure or catch crops [27]. The latter is used in the context of a crop sown to retain excess nutrients from the preceding crop and/or prevent nutrient leaching in catchment areas
3. Denmark has a total area of 43,095 km^2, and roughly two thirds of that is under agricultural land management [31].
4. Costs for new technology, fertilizers and herbicide or tillage, although commonly cited cover cropping cultivation costs [27,48,70], will not be necessary for under-sown crops. Opportunity cost of land are not relevant as under-sown crops do not displace or replace winter crops [36].
5. I.e. whether $\beta < 1$ or $\beta > 1$.
6. The expected sequestration obtained with cover cropping in an individual country is small in relation to the global emissions [30], and thus there is no reason to assume decreasing marginal benefits in relation to the scale of implementation.
7. See table 10 in Taghizadeh-Toosi and Olesen [31].
8. The per hectare sequestration coefficient is independent of the size category.
9. We consider as spring crops common spring wheat, spring barley, oats and spring rape.
10. In 2023 year value.
11. Comparing to the above-mentioned cultivation costs, the average transaction costs then constitute 64% of the total per hectare costs, which are equal to 84.23 €/ha.
12. The private transaction costs then represents approximately 72% of the suggested agricultural carbon tax of 220 €/tCO2e [58].
13. The use of potential taxes or subsidies as marginal benefits or damages has been employed previously in optimization studies. Examples are early use in Maler [71], as well as applications by Elofsson [72], assessing abatement of nitrogen emissions in the Baltic Sea and Tang & Wang [73] to model the value of agricultural carbon reductions in China.
14. The Danish targeted catch crop scheme of applies a subsidy of 67.02 €/ha, however, the subsidy targets nitrogen leaching, not carbon sequestration. Hence, it is not relevant in this context.
15. Note that although the authors also include project area as a covariate, the found effect is close to zero in magnitude and not significant. Thus, we disregard it in the equation.
16. Converted to 2023 year value.

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Disclosure statement

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Data availability statement

The authors confirm that the data supporting the findings of this study are either from clearly outlined secondary sources or available within the article and/or its supplementary materials. Code files for reproducing the results on GAMS are available from the corresponding author, upon reasonable request.

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Appendices

Appendix A

Table A1. **Modelling parameters and values used in benchmark model.**

Parameter	Unit	Value used
Per hectare cultivation cost (*c*)	€/ha	30
Scale parameter on transaction cost function (*k*)	–	159
Elasticity in transaction cost function (β)	–	1
Marginal benefit of sequestration (*b*)	€/tCO_2e	Varying between 0 and 500 (=220 for baseline comparisons)
Decreasing marginal productivity of sequestration (α)	–	0.9
Sequestration coefficients (s_i)	tCO_2e	See Table A2

Note: Cultivation cost from Hasler et al. [48] and scale and elasticity in transaction cost function from Phan et al. [42] and Mettepenningen et al. [14], following a calibration procedure described in Appendix B. Remaining parameters are assumed by the authors. The justification for the range of varying carbon prices used is described in detail in section 3.6.

Table A2. Farm types, number of farms per type and values for land availability for cover cropping and per hectare sequestration per farm type used in baseline model simulation [50].

Farm type	Land availability for cover cropping per farm in hectares ($\bar{A}_i$)	Per hectare sequestration (s_i) in tCO_2e	Number of farms (m_i)
1. Tiny plant farm in Capital Region	0.003	0.13	489
2. Tiny plant farm in Zealand	0.591	0.18	1,128
3. Tiny plant farm in Southern Denmark	0.435	0.25	1,801
4. Tiny plant farm in Central Jutland	0.488	0.29	2,283
5. Tiny plant farm in North Jutland	0.222	0.34	1,411
6. Tiny cattle farm in Capital Region	0.002	0.14	503
7. Tiny cattle farm in Zealand	0.468	0.21	746
8. Tiny cattle farm in Southern Denmark	0.376	0.09	1,379
9. Tiny cattle farm in Central Jutland	0.411	0.05	1,404
10. Tiny cattle farm in North Jutland	0.187	0.02	1,073
11, Tiny pig farm in Capital Region	–	0.14	0
12. Tiny pig farm in Zealand	0.164	0.21	6
13. Tiny pig farm in Southern Denmark	0.184	0.22	35
14. Tiny pig farm in Central Jutland	0.411	0.23	50
15. Tiny pig farm in North Jutland	0.170	0.26	40
16. Small plant farm in Capital Region	0.010	0.13	182
17. Small plant farm in Zealand	2.041	0.18	669
18. Small plant farm in Southern Denmark	1.427	0.25	996
19. Small plant farm in Central Jutland	1.484	0.29	1,164
20. Small plant farm in North Jutland	0.671	0.34	604
21. Small cattle farm in Capital Region	0.009	0.14	124
22. Small cattle farm in Zealand	1.980	0.21	152
23. Small cattle farm in Southern Denmark	1.354	0.09	399
24. Small cattle farm in Central Jutland	1.446	0.05	305
25. Small cattle farm in North Jutland	0.688	0.02	254
26. Small pig farm in Capital Region	–	0.14	0
27. Small pig farm in Zealand	–	0.21	0
28. Small pig farm in Southern Denmark	1.759	0.22	14
29. Small pig farm in Central Jutland	1.575	0.23	29
30. Small pig farm in North Jutland	–	0.26	0
31. Medium plant farm in Capital Region	0.022	0.13	198
32. Medium plant farm in Zealand	4.852	0.18	641
33. Medium plant farm in Southern Denmark	3.582	0.25	805
34. Medium plant farm in Central Jutland	3.767	0.29	1,066
35. Medium plant farm in North Jutland	1.670	0.34	634
36. Medium cattle farm in Capital Region	0.026	0.14	19
37. Medium cattle farm in Zealand	4.286	0.21	48
38. Medium cattle farm in Southern Denmark	3.786	0.09	334
39. Medium cattle farm in Central Jutland	3.852	0.05	302
40. Medium cattle farm in North Jutland	1.825	0.02	206
41. Medium pig farm in Capital Region	0.028	0.14	5
42. Medium pig farm in Zealand	7.158	0.21	14
43. Medium pig farm in Southern Denmark	4.081	0.22	89
44. Medium pig farm in Central Jutland	4.363	0.23	68
45. Medium pig farm in North Jutland	2.017	0.26	33
46. Big plant farm in Capital Region	0.048	0.13	89
47. Big plant farm in Zealand	10.778	0.18	414
48. Big plant farm in Southern Denmark	7.652	0.25	377
49. Big plant farm in Central Jutland	8.404	0.29	365
50. Big plant farm in North Jutland	3.664	0.34	247
51. Big cattle farm in Capital Region	0.039	0.14	22
52. Big cattle farm in Zealand	9.800	0.21	29
53. Big cattle farm in Southern Denmark	7.913	0.09	383
54. Big cattle farm in Central Jutland	8.303	0.05	303
55. Big cattle farm in North Jutland	3.784	0.02	198
56. Big pig farm in Capital Region	0.070	0.14	9
57. Big pig farm in Zealand	11.302	0.21	32
58. Big pig farm in Southern Denmark	7.686	0.22	158
59. Big pig farm in Central Jutland	8.572	0.23	127
60. Big pig farm in North Jutland	3.977	0.26	81
61. Large plant farm in Capital Region	0.143	0.13	29
62. Large plant farm in Zealand	34.139	0.18	364
63. Large plant farm in Southern Denmark	22.728	0.25	277
64. Large plant farm in Central Jutland	24.155	0.29	378
65. Large plant farm in North Jutland	11.264	0.34	182
66. Large cattle farm in Capital Region	–	0.14	0
67. Large cattle farm in Zealand	32.495	0.21	6
68. Large cattle farm in Southern Denmark	17.528	0.09	287
69. Large cattle farm in Central Jutland	22.310	0.05	232
70. Large cattle farm in North Jutland	8.492	0.02	155
71. Large pig farm in Capital Region	0.127	0.14	12
72. Large pig farm in Zealand	27.268	0.21	57
73. Large pig farm in Southern Denmark	20.093	0.22	148
74. Large pig farm in Central Jutland	21.572	0.23	176
75. Large pig farm in North Jutland	9.383	0.26	100

Note: Land availability was calculated by the authors based on data from Nielsen et al. [36] and Statistics Denmark [49,50] as described in section 3.7. Per hectare sequestration coefficients were calculated from Taghizadeh-Toosi and Olesen [31] as described in section 3.2. Number of farms is from Statistics Denmark [49].

Table A3. Percentage change in the sequestration output when parameters are decreased or increased by 10% relative to baseline values and using carbon price of 400 €/tCO_2e, model with transaction costs.

Parameter	10% increase	10% decrease
Scale parameter o transaction cost function (k)	−3.8 %	5.1%
Sequestration coefficient (s_i)	15.8%	−15.7%
Exponent in sequestration function (α)	27.8%	−30.4%
Per hectare cultivation cost (c)	−5.72%	<0.1% change
Per hectare cultivation cost (c_i) of tiny farms	<0.1% change	<0.1% change
Per hectare cultivation cost (c_i) of small farms	<0.1% change	<0.1% change
Per hectare cultivation cost (c_i) of medium farms	<0.1% change	<0.1% change
Per hectare cultivation cost (c_i) of big farms	−1.6%	<0.1% change
Per hectare cultivation cost (c_i) of large farms	−4.0%	5.2%

Appendix B

To calibrate the transaction cost function, we consider Equation (B.1) that follows, equal to Equation (3) in the above manuscript.

$$T_i = kS_i^{\beta}. \tag{B.1}$$

Dividing by sequestration (S_i), we obtain Equation (B.2) below:

$$\frac{T_i}{S_i} = kS_i^{\beta-1}. \tag{B.2}$$

We now turn to the regressions estimated by Phan et al. [42]. Using results from a survey with forestry project developers, the authors estimate how establishment costs (in USD/tCO_2e) are determined by project characteristics, including sequestration (in tCO_2e/ha*yr). They estimate Equation (B.3) as follows:

$$\frac{T_i}{S_i} = p + g*\frac{S_i}{A_i}, \tag{B.3}$$

where p is the sum of the coefficients estimated for the controls included by the authors, i.e.: Project duration (years), Co-objectives (yes = 1), Sale of carbon credits (yes = 1), Past experience (yes = 1), Farmers as land users (yes = 1), Land owner is land user (yes = 1), Foreign funders (yes = 1), Mixed funding (yes = 1), Developer's number of roles, Market type (CDM = 1), Latin-America (yes = 1), External TCs (yes = 1). Considering a project duration of 1 year, no co-objectives, no sale of carbon credits, no past experience, no landowner as land-user, not Latin America, 0 number of roles for the developer and non-CDM market type, with domestic funders only and farmers as land users, p will be equal to 12.122. The parameter g represents the increase in per ton of carbon transaction costs for an increase in 1 tCO_2e per hectare, and is estimated to be 0.012 by Phan et al. [42][15].

We can thus equate Equation (B.3) to Equation (B.2):

$$\frac{T_i}{A_i} = p + g*\frac{S_i}{A_i} = kS_i^{\beta-1}. \tag{B.4}$$

Differentiating both sides of Equation (B.4) with respect to sequestration (S_i) we will have that:

$$\frac{g}{A_i} = k(\beta-1)S_i^{\beta-2}. \tag{B.5}$$

Phan et al.'s [42] data is based only on establishment costs of forestry projects in Latin America, Asia and Africa, hence it is necessary to calibrate the transaction costs function so that it is pertinent for the context of our study. For that, we use the study by Mettepenningen et al. [14], that finds farm reported transaction costs for labor hours and operational and administrative costs to be 54.23 €/ha[16] on average for agri-environmental schemes in Europe. We can substitute this data into Equation (B.1) as follows:

$$54.23 = k*S_i^{\beta}A_i^{-1}, \text{ or } 54.23 - k* S_i^{\beta}A_i^{-1} = 0. \tag{B.6}$$

We can now have two Equations (B.5) and (B.6) that illustrate the desired behavior of the transaction cost function in relation to the marginal and average transaction costs, respectively. Assuming $\alpha \neq 1$, we can re-write Equation (B.5) as:

$$k = \frac{g}{(\beta-1)}\frac{S_i^{2-\beta}}{A_i}. \tag{B.7}$$

Substituting Equation (B.7) into Equation (B.6) yields:

$$54.23 = \frac{g}{(\beta-1)}\frac{S_i^{2-\beta}}{A_i}*S_i^{\beta}A_i^{-1}, \text{ or } 54.23 = \frac{g}{(\beta-1)}\frac{S_i^2}{A_i^2}. \tag{B.8}$$

Solving for β, we have that:

$$\alpha = \frac{g}{54.23}\frac{S_i^2}{A_i^2} + 1 \tag{B.9}$$

Assuming A_i equal to 3.62, which is the average area potentially available for cultivating cover crops in Denmark per farm, and S_i equal to 3.62 times 0.33, the latter being the average sequestration provided by cover crops in tCO_2e as calculated from Taghizadeh-Toosi & Olesen [31], and substituting the value g for 0.012 from Phan et al. (2016), we can find the value of α that solves the system:

$$\alpha = \frac{0.012}{54.23}\frac{1.19^2}{3.62^2} + 1 \cong 1. \tag{B.10}$$

Substituting back to Equation (B.7), we will have $k \cong 159$.

Therefore, in the empirical context of our analysis, we model transaction costs with α equal to one and using the parameter value of 159 for the scale coefficient k, as presented in the methods section of this paper.