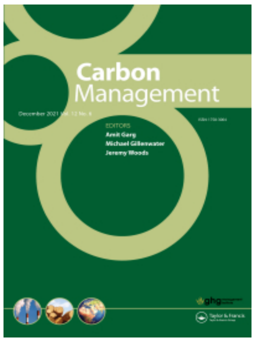

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Offset ratios and temporary contract designs for climate integrity in carbon farming

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ABSTRACT
In this study, we examine how to enhance the climate integrity of carbon credits from carbon farming practices. The key requirements for climate integrity include permanence, additionality, and measurement and verification. Farmers are typically willing to make carbon contracts for a finite time only in voluntary markets or with the government and receive carbon credits to sell as offsets. This contradicts the requirement of the permanence of carbon sequestered in soils. To solve this problem and to facilitate greater participation by farmers in carbon sequestration, we show how temporary contracts can be made to address the issue of permanence by using offset ratios. The notion of the offset ratio refers to the share of one emission unit that one unit of temporary sequestered carbon replaces. Thus, the offset ratio transforms temporary sequestration to permanent emissions reductions. We propose the use of a discounting method to calculate the offset ratio. The ratio varies with the carbon contract length, employed discount rate, and assumptions about the evolution of the soil carbon stock. We apply this approach to cultivating catch crops for carbon sequestration on a north–south gradient in Finland, Denmark, and France. We show that the offset ratio approach works well for every selected country. Carbon farming contracts are profitable for farmers provided that revenue under the contract exceeds that in the baseline. Profitability is highly dependent on catch crop cost, annual increase in soil carbon, and the discount rate. We apply offset ratios to assess the climate integrity of some existing crediting programs and find that the discounting method yields a lower offset ratio in almost all cases yielding a lower number of credits than launched in these programs.

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Introduction

Agriculture is currently a considerable source of greenhouse gas (GHG) emissions but can potentially contribute greatly to climate change mitigation. Agriculture is responsible for ∼12% (6.2 $GtCO_2e$/y, CO_2e = carbon dioxide equivalent) of total anthropogenic GHG emissions globally [1]. Its share increases to ∼21% (14.1 $GtCO_2e$/y) when land use and land-use changes driven by agricultural activities are taken into account [1]. In recent years, carbon farming has been proposed in global agendas as a promising mitigation practice. The global technical potential of soil carbon (C) sequestration ranges between 2.3 and 5.3 $GtCO_2e$/y [2]. The "4 per 1000" initiative adopted at COP 21 targets a yearly 0.4% increase in global soil organic carbon (SOC) stock, focusing on agricultural soils [3,4], while local policies, such as those of the European Commission aim to create incentives for carbon farming and the certification of C removal in the agricultural sector [5].

A recent EU handbook on carbon farming [6] states that carbon farming generally refers to the active management of all C pools, flows, and GHG fluxes (CO_2, CH_4, and N_2O) at the farm level from both land and livestock, with the explicit purpose of mitigating climate change. This handbook identifies C sequestration on mineral soils, rewetting organic soils, agroforestry, and livestock as the main thematic areas for carbon farming [6]. Thus, we employ the following working interpretation of carbon farming in this paper. *Carbon farming refers to agricultural management practices or land-use changes that sequester C from the atmosphere in agricultural soils or prevent soil C release from these soils to the atmosphere—both of which are defined in net terms; that is, possible changes in GHG fluxes*

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due to these practices or land-use change are considered cobenefits or codamages.

The increased interest in carbon farming has until recently reflected a response by farmers to the increasing demand for carbon credits by food processing companies to offset their emissions to achieve carbon neutrality (see, e.g. [7,8]). A recent agreement on the Green Claims Directive in the EU limits the use of climate neutrality claims considerably [9], but its effect remains to be seen. Nevertheless, voluntary activities may have a more significant role than government policies. For instance, the Common Agricultural Policy (CAP) of the EU has thus far only weakly incorporated climate mitigation issues (e.g. [10]). In other parts of the world, several voluntary carbon credit programs (see, e.g. [11–13]) already reward agricultural management practices that promote climate change mitigation. In 2022, the transaction volume of voluntary carbon offsets from agriculture was ~3.8 MtCO_2e, and the growth in the volume compared to the previous year, 283%, exceeded that of all other sectors [14].

By nature, carbon farming practices usually provide only temporary C sequestration. However, the treatment of permanence in the existing programs is insufficient, as they do not cope well with temporary contracts. Previous literature focusing on voluntary offsetting within compliance markets, such as the Compliance Offset Program in the California Cap and Trade Program, demonstrates a concern for overcrediting because of inflated baselines, nonadditional projects, and perverse incentives to increase emissions [15–18]. These worries are equally important for purely voluntary markets from the perspective of climate integrity, as identified in the literature [17]. Therefore, our overarching research question is how to ensure the climate integrity of offsets from temporary contracts on agricultural practices as an incentivization mechanism for carbon farming. Noting that other mechanisms, such as activity- and area-based payments also exist, here, we focus solely on offsets provided through a carbon contract. Another issue related to offsetting is how to design market institutions to effectively promote offsetting, but this aspect falls outside of our analysis. We condense the main principles for climate integrity in agriculture, focusing on the question of permanence. We use offset ratios to address temporary sequestration, and for this calculation, we propose the use of a discounting method. The offset ratio transforms temporary sequestration to permanent emissions reductions.

We illustrate our approach using catch crops (also known as cover crops) as a case study. Catch cropping is an old practice but its role as a climate mitigation means has recently attained more attention. The average annual C sequestration potential of catch crops is globally estimated to ~0.32 tC/ha (see, e.g. [19,20]). Catch crops are currently widely used to produce voluntary carbon credits. Large companies, such as Bayer [21] and Cargill [22], have recently established carbon farming programs to offset their own emissions, also mentioning catch crops as one potential measure. The Australian Emissions Reduction Fund allows for soil C sequestration and reduction of CH_4 emissions in agricultural systems to obtain Australian carbon credit units [23]. The Humusaufbau-Projekt of the Ökoregion Kaindorf in Austria aims to increase C sequestration in agricultural soils by allowing for firms to buy CO_2 certificates from farmers [13]. Indigo, Nori, Agoro Carbon Alliance, Bayer Carbon, and Corteva, among others, promote carbon sequestration in the U.S. (see [11] for a closer analysis).

However, as Smith et al. [24] emphasize, if practices that retain C are not maintained, there is a risk of reversibility of C sequestration. Therefore, carbon contracts must account for this aspect, and our approach on the offset ratio complies with this. To account for regional differences, we apply our approach to cover crops in three different climatic regions in Europe: Finland (boreal), Denmark (north temperate), and France (south temperate). Focusing on the north-south gradient allows us to examine the relation between carbon sequestration in soils *vis-á-vis* the state of soil carbon in arable lands and growing conditions (see, e.g. [25–28]). A global analysis of the SOC stock and the capacity to store more SOC shows that Finland and Denmark have both higher soil C content and saturation levels compared to France [29]. This suggests soil C sequestration could last longer in France.

The rest of the paper is organized as follows. Section Carbon farming and climate integrity: key issues describe the relation between carbon farming and climate integrity. Section The economic framework: contracts to deliver carbon credits from agriculture provide the economic framework used in the empirical case studies of catch crops in Section Empirical application: catch crops for C sequestration. We discuss the main results and their policy implications in Section Discussion. Section Conclusions provides our conclusions.

Carbon farming and climate integrity: key issues

The creation of incentives for carbon farming involves the problem of transforming the potentially large capacity for mitigation to feasible economic actions that also fulfill the requirements of climate integrity. It is relatively easy to indicate the basic requirements for ensuring the climate integrity of carbon farming at a general level. These criteria are similar to those originally developed to ensure climate integrity under the Kyoto Protocol's Clean Development Mechanism[1] and are often applied *mutantis mutandis* under various voluntary carbon crediting schemes. Carbon credits should be truly additional, verifiable, and ideally permanent (e.g. [30,31]). This section is devoted to further elaborating upon the key concepts of climate integrity for carbon farming at the farm level and within national boundaries.

Additionality, permanence, and verification at the farm level

One of the key requirements of climate integrity is *additionality*. Carbon credits are considered additional if GHG emission reductions would not have occurred in the absence of the project, which would not have taken place without the crediting mechanism. Defining additionality therefore requires the consideration of a *baseline scenario* indicating what would have happened without the project and revenue from the sales of carbon credits. This baseline scenario shows whether soil C (and/or GHG emissions) would decrease or increase over the chosen period under privately optimal management and prevailing market and policy conditions. The baseline scenario thus presents the most profitable management without the crediting mechanism. Nonadditionality and inflated baselines are identified as key sources for overcrediting in some existing voluntary programs (see, e.g. [15–18]). The FAO [32] suggests using a five-year baseline scenario, but the baseline may also be longer. This baseline is then used as the basis for estimating the amount of carbon credits generated by comparing the actual emissions/removals that occur after the project is implemented with estimates of emissions/removals that would have occurred in the absence of the project. For carbon farming, a natural starting point is a field parcel where the farmer produces credits and where the amount of C sequestration or emissions reductions need to be assessed. To produce carbon credits from soil C sequestration, a farmer must change land management practices in at least one field parcel, and the increase in soil C or reduction in emissions must be estimated against the baseline scenario and subsequently measured and verified.

Figure 1 presents our framework for additionality. The graph begins with the average C content of the topsoil in agricultural soils. Assuming a constant annual decrease in soil C content gives the linearly decreasing black baseline curve in Figure 1. When a carbon farming practice, such as catch crops, is adopted, we must compare the evolution of the soil C stock under the baseline and the new practice. The blue line indicates the evolution of the soil C stock under catch crops as a carbon farming practice, given that the annual increase in the soil C stock *via* catch crops decreases annually by a constant rate (e.g. [33–36]). Note that even though the soil C stock decreases in the example with the carbon farming practice, the decrease is slower than that in the baseline treatment. The additional benefit from carbon farming is the gray-shaded area, i.e. the area between the baseline and the carbon farming curves.

In this context, it is important to consider the *project boundary*, which is also closely related to eligible activities and C accounting. Defining eligible management practices provides the possibility of restricting practices to those that have been demonstrated to be effective (such as technology choices and land-use decisions), as in some voluntary markets (see, e.g. [13]). Project boundaries define which emissions are accounted for and which are not considered in the net emissions calculations of a proposed practice. The consideration should be project- and practice-specific; it is important to include all emissions that are directly affected by the activity. An important part of defining project boundaries is

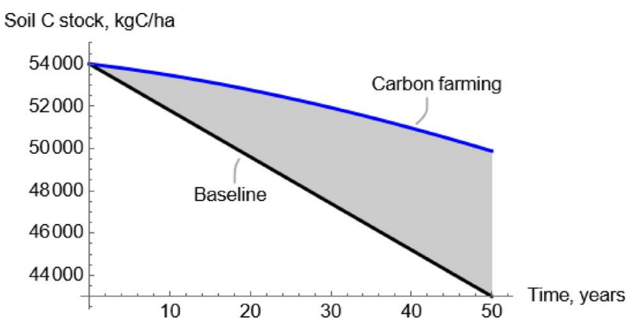

Figure 1. Example of the potential evolution of the soil C stock in a baseline scenario and with a carbon farming practice. The additional benefit from carbon farming is represented by the shaded area between the baseline and the carbon farming curves.

determining whether a project is likely to have unintended impacts on GHG emissions, for example, through *leakage* outside the project boundary, i.e. GHG emissions shifting elsewhere as a result of the carbon crediting scheme. Leakage at the farm level, called *slippage*, should also be prevented [37,38]. Farmers have multiple field parcels in production, and when allocating one parcel to carbon credit production, practices in other parcels may change toward more polluting practices. When the project boundary covers the entire farm, it ensures that net emissions reductions or net C sequestration at the field parcel also occur at the farm level.

Ensuring climate integrity also requires that emission reductions be subject to regular and reliable measurement, reporting, and verification (MRV; for recent reviews of MRV approaches to soil C changes, see Smith et al. [24] and Oldfield et al. [39,32]). Furthermore, there must be an efficient penalty for breaching a carbon contract (see, e.g. [40]). Given the heterogeneity of agricultural soils and practices, measurements may contain ambiguity and uncertainty. This can be taken into account by uncertainty ratios that require a reduction in emissions or C sequestration of more than 100% to give one credit. Such practices must be applied during the entire crediting period, and ideally, the results should be verified by an independent expert.

Finally, *permanence* is an important but challenging issue in the context of carbon credits issued on the basis of C sequestration. Ideally, sequestered C needs to remain in the soil for a long time, and the reduction in soil emissions must be long lasting. However, the devil is in the details; for instance, questions remain about what is considered long-lasting, whether C sequestered in soil will stay there forever or whether (and how quickly) it is released to the atmosphere, and how temporary sequestration should be handled. A widely used standard for permanence in the context of carbon crediting is that the sequestered C should remain in the soil for at least 100 years (see, e.g. [30,41]). However, market prices play an important role in the annual choices of crops and management practices, and farmers are not willing to commit to long-term agreements and prefer the flexibility to reorganize production at the farm level in response to changing market conditions (see, e.g. [42]).[2] Apart from receiving carbon credits and the direct profitability of a carbon credit contract, the co-benefits of carbon farming practices, such as increased soil fertility, soil health, and water holding capacity, as well as nonmonetary ecological benefits, might also play an important role in farmers' decision-making [45,46].

The poor feasibility of long contracts leads to demand for temporary carbon credits. For instance, the Australian Emissions Reduction Fund offers farmers two alternatives: 100-year and 25-year long permanence, with a contract of 15 years for avoided deforestation and 25 years for other sequestration projects [23]. In Austria, the Humusaufbau-Projekt of the Ökoregion Kaindorf requires at a minimum a 10-year permanence [13], while in the U.S., most contracts are for 5 or 10 years at the shortest, and including also a potential retention period [40]. Notably, producing temporary credits is also desirable for society: any delay in GHG emissions or early removal of C from the atmosphere is welcomed given that GHG emissions accumulate over time in the atmosphere. Temporary C sequestration may also trigger additional sequestration through improved crop yields if the soil quality improves. Therefore, societies should develop methods to account for the climate contribution of the delay in emissions or increase in early removals provided by temporary credits. In the case of voluntary carbon markets, society should establish offsetting rules to ensure full offsetting of buyers' emissions with temporary credits. The *offset ratio* determines how many emission units one carbon credit from temporary projects compensates. For voluntary carbon markets to develop, the additionality of credits and rules guaranteeing full offsetting are crucial, as they build the buyer's trust in trades.

Literature sources do not provide an unambiguous answer for the methods to use in estimating offset ratios (see, e.g. [47–51]). Possible methods to calculate the offset ratio include, for instance, discounting, biophysical discounting, and ton-year accounting. The ton-year accounting system utilizes the absolute global warming potential: "the cumulative radiative forcing over a given time horizon of a unit mass of GHG released to the atmosphere at one time" [48]. It was introduced to international climate policy within the Kyoto Protocol and is used in LULUCF projects (see, e.g. [48]). The ton-year accounting system includes various methods that all use the idea of radiative forcing. The two most commonly mentioned methods are the Lashof method and the Moura-Costa method. The discounting method ([49], *ex ante* discounting in Ref. [50]), accounts for the fact that increasing C sequestration or decreasing emissions today benefits mitigation more than if they happen in the future. In other words, the benefits or damages occurring in the future have less value than those occurring today. The *ex-ante* biophysical discounting proposed by Leifeld [51] accounts for the atmospheric CO_2 content and the longevity of sequestration relative to a permanent sink. In the following sections, we formalize the approaches and discuss their implications. We employ the discounting method, as it best reflects the economic and social aspects of climate change mitigation and enables the consideration of the longevity of carbon farming practices.

Voluntary mechanisms, markets, and national climate policy

When extending climate integrity considerations beyond the farm level, the question arises of how to ensure that no C leakage occurs *via* adjustments in agricultural markets by nonparticipating farmers as a response to possible changes in crop prices caused by carbon farming. A voluntary carbon market emerges through the actions of suppliers and demanders. This market may emerge even if there is mandatory national climate policy toward agriculture provided there is private demand for carbon credits, but the market will be larger if mandatory policies are absent or lax. By definition, the voluntary carbon market comprises a share of farmers but not all. This feature may create C leakage if the voluntary production of carbon credits leads to a reduced supply of agricultural products. A reduced supply increases prices, and thereby, farmers increase production intensities and possibly land area available for cultivation, both of which increase GHG emissions. This possibility may arise, for instance, if a greater land area is set aside for grasslands or forests and if the prices of cereal crops increase. For instance, in the Compliance Offset Program in the California Cap and Trade Program, leakage in forestry-based projects reached levels as high as 80% [52], and in the Conservation Reserve Program in the U.S., which is aimed at reducing soil erosion and improving water quality, leakage is estimated to constitute 20% of the conserved area [53]. Voluntary markets should be designed so that they generate extra credits to counteract leakage if it is assessed as a relevant risk. Leakage would be absent or minor under a well-designed mandatory policy comprising all farmers. However, efficient carbon policies in agriculture have been rare thus far. For example, in the latest U.S. farm policy revision, the 2018 Farm Act, ~7% of the total outlay ($428 billion) was allocated to conservation programs [54], but climate change mitigation or adaptation were not mentioned as issues relating to agriculture [55] (for the EU, see, e.g. [10]).

An additional issue related to climate integrity at the national level is double dipping, when farmers receive double payments for a single practice [38]. For instance, farmers in the EU may receive a CAP payment for using catch crops. Given that catch crops sequester C, farmers may sell carbon credits and receive a second compensation. Thus, the question is whether society would accept selling credits from management practices that receive CAP support payments, that is, whether double dipping is questionable from an additionality perspective. In the following sections, we provide a numerical analysis of the features discussed above.

The economic framework: contracts to deliver carbon credits from agriculture

A contract to provide carbon credits lies at the heart of both voluntary carbon markets and national agricultural policy. Following Antle et al. [56], we develop a contract model for C sequestration, but the framework equally fits the reduction in GHG emissions below a given baseline. The farmer makes carbon contracts either with a manager of the voluntary market or with the government.

Consider the amount of C in the soil in any field parcel j, which depends on local biological and physical variables and the cultivation history. Thus, we define C_j^i as the C storage of soil (tC/ha) in this field under management practices i and C_j^s under management practices s. Assume further that a shift from practice i to practice s increases C storage in soil over time; thus, $C_j^s > C_j^i$. Define the annual average increase in soil C from this shift, denoted by Δc_j^{is}, with $\Delta c_j^{is} = (C_j^i - C_j^s)/X$, where X denotes the period of time when the C increase is saturated. If leakage is expected to occur at the national or market level, precautionary measures suggest scaling down the expected C sequestration in each project to match the expected leakage. Once the potential carbon credits have been defined over the relevant set of practices, the nature of the contracts can be examined.

The contract may rely on two alternative payment types: hectare-based and ton-based payments; the former represents a practice-based payment, and the latter is a result-based payment.

A payment per hectare refers to a constant payment for each hectare in which the farmer adopts the C sequestering practice. Thus, this payment is based on an average estimate of C sequestration under the chosen practice, not the actual measured sequestration. The knowledge requirements under this payment are the following: information on previous management practices and new management practices, the length of the contract, and the size of the payment. *A ton-based payment* is related to actual sequestered C and its maintenance over time; it requires adequate measurement technology and has higher knowledge requirements. One must determine C storage in the baseline scenario, the contract length, the credit price, and the amount of C sequestration and predict its time path, and measure the evolution of soil C. Referring to the above notation, one needs to define the expected increase in the soil C, $E[\Delta c_j^{is}]$, and its time path.

Once the natural science requirements are known, the farmer must consider whether to promote C sequestration for carbon credits, given that a switch to C-sequestering cultivation practices causes some costs, at least in the short term. We adopt the following notation. Let $\boldsymbol{e}_j$ denote the environmental characteristics of the field, p_j denote the annual output price of the crop grown in the parcel, $\boldsymbol{w}_j$ denote a vector of annual input prices, $\boldsymbol{z}_{jt}$ denote capital services and r denote the real interest rate. Then, the net present value (NPV) of profits from practice i in field j at time t can be determined as $NVP_j^i = \sum_{t=1}^{T} D_t[\pi_j^i (p_{jt}^i, \boldsymbol{w}_{jt}^i, \boldsymbol{z}_{jt}^i; \boldsymbol{e}_j)]$, where $D_t = (\frac{1}{1+r})^t$. A change from management practice i to practice s may involve fixed costs, such as the acquisition of new machinery, as well as variable costs. Therefore, the farmer must determine the NPV of profits from practice s and payments for credits and compare them with the NPV of profits from management practice i. The NPV from carbon farming is given by $NPV_j^{is} = \sum_{t=1}^{T} D_t\left[\pi^s\left(p_{jt}^s, \boldsymbol{w}_{jt}^s, \boldsymbol{z}_{jt}^s; \boldsymbol{e}_j\right) + g_j^{is}\right] - I^{is}$, where g_j^{is} is the payment to carbon credits and I^{is} is the required investment in management practice s. Assuming C is sequestered permanently and depending on the type of carbon payment, the farmer receives $g_j^{is} = PE[\Delta c_j^{is}]$ under a per-ton agreement, where P is the per-ton credit price, and $g_j^{is} = g$ under a per-hectare payment (i.e. constant).

If the sequestration is temporary, we need to change the carbon payment by modifying the expected C sequestration $E[\Delta c_j^{is}]$. Permanence was required to ensure that credits were comparable to a reduction of one unit of GHG emissions. If the contract is made for a short period, T, this must be taken into account through the offset ratio to ensure the climate integrity of offsetting. The offset ratio can be determined by assessing the climate benefits of temporary removals. This assessment crucially depends on what happens to soil C when the contract ends and when farmers may switch to other management practices. There are multiple possibilities, ranging from a quick release to the atmosphere to a permanent increase in soil C, making this an empirical question that we focus on in the next section. A good carbon contract takes the process of release into account. Nonetheless, an immediate release of all sequestered C is not realistic; thus, we consider only gradual release in the following analysis. For the analysis, we define temporary credits with the help of the offset ratio, denoted by $\phi(T, \theta)$, which is a function of the contract length, T, and the (possible) uncertainty factor, θ. Thus, the amount of temporary credits is given as $\phi(T, \theta)E[\Delta c_j^{is}]$.

The farmer makes a contract to produce carbon credits if $NPV_j^{is} \geq NPV_j^i$ (note that in the absence of crediting, the farmer would have $NPV_j^s < NPV_j^i$, showing that practice s would not be elected without the crediting). If no investment is needed, the analysis simplifies to a comparison of annual profits, and the farmer makes an agreement if $\pi_j^s + g_j^{is} \geq \pi_j^i$. This condition requires that the carbon payment be sufficiently high, that is, $g_j^{is} \geq \pi_j^i - \pi_j^s$. In the case of equal profits, the farmer remains indifferent whether to have a contract. A look at the indifference relation of the NPVs suggests that higher carbon prices and higher prices of crops under management practices s increase the profitability of carbon farming, while higher input costs for practice s and higher crop prices under practice i decrease the profitability of carbon farming. For permanent credits, the real interest rate has no effect on the comparison, as it is equal for both management practices, but it matters for temporary credits through the calculation of the offset ratio (as shown in Section Offset ratio and determination of the amount of carbon credits).

Overall, the model outlined here is instructive and simple. However, many details impact the choices. To this end, we next carry out a numerical analysis to present and discuss the crucial features.

Empirical application: catch crops for C sequestration

We apply the framework in three countries and consider ordinary cultivation, adding to it as a new practice the use of catch crops to promote C sequestration. Thus, the payment is levied on the annual increase in soil C above the baseline. Furthermore, we follow IPCC's accounting rules, which omit C embodied in harvested agricultural yields and emissions from food and focus on net emissions from soil and cultivation practices in addition to soil C [57]. For a net climate benefit, all emissions need to be accounted for, including CO_2, N_2O, and CH_4 as CO_2e, as well as soil emissions and emissions from management practices. To keep the analysis as clear as possible, we assume that farmers sow and end catch crops as an integral part of the field operations related to the main cultivated crop. This means that emissions from management practices are unaffected by the use of catch crops. Furthermore, emissions from catch crop seed production are assumed to be insignificant. Thus, the only change in net emissions results from the change in soil C due to catch crop cultivation. The main crop is barley (cultivated in monoculture with no-till), and Italian ryegrass is used as a catch crop as one of the main species used in Europe [58]. For all the countries, we focus on mineral soils, which are the most suitable for carbon farming. Keeping in mind the requirement of the permanence of sequestered C, we consider contracts of varying lengths, the maximum being 30 years. The chosen range covers the minimum projection of 20 years to predict changes in soil C in the project and the baseline recommended by the FAO [32]. We focus on a ton-based payment but ultimately calculate payments as €/ha, which is comparable with a payment per hectare scheme in terms of the profitability for the farmer.

Soil C stock development

In Finland, the postulated annual increase in the soil C stock after introducing catch crops to barley monoculture under no-till on mineral soils is 175 kgC/ha [59]. For Denmark, the annual increase in soil C stock is 258 kgC/ha ([20], based on [60]), and in France, it is 166 kgC/ha (based on [20,61]). The C stock increase rate declines with time (see, e.g. [30,62]) because the amount of C in the soil saturates over time. In economic terms, the marginal benefit from the contract decreases over time. The saturation level of soil C is likely not reached within 30 years after a management change, which is the longest contract period considered, but the sequestration rate declines over time by at least 1% annually [33–36]. Based on the differences between soil C stock and the capacity to store more C in global and regional studies [29,63], the below calculations use 3% as the annual reduction in soil C increase for Finland and Denmark and 1% for France. Note, however, that these values rely only weakly on literature but nevertheless demonstrate differences in the sequestration potential and soil properties in the three countries. Using varying rates allows us to showcase the effects on the offset ratio and on the profitability of a carbon credit contract.

We also assume (as a safety principle to avoid overestimating the climate benefit) that once the contract ends, the farmer returns to the baseline management, which is barley monoculture without catch crops. Once the contract ends and management practices change, the soil C stock starts to gradually decrease back to its baseline level. Given the uncertainty of C release because of management changes (e.g. [64]), we consider three alternatives for C stock development, where the increase and decrease in soil C stock are otherwise symmetrical but the pace of the decrease in comparison to the increase changes.[3] In the basic case, the soil C stock decreases back to the baseline level at the same rate and period as it increases (i.e. the release of C to the atmosphere takes as long as the contract has length). In the second case, the C stock decreases more rapidly—in half the time of the increase. In the third case, the reduction is slower, taking twice as long as the increase. These three assumptions are identical for all the case studies. The estimated delay in the decrease in soil C back to the baseline affects the contract terms for the farmer. Figure 2 presents these three cases. We study how these three cases affect the offset ratio and thus the profitability of the contract for the farmer.

With respect to additional soil C stock development above the baseline, credits can be generated in different ways. We could use the absolute annual increase in stock, which varies and decreases over time, or an average of the annual increases during the contract period. An average annual increase gives a constant flow of credits, meaning a constant flow of credit revenue. An annual constant revenue is not mandatory but simplifies the calculation considerably. Using the average additional annual stock increase means, in practice, overcrediting at the beginning of the contract and undercrediting at its end. Another aspect to consider is whether credited sequestration is obtained only from the strict increase in soil C stock or whether the cumulative stock increase during the contract is credited. If only the absolute annual increase is chosen (used in Ref. [32]), the amount of credits would be small, and thereby, credit revenues for the farmer would be negligible. Crediting the cumulative stock also essentially means rewarding C stock maintenance, which is beneficial for climate change mitigation, as emissions are delayed. In this article, the basis for the annual credit amount is the average annual cumulative C stock (the area under the black "Additional C stock increase" curve divided by contract length; see Figure 2; note that this is equivalent to the shaded area in Figure 1). This value (and credit amount) is independent of the additional C stock decrease rate, as it is defined solely based on the stock increase. Table A1 in Appendix A presents the average annual cumulative soil C stocks with different contract lengths. The average annual cumulative soil C stock increases with longer contracts (due to the cumulative calculation) and with a slower annual reduction in the annual stock increase. CO_2 emissions are given in parentheses in Table A1 to facilitate easy comparison with the forthcoming results.

Note that the values in Table A1 imply that C is sequestered to the soil due to catch crops, as presented in Figure 2, and that the field is managed in a way that prevents sequestered C from being released back to the atmosphere (i.e. no plowing). To account for any possible C releases during the contract, one could use as an example a ratio of 10%, denoting that 90% of the values in Table A1 constitute the net increase in the soil C stock.

Offset ratio and determination of the amount of carbon credits

The actual credit quantity is calculated from the average annual cumulative C stock due to catch crop inclusion by multiplying it by the offset ratio (term $\phi(T,\theta)E[\Delta c_j^{is}]$ in the economic framework). The offset ratio corresponds to the requirement of permanent sequestration and translates temporary sequestration to temporary contracts. It defines how many permanent credits (1 tCO_2e/credit) can be offset with one credit produced within the contract ($\leq$1). The inverse of the offset ratio defines how many carbon credits from temporary projects are needed to compensate for one unit of emissions. The shorter the contract is, the more credits are needed. For a 100-year contract, the offset ratio approaches the value of 1, indicating that permanence requires 100 years of contracts or maintenance of sequestered C, just as is required for voluntary carbon projects in the Compliance Offset Program in the California Cap and Trade Program [41]. To calculate the offset ratio, we use the discounting method but also briefly discuss how these values differ from those obtained with the ton-year accounting system. We subtract the discounted sum of annual stock decreases from the discounted sum of annual stock increases and divide this by the discounted sum of the annual stock increases. The offset ratio can further be expressed as one minus the share of the discounted sum of the annual stock decreases over the discounted sum of the annual stock increases (Equation 1). This approach is similar to that presented by Gulati and Vercammen [65], who emphasize that the payment should include the

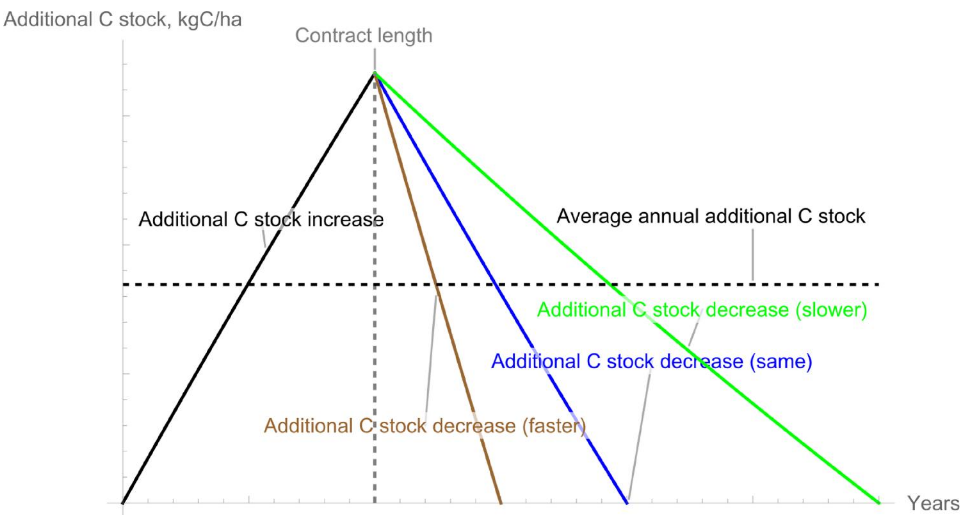

Figure 2. Example of the development of additional C stock (cumulative increase and decrease) due to catch crop inclusion during and after a contract with three alternatives for the stock decrease: same as the contract period, half of it or double it.[4]

positive value of accumulated C and the negative value of C released to the atmosphere during the post-contract period.

We denote the annual soil C stock increase by c (c is set to 175 kgC/ha for Finland, 258 kgC/ha for Denmark, and 166 kgC/ha for France). Further, we account for the annual reduction in this increase by a multiplier $(1-q)^t$, where q denotes the annual growth decrease (1 or 3% as 0.01 and 0.03, respectively) and t denotes time (starting from the beginning of the contract). Similarly, the annual reduction in the soil C stock after the contract period is denoted by $\hat{c}(T, \hat{T})$. When the contract ends and the annual stock decreases, its rate depends on the size of the accumulated C stock (which depends on the contract length, T) and whether the stock decreases at the same rate as or slower or faster than the increase; $\hat{T}$ is the time in which the C stock returns to the baseline after the contract ends. Thus, the offset ratio is dependent on the assumptions of the evolution of the soil C stock changes after the actual contract ends. Finally, r is the real discount rate (3%). The offset ratio is calculated as follows:

$$\phi(T,\theta) = \left(1 - \frac{\int_T^{T+\hat{T}} \left[\hat{c}(T,\hat{T})(1-q)^{t-T}(1+r)^{-t}\right] dt}{\int_0^T \left[c(1-q)^t(1+r)^{-t}\right] dt}\right) * \theta \quad (1)$$

When T increases, the offset ratio approaches unity, and one ton of sequestered C fully offsets one unit of emissions. Assuming that the discount rate is the same, do offset ratios differ between countries? The answer depends on parameters c, $\hat{c}$, and q, that is, on sequestration during the contract and release of soil C after the contract ends.

Table 1 lists the offset ratios in all three countries. The table shows that the offset ratio increases with contract length and discount rate and with a slower decrease in stock relative to the increase in stock. A slower stock decrease is beneficial for climate mitigation, as it delays emissions, resulting in a higher offset ratio and thereby a greater credit amount. A higher discount rate places less emphasis on damage occurring in the future from released C, thus giving a higher offset ratio. Therefore, a higher discount rate leads to a higher return on the credit supplier. Note that with a lower discount rate, the offset ratio does not approach unity within 100 years. Differences between the three countries result from the differences in the evolvement of soil C. As the annual increase in soil C due to catch crops decreases faster in Denmark and Finland relative to France, also the offset ratio is lower in Finland and Denmark assuming an equal discount rate.

Equation (1) also includes the uncertainty factor θ, which has a value of $0 < \theta \leq 1$. The uncertainty factor facilitates the accounting of case-by-case uncertainties. These uncertainties range from the accuracy of measurement of C sequestration and emission fluxes across soil types and regions. Furthermore, they help in taking into account the effects of stochastic variations in weather conditions on soil C accumulation. In Table 2, we assume no uncertainty and set θ equal to one. If some uncertainty is accounted for, θ is <1, which reduces the amount of credits obtained from the contract.

Calculating offset ratios with the ton-year accounting system would result in either higher or lower values depending on the chosen method (calculated based on [48]). The Lashof method, which focuses on the benefit of delayed emissions, yields considerably lower offset ratios than does the discounting method (e.g. the offset ratio is only 0.07 for a 10-year contract while the discounting method yields 0.256), although the offset ratio approaches the value of 1 with a 100-year contract in both methods. The Moura-Costa method considers removing and storing 1 tC for 48 years to be equal to avoiding 1 tC pulse emissions (i.e. an offset ratio of 1 for a 48-year contract and ~2 for a 100-year contract), thus yielding considerably

Table 1. Offset ratios for all three countries (decrease in the annual soil C increase 1% for France and 3% for Denmark and Finland) for contract lengths up to 100 years with a 3% discount rate, and sensitivity results for different discount rates (1 and 5%) when the increase and decrease rates are equal.

	Contract length, years					
	5	10	15	20	30	100
1 or 3%, same decrease	0.137	0.256	0.358	0.446	0.588	0.948
1%, faster decrease	0.106	0.202	0.290	0.370	0.506	0.927
1%, slower decrease	0.195	0.346	0.464	0.558	0.691	0.961
3%, faster decrease	0.107	0.205	0.296	0.379	0.522	0.940
3%, slower decrease	0.192	0.337	0.447	0.533	0.657	0.950
Sensitivity, discount rate 1%	0.049	0.095	0.139	0.180	0.258	0.630
Sensitivity, discount rate 5%	0.216	0.386	0.519	0.623	0.769	0.992

Table 2. Annual credit amounts in kgC/ha (and $kgCO_2e$/ha) for contract lengths up to 30 years with a 3% discount rate (decrease in the annual soil C increase 1% for France and 3% for Denmark and Finland).

	Contract length, years				
	5	10	15	20	30
Finland	59 (217)	217 (794)	447 (1640)	731 (2681)	1399 (5131)
Denmark	87 (320)	319 (1171)	659 (2418)	1078 (3953)	2063 (7565)
France	56 (206)	205 (753)	424 (1556)	694 (2543)	1327 (4867)

greater offset ratios than the discounting method (giving 0.758 for the 48-year contract) or the Lashof method (giving 0.38).

The above discussion shows that for temporary carbon credits, there is no unique way of determining the offset ratio. Therefore, offsetting rules are not unique or determined solely by science but are partly subject to social consideration. Irrespective of the chosen method, the offset ratio enters the credit revenue calculation as a contract-specific value, depending on the contract length and stock development assumptions, and thus directly affects the farmer's revenue from the contract.

The annual credit amounts to the farmer presented in Table 2 and with details in Table A2 in Appendix A are obtained by combining the annual average cumulative soil C stocks from Table A1 and the offset ratios from Table 1. CO_2-equivalent emissions are given in parentheses to facilitate the determination of potential revenue, as the carbon price is usually given for CO_2-equivalents. The results highlight that the realized annual credit amounts received from short contracts are small and vary between 43 and 118 kgC/ha for 5-year contracts in all three countries. These tables make it evident that annual credit amounts increase strongly with contract length. A comparison between 5- and 30-year-long contracts shows that the increase is 16- to 27-fold. As discussed above, the use of other calculation methods for the offset ratio directly affects these values.

Credit revenue and profitability of C sequestration

The profitability of providing temporary carbon credits through catch crop cultivation depends on the difference in profits between barley cultivation with and without catch crops (and with no carbon credit contract) ($\pi_j^i - \pi_j^s$ in the economic framework). This cost difference sets the minimum level for the annual credit revenue for a profitable carbon contract. We now numerically illustrate the dependency of profits on the carbon price and contract length. In the case studies, the only additional costs related to catch crops are assumed to be the seed costs. Possible national subsidies for catch crops are omitted. Thus, it is sufficient to compare annual credit revenue to the annual catch crop cost. In Finland, the additional cost is 77 €/ha.[4] For Denmark, the additional cost related to catch crops is 41 €/ha,[5] and for France, the cost is set to 57 €/ha.[6] Note that this profit difference or additional cost varies between countries, years, and individual farms. Here, the additional costs presented are used as a benchmark to illustrate contract profitability and the effect of different choices and assumptions on profitability. The differences in the cost estimates result likely from varying market conditions and possibly varying cost items included in the different sources.

The annual credit revenue of a carbon contract is calculated in terms of tCO_2e as follows: offset ratio × average annual cumulative soil C stock due to catch crops (tCO_2e/ha) × credit price (€/tCO_2e), giving the annual credit revenue in €/ha. Recall that the annual soil C stock increase due to catch crops was 175 kgC/ha for Finland, 258 kgC/ha for Denmark, and 166 kgC/ha for France. Drawing on these data and assumptions concerning the release of carbon from the soil after the contract, Table 3 compiles the annual credit revenues in different cases, while Tables A3–A5 in Appendix A presents the detailed results. The contract length and credit price combinations yielding a value exceeding the additional cost of catch crops define the cases in which the contract is profitable; these values are bolded in the tables.

Table 3 shows that a 5-year contract is never profitable in any country. A 10-year long carbon credit contract becomes profitable in Denmark by a carbon price of 50 €/tCO_2e and in France by a price of 80 €/tCO_2e but not in Finland under any considered carbon price. Surprisingly, in Finland, even a 15-year-long contract requires a very high carbon price. For the lowest credit price of 20 €/tCO_2e, a 30-year contract would be required in Finland and France while in Denmark a 15-year contract would suffice. To interpret these findings, note that the results are driven by the annual sequestration rate and the additional cost related to catch crops. In Finland, the cost is relatively high while the sequestration is relatively low. In France, the costs are lower but also sequestration is low. In Denmark, costs are low and sequestration is high. With a slower decrease rate for the annual

Table 3. Annual credit revenue (€/ha) with varying contract length and credit price.

		Contract length, years				
Country	Credit price, €/tCO_2	5	10	15	20	30
Finland	20	4	15	30	47	**85**
	35	7	26	52	**83**	**149**
	50	10	37	74	**118**	**213**
	80	17	59	**119**	**189**	**341**
Denmark	20	6	22	**44**	**70**	**126**
	35	11	38	**77**	**122**	**220**
	50	15	**55**	**110**	**174**	**315**
	80	25	**88**	**176**	**278**	**503**
France	20	4	15	31	51	**97**
	35	7	26	54	**89**	**170**
	50	10	38	**78**	**127**	**243**
	80	16	**60**	**124**	**203**	**389**

The increase and decrease rates for C stock are equal. The profitable combinations for farmers are bolded. Decrease in the annual soil C increase is 1% for France and 3% for Denmark and Finland.

soil C increase, additional combinations of contract length and credit price become profitable. If the initial annual C stock change turned out to be higher or if the additional cost related to catch crops was smaller, then shorter contracts and lower credit prices would also become profitable. We must emphasize, however, that the data are scarce.

We next focus on the NPVs of the countries. NPVs denote the present value of all future profits and costs during the duration of the contract. This value allows for comparison between baseline management and contracts with different specifications also in cases with investment costs. The NPV is calculated as follows: (annual credit revenue − annual additional costs related to catch crops) × $\frac{1-(1+r)^{-T}}{r}$, where T is the contract length and r is the discount rate. Table 4 presents the results for all countries, while Tables A6–A8 in Appendix A present sensitivity results relative to the discount rate for the Danish case. Bolded values indicate a positive value, i.e. a profitable contract for the farmer. With positive values, the NPV increases as the contract length or credit price increases, and as the annual C stock decrease becomes slower. If the annual net revenue comprising credit revenue and catch crop cost is negative, having a longer contract can make the contract more unprofitable. Table 4 repeats the results obtained from Table 3. The discount rate plays an interesting role in profitability (see Tables A6–A8 in Appendix A). In general, a higher discount rate should decrease the NPV as future revenues are valued less. In our case, a higher discount rate increases the offset ratio considerably. This increases annual credit revenues and thereby the NPV of the net revenues from the contract.

Table 4. NPV of annual credit revenue subtracted by the annual cost related to catch crops (€/ha) with varying contract length and credit price.

		Contract length, years				
Country	Credit price, €/tCO_2	5	10	15	20	30
Finland	20	−333	−530	−564	−443	**164**
	35	−319	−435	−297	**84**	**1418**
	50	−305	−340	−31	**611**	**2673**
	80	−276	−149	**502**	**1665**	**5182**
Denmark	20	−161	−166	**30**	**420**	**1654**
	35	−140	−26	**423**	**1196**	**3504**
	50	−119	**114**	**815**	**1973**	**5354**
	80	−76	**395**	**1601**	**3527**	**9053**
France	20	−243	−359	−311	−94	**787**
	35	−229	−263	−33	**473**	**2218**
	50	−215	−167	**246**	**1041**	**3649**
	80	−187	**26**	**803**	**2176**	**6511**

The increase and decrease rates for C stock are equal. Positive values indicate profitable combinations for farmers, and these are bolded. Decrease in the annual soil C increase is 1% for France and 3% for Denmark and Finland.

Figure 3 illustrates the results in Table 4. The crossing point on the horizontal axis denotes the year in which the given contract becomes profitable. The figure clearly shows the differences in the profitability of contracts between the three countries (see Figure 3(a)). In Denmark, the required contract length is the shortest due to the highest annual increase in soil C and the lowest cost related to catch crops. In Finland, the modest increase in soil C and the highest catch crop cost result in the longest contracts required. Figure 3(b) presents the NPVs in the case where the catch crop cost would be equal among the three countries. Now, the differences are based solely on the annual soil C increase and the assumed decrease rate of this increase. The effect of a higher or lower discount rate is shown in Figure 3(c) for France. This clearly illustrates the effect of the discount rate on the offset ratio and thereby on the NPV. Figures 3(a–c), on the one hand, highlight the differences in the economic situation and mitigation potential between countries and climatic zones. On the other hand, they show how the offset ratio approach is applicable to varying circumstances. Note, again, that the results on the required contract length are highly sensitive to the additional cost for catch crops, both the seed cost and the applied amount of seeds per hectare. In favorable circumstances and with a high credit price, catch crops can become profitable for the farmer between 5 and 10 years.

A comparison of offset ratios to carbon crediting on some selected carbon programs

We next use the offset ratios from the discounting method to evaluate the permanence requirements and released credits in some existing crediting programs. We assess the offset ratios based on the contract length and the possible retention period after the contract period and on the possible reduction in credit amount due to the temporary nature of soil C sequestration. Australian Emissions Reduction Fund, Humusaufbau-Project, Bayer, and Cargill provide instructions and crediting principles that can be used to determine program-based offset ratios and we compare these to our applied discounting method. Table 5 presents the permanence requirements and the resulting offset ratios in these four crediting programs.

In the Australian Emissions Reduction Fund, the amount of credits is reduced by 20% if a 25-year permanence period is chosen over a 100-year permanence period [69]. This reduction is equal to an offset ratio of 0.8. Using our approach, a 25-year contract with the same soil C increase and decrease rates yields an offset ratio of 0.52 (see Table 1). Thus, by this approach credits should be reduced by 48% instead of the used 20%. The 100-year retention period with no reduction in the credit amount equals to an offset ratio of 1, while the discounting method gives an offset ratio of 0.95. For the Humusaufbau-Projekt of the

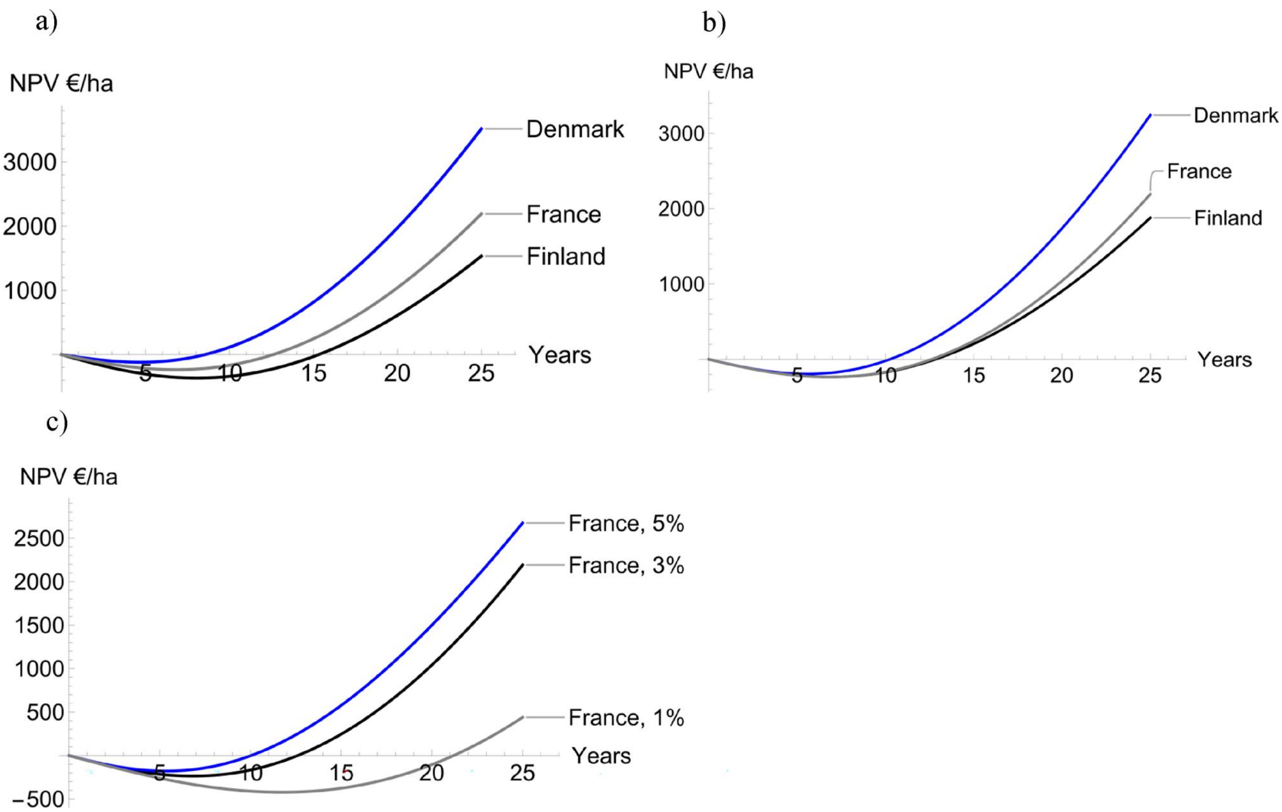

Figure 3. The net present value (NPV) of credit revenue subtracted by the additional cost related to catch crops (a) with a 50 €/tCO_2e credit price; (b) with a 50 €/tCO_2e credit price but with all countries having the same catch crop cost as France; (c) in France with varying discount rate and a credit price of 50 €/tCO_2e. The increase and decrease rates of the soil C stock are equal. Years denote the contract length.

Table 5. Comparison of offset ratios from selected programs based on the programs' permanence requirements and based on the discounting method.

		Offset ratio based on	
Program	Permanence	The program's permanence requirement	The discounting method
Australian Emissions Reduction Fund [23]	100 years with no reduction in credit amount	1	0.95
Australian Emissions Reduction Fund [23]	25 years with a 20% reduction in credit amount	0.80	0.52
Humusaufbau-Projekt [13]	5–7-year contract + a minimum of 5-year retention period (calculated as 10-year permanence); no mention of a reduction in credit amount	1	0.26
Bayer [70]	10-year contract + 10-year retention period (calculated as a 20-year contract); no mention of a reduction in credit amount	1	0.45
Cargill [71]	1-year contract; no mention of a reduction in credit amount	1	0.029

Ökoregion Kaindorf, a permanence of minimum of 10 years is required, but there is no mention of reducing credits [13], yielding an offset ratio of 1. In the discounting method, a 10-year contract would yield an offset ratio of 0.26, giving a striking difference. There is also no mention (at least in the public sources) of a credit reduction in the programs of Bayer [21,70] and Cargill [22,71], giving again an offset ratio of 1. The discounting method would yield an offset ratio of 0.029 for the 1-year contract of Cargill, and 0.45 for the 20-year permanence of Bayer. Thus, all considered programs give a higher number of credits than the discounting method. The only exception is when the program requires a 100-year permanence. We also note that the programs do not explain the grounds for their choices of offset ratios. Adopting the discounting method in these programs would decrease the number of credits produced, as well as the profitability for the credit supplier. Our recommendation to these programs is to reassess the applied offset ratios and also report explicitly how they have been determined.

Discussion

We examined how to enhance the climate integrity of offsets from temporary contracts on agricultural practices as an incentive mechanism for carbon farming. We suggested that offset ratios be derived using a discounting method and outlined general requirements concerning permanence, measurement and verification, and multiple dimensions of additionality. To examine the application of these principles, we used empirical examples to illustrate complexities relating to crediting carbon farming.

Climate integrity

The accuracy of C sequestration and GHG emission measurements is crucial for calculating these impacts, as emphasized in many studies (e.g. [24,62,72]). We acknowledge uncertainties in our case examples and note that much work is needed to increase the precision of estimates of the climate impacts of multiple management practices. Interfaces to meet the high information requirements are currently under development, such as that of the Field Observatory (fieldobservatory.org). However, it is possible that promoting carbon farming can create enhanced incentives to improve measurement technology to ensure that the goals of increased soil C are reached.

Our approach to carbon contracts creates a new angle to the permanence issue, namely, the determination of the status of temporary carbon credits. We introduced the offset ratio to indicate how much a share of one temporary reduction unit (C sequestered or GHG emissions reduced) offsets one unit of GHG emissions. This offset ratio is a function of the relative difference between the C stock increase and decrease, contract length, and the discount rate applied for the damage value when the reduction unit is released into the atmosphere. The damage depends on the speed at which C is released into the atmosphere, which is an issue that has seldom been studied. Furthermore, if the measurement uncertainty is regarded as high, the offset ratio can be adjusted accordingly.

There are several approaches to determine the status of temporary credits, which mostly converge at the same value in a 100-year horizon and under a 3% discount rate. However, these approaches lead to considerably different offset ratios for contracts between 0 and 50 years, indicating that social considerations enter the determination of offset ratios and the required C sequestration to produce one carbon credit. Discussion is needed to determine whether to favor higher or lower estimates for offset ratios because temporary contracts are very important for both voluntary markets and government policy. Approaches providing higher offset ratios may be preferable, as they promote carbon farming from the outset, whereas approaches with lower offset ratios can be defended from the standpoint of climate integrity. Our finding from a small set of crediting programs suggests that currently the applied offset ratios and authorized credits are high relative to those derived from applying the discounting method.

Note finally that the climate integrity of temporary carbon credits also depends on leakage, which presents a challenge, especially for voluntary carbon markets but possibly also for mandatory policies covering all farmers. A distinction can be made between market-induced leakage and leakage within a farm (slippage). Slippage can be prevented when the contract covers the whole farm. Project boundaries to prevent "local leakage" were suggested by Murray et al. [50]. Estimating leakage at the market level requires examination using a sectoral or even a more comprehensive model. The larger the boundaries of the voluntary system are, the lower the risk of leakage. However, connecting an increase in emissions to a specific carbon contract is extremely difficult.

One way to address the risk of leakage is through the collection of money for a "buffer fund" by increasing the credit price by a certain amount. Another possibility would be to impose another ratio in addition to the offset ratio, which would set aside a certain percentage of credits to be used as a "credit buffer". In the case of leakage or slippage, buffer funds could be used to buy credits, or credits from the credit buffer could be canceled. The FAO [32] recommends a 5% risk of reversal discount for soil C projects, while in voluntary programs, the required share of credits placed in a credit buffer often varies between 5 and 30% (see, e.g. [11,17,73,74]). Although most of these buffers are primarily used to mitigate possible reversals due to, e.g. natural conditions, they could also act as leakage/slippage buffers. The acceptable amount of slippage and leakage is also a political question: how large is the risk of reversed climate benefits that we are willing to accept as a society? Monitoring whole farms is expensive, but a "good enough" MRV system is required to create a market for carbon credits.

We only considered one practice for carbon farming, catch cropping on mineral soil, but the approach used here is applicable to other practices as well. When creating a market for carbon credits from agriculture, the first eligible practices, such as those studied in this article, should be well-known and tested. With the accumulation of experience, additional practices could be included. Depending on the country, current knowledge suggests that, for instance, agroforestry, deep-rooted crops, crop rotations, perennial crops, and different tillage practices would be good candidates, even though they were not studied in this paper. For all of the above practices, the core principles of climate integrity must be considered.

Economic feasibility

Carbon farming is an economically viable option only if it is profitable for the farmer. One of the most often mentioned reasons for not adopting catch crops among European farmers is the high cost compared to the benefits [58]. Determination of the offset ratio is crucial for facilitating temporary credit contracts between farmers and buyers (the government or companies). The profitability of carbon farming depends on multiple issues. From the climate angle, the amount of C sequestered through agricultural practices and the permanence (or speed of release) of sequestered C are crucial, as discussed above. For any given carbon price, more C sequestering practices and the slow release of sequestered C always yield higher revenue. Turning to prices and costs, for any given C sequestration rate profits increase with carbon prices and decrease with the costs of carbon farming practices. The discount rate plays an interesting role: a higher discount rate increases the offset ratio (by reducing the impact of future damage from released C) but decreases the value of future credit revenues, resulting in total to a higher NPV. This finding is in line with those of Gulati and Vercammen [65], who noted that a higher discount rate can make longer contracts profitable for the farmer.

The profitability of carbon contracts increases with contract length because the number of credits and social benefits from carbon farming increase strongly with contract length. This is especially important for cases in which only soil C is credited, as long contracts as well as high credit prices are needed. Adding changes in other GHG emissions to the amount of credit is justified from a climate integrity perspective, as it ensures that GHG emissions within the system boundaries are included. However, in our calculations, other GHG emissions were assumed constant when introducing catch crops. Whether farmers are willing to sign long-term contracts is an open question, as the literature suggests that they favor short-term contracts. For instance, Graming and Widmar [75] find that farmers in the U.S. Corn Belt region require greater compensation for multiperiod contracts (see also [42]). However, in general, using offset ratios would allow for more flexibility in contracts for catch crop adoption in terms of contract length, making shorter contracts a viable option in certain cases.

The presence of slippage and leakage challenges climate integrity as well as the profitability of carbon credit contracts. Slippage can be eliminated when contracts cover the total farm area. This is not as easy a task as one would think. Locking production for years when market prices change tends to reduce flexibility and profits. Should the carbon contract entail a premium for this rigidness if the carbon price is exogenous, determined by the market or the government? How to account for this aspect in the design of governmental policies is an interesting question.

Existing agricultural policies and support schemes complicate economic incentives for carbon farming. If revenue from carbon credits is paid above the existing payments, the question of additionality emerges *via* the whole payment system. When farmers earn revenue from a land area where they already receive subsidies for a given management practice, in the literature, this is called double dipping (see, e.g. [38,76]; it is also known as double-funding in Ref. [77]). Recall our example of catch crops. We used catch crops as a potential carbon farming practice due to data availability. However, farmers in the CAP in the EU can currently receive subsidies for catch cropping. The payment was omitted from the analysis. In reality, however, public funds for a single agri-environmental measure are limited and unavailable for all available areas. Thus, additional areas for catch crops could be achieved through the use of voluntary payments in addition to public funding. This requires proper coordination (registry) at the country level to keep track of the land areas under carbon farming. The defining question is the purpose of the payments, i.e. whether the other payment also targets climate mitigation. If a practice, such as the use of catch crops, provides both climate benefits targeted by carbon credits and reductions in nutrient loading targeted by CAP payments, then “the farmer is simply being paid for delivering two public goods” [77]. An important question is whether societies should allow double dipping in the promotion of climate policy or whether existing agricultural policies should accommodate the requirements of carbon farming.

Conclusions

Our main finding is that ensuring the climate integrity of offsets from temporary contracts on agricultural practices is complicated but feasible. Second, the temporary nature of carbon credits is welcomed, and the challenge of permanence can be taken into account using offset ratios that indicate the share of emissions offset by one unit of temporary sequestration. However, offset ratios are subject to social deliberation, as they differ considerably based on the chosen methodology and discount rate. Comparing the offset ratios based on the discounting method to those obtained from existing programs reveals large differences: the permanence requirements of the studied existing programs vary considerably, and they authorize more carbon credits than the discounting method would suggest. Third, carbon contracts are profitable for farmers when the contracts are long enough and credit prices are sufficiently high. In favorable circumstances, shorter contracts might also prove profitable. Balancing between the shorter contracts preferred by farmers and the longer contracts required for profitability that are preferred for climate integrity remains a challenge. In the long term, a higher soil C content increases crop yields and thus, the profitability of carbon farming (see, e.g. [78]); however, this simultaneously increases the marginal opportunity cost of the contract and could therefore decrease the optimal contract length for the farmer [65].

This study raises multiple questions for future research. A fundamental question is how to design market institutions to effectively promote offsetting, but this aspect was beyond our analysis (see [15,16]). A well-functioning market would benefit from developments in the agronomic basis of carbon farming and measurement techniques for GHG fluxes. The understanding of best management practices should be deepened and spread more efficiently to all farmers (here, the research emphasizes bottom-up approaches with peer-to-peer learning, e.g. [45,46]), e.g. on the effect of increased soil C content on crop yields locally. Scientifically derived and approved emissions/sequestration factors for different soils and management practices should be developed either in the form of constant values (which are updated as new knowledge emerges) or assessment tools, such as carbon calculators. The greatest challenge relates to government policies and their relation to voluntary carbon markets. How should existing agricultural policies be revised to promote carbon farming, and how should the relationship between current policies and carbon credit markets serve to incentivize carbon farming without double dipping? Finally, in addition to providing a good basis for carbon farming, one should focus on how co-benefits and co-damages, especially those related to changes in nutrient loading and biodiversity, affect the benefits of carbon farming.

Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Notes

1. See Article 12 of the Kyoto Protocol and related guidance: https://cdm.unfccc.int/Reference/Guidclarif/index.html.
2. In addition, from a climate point of view, agricultural policies are commonly designed for a short period of time, after which the rules may be changed (for instance, the agricultural policy in the U.S. is generally revised every five years; [43], and the design period of CAP in the EU is six years; [44]). Thus, both governmental policy and voluntary carbon markets must find ways to solve the challenge of permanence.
3. For the altered stock decrease, at least three calculation methods could be used (examples for the Finnish case): duplication/halving (1) the time of stock decrease (same as contract length in the basic case), (2) the rate of the stock decrease (5 or 10% in the basic case), or (3) the initial annual stock change (175 kgC/ha in the basic case). We employ the first option, duplicating/halving the decrease time, as the two other options are solvable for a slower decrease only for rather short contract lengths (in contracts of more than ∼10 years, C stock does not mathematically reduce back to the baseline level, even within several hundreds of years, which would be an unrealistic assumption).
4. In Figure 2, the baseline C stock in the soil is assumed to be constant but, in practice and as shown in Figure 1, the baseline soil C content may increase or decrease. For example, in boreal mineral soils in Finland, the estimated annual decrease of soil C is 220 kgC/ha [80]. FAO [32] presents four theoretical possibilities for C stock development under the baseline (business as usual) and alternative management practice. In our analysis, catch crops provide the same annual additional C sequestration irrespective of how the baseline C stock evolves.
5. Seed price for ryegrass used as a catch crop in 2019 of 7.70 €/kg, while catch crop seeds were used at 10 kg/ha [66].
6. Price in 2019 for perennial ryegrass seeds 3092 DKK/100 kg [67], altered to euros according to Ref. [68]. The amount used was 10 kg/ha.
7. Based on survey published in 2019: seed price 5.72 €/kg [58] with a quantity of 10 kg/ha (assumed to be the same as in other countries).

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Appendix A

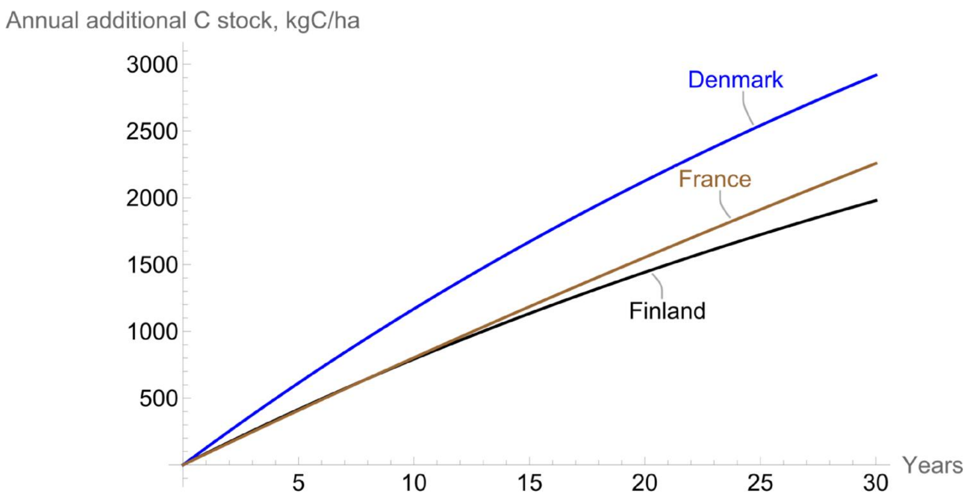

Figure A1. Average annual cumulative soil C stock for contract lengths up to 30 years. Decrease in the annual soil C increase is 1% for France and 3% for Denmark and Finland.

Table A1. Average annual cumulative soil C stock (kgC/ha (kgCO_2/ha)) for contract lengths up to 30 years.

	Contract length, years				
	5	10	15	20	30
Finland	416 (1526)	793 (2906)	1134 (4156)	1443 (5290)	1979 (7257)
Denmark	613 (2249)	1168 (4284)	1671 (6127)	2127 (7799)	2918 (10688)
France	408 (1496)	803 (2944)	1185 (4344)	1554 (5699)	2258 (8278)

C is converted to CO_2 using the ratio 44/12 (see, e.g. [79]). Decrease in the annual soil C increase is 1% for France and 3% for Denmark and Finland.

Table A2. Annual credit amounts in kgC/ha (and $kgCO_2e/ha$) for contract lengths up to 30 years with a 3% discount rate.

	Decrease rate relative to the increase	Contract length, years 5	10	15	20	30
Finland	Faster	44 (163)	163 (597)	336 (1231)	547 (2004)	1032 (3785)
	Same	57 (210)	203 (744)	406 (1488)	644 (2361)	1164 (4267)
	Slower	80 (293)	267 (979)	507 (1859)	770 (2822)	1301 (4770)
Denmark	Faster	66 (240)	240 (880)	495 (1814)	806 (2955)	1522 (5580)
	Same	84 (309)	299 (1096)	598 (2194)	949 (3481)	1716 (6291)
	Slower	118 (432)	393 (1443)	747 (2741)	1135 (4160)	1918 (7033)
France	Faster	43 (159)	163 (596)	344 (1261)	575 (2107)	1143 (4191)
	Same	56 (206)	205 (753)	424 (1556)	694 (2543)	1327 (4867)
	Slower	80 (292)	278 (1020)	550 (2017)	866 (3177)	1560 (5720)

Decrease in the annual soil C increase is 1% for France and 3% for Denmark and Finland.

Table A3. Annual credit revenue (€/ha) in Finland with varying contract length and credit price.

C stock decrease rate relative to the increase rate	Credit price in €/tCO_2	Contract length, years 5	10	15	20	30
Faster	20	3	11	25	40	76
	35	6	21	43	70	**132**
	50	8	30	61	**100**	**189**
	80	13	48	**98**	**160**	**303**
Same	20	4	15	30	47	**85**
	35	7	26	52	**83**	**149**
	50	10	37	74	**118**	**213**
	80	17	59	**119**	**189**	**341**
Slower	20	6	20	37	56	**95**
	35	10	34	65	**99**	**167**
	50	15	49	**93**	**141**	**239**
	80	23	**78**	**149**	**226**	**382**

Decrease in the annual soil C increase is 3%. Values exceeding 77 €/ha, i.e. profitable combinations for farmers, are bolded.

Table A4. Annual credit revenue (€/ha) in Denmark with varying contract length and credit price.

C stock decrease rate relative to the increase rate	Credit price in €/tCO_2	Contract length, years 5	10	15	20	30
Faster	20	5	18	36	**59**	**111**
	35	8	31	**64**	**103**	**195**
	50	12	44	**91**	**148**	**279**
	80	19	**70**	**145**	**236**	**446**
Same	20	6	22	**44**	**70**	**126**
	35	11	38	**77**	**122**	**220**
	50	15	**55**	**110**	**174**	**315**
	80	25	**88**	**176**	**278**	**503**
Slower	20	8	29	**55**	**83**	**141**
	35	15	**50**	**96**	**146**	**246**
	50	22	**72**	**137**	**208**	**352**
	80	35	**115**	**219**	**333**	**563**

Decrease in the annual soil C increase is 3%. Values exceeding 41 €/ha, i.e. profitable combinations for farmers, are bolded.

Table A5. Annual credit revenue (€/ha) in France with varying contract length and credit price.

C stock decrease rate relative to the increase rate	Credit price, €/tCO_2	Contract length, years 5	10	15	20	30
Faster	20	3	12	25	42	**84**
	35	6	21	44	**74**	**147**
	50	8	30	**63**	**105**	**210**
	80	13	48	**101**	**169**	**335**
Same	20	4	15	31	51	**97**
	35	7	26	54	**89**	**170**
	50	10	38	**78**	**127**	**243**
	80	16	**60**	**124**	**203**	**389**
Slower	20	6	20	40	**64**	**114**
	35	10	36	**71**	**111**	**200**
	50	15	51	**101**	**159**	**286**
	80	23	**82**	**161**	**254**	**458**

Decrease in the annual soil C increase is 1%. Values exceeding 57 €/ha, i.e. profitable combinations for farmers, are bolded.

Table A6. **NPV (€/ha) of annual credit revenue subtracted by the annual cost related to catch crops in Denmark with varying contract length, credit price, and discount rate; the C stock increase and decrease rates are equal.**

		Contract length, years				
Discount rate	Credit price, €/tCO_2	5	10	15	20	30
1%	20	−190	−315	−339	−240	**356**
	35	−182	−258	−162	**142**	**1425**
	50	−175	−200	**15**	**523**	**2494**
	80	−159	−85	**368**	**1284**	**4632**
	100	−148	−8	**604**	**1792**	**6057**
3%	20	−161	−166	**30**	**420**	**1654**
	35	−140	−26	**423**	**1196**	**3504**
	50	−119	**114**	**815**	**1973**	**5354**
	80	−76	**395**	**1601**	**3527**	**9053**
	100	−48	**582**	**2125**	**4563**	**11,519**
5%	20	−137	−64	**230**	**695**	**1892**
	35	−106	**127**	**725**	**1604**	**3788**
	50	−74	**319**	**1221**	**2512**	**5684**
	80	−11	**702**	**2211**	**4329**	**9477**
	100	**32**	**957**	**2871**	**5540**	**12,005**

Decrease in the annual soil C increase is 3%. Positive values indicate profitable combinations for farmers; these are bolded.

Table A7. **NPV (€/ha) of annual credit revenue subtracted by the annual cost related to catch crops in Denmark with varying contract length, credit price, and discount rate; the C stock decrease is faster than the increase.**

		Contract length, years				
Discount rate	Credit price, €/tCO_2	5	10	15	20	30
1%	20	−193	−332	−387	−336	**124**
	35	−187	−287	−246	−28	**1018**
	50	−181	−242	−106	**281**	**1912**
	80	−169	−152	**175**	**898**	**3701**
	100	−160	−92	**363**	**1309**	**4893**
3%	20	−167	−203	−61	**263**	**1376**
	35	−151	−90	**264**	**922**	**3017**
	50	−135	**22**	**589**	**1582**	**4657**
	80	−102	**247**	**1238**	**2901**	**7939**
	100	−80	**398**	**1672**	**3780**	**10,126**
5%	20	−146	−109	**134**	**552**	**1700**
	35	−121	**48**	**557**	**1352**	**3452**
	50	−96	**206**	**980**	**2153**	**5205**
	80	−46	**521**	**1826**	**3755**	**8710**
	100	−13	**732**	**2390**	**4822**	**11,046**

Decrease in the annual soil C increase is 3%. Positive values indicate profitable combinations for farmers, these are bolded.

Table A8. **NPV (€/ha) of annual credit revenue subtracted by the annual cost related to catch crops in Denmark with varying contract length, credit price, and discount rate; the C stock decrease is slower than the increase.**

		Contract length, years				
Discount rate	Credit price, €/tCO_2	5	10	15	20	30
1%	20	−186	−286	−260	−93	**659**
	35	−174	−206	−24	**398**	**1955**
	50	−163	−126	**211**	**889**	**3251**
	80	−140	**33**	**683**	**1871**	**5843**
	100	−125	**140**	**997**	**2526**	**7570**
3%	20	−150	−107	**160**	**621**	**1945**
	35	−120	**77**	**650**	**1550**	**4013**
	50	−91	**262**	**1141**	**2478**	**6081**
	80	−31	**631**	**2123**	**4335**	**10,216**
	100	**8**	**877**	**2777**	**5573**	**12,973**
5%	20	−122	**2**	**353**	**856**	**2059**
	35	−79	**244**	**941**	**1885**	**4080**
	50	−36	**485**	**1528**	**2914**	**6103**
	80	**50**	**968**	**2703**	**4972**	**10,146**
	100	**108**	**1290**	**3486**	**6344**	**12,842**

Decrease in the annual soil C increase is 3%. Positive values indicate profitable combinations for farmers, these are bolded.