DREAM
Danish Research Institute for
Economic Analysis and Modelling

GREEN REFORM

Land use and land-use change emissions in GreenREFORM

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1 Introduction

This memo documents how the land use module of GreenREFORM works and, in particular, our approach to modelling LULUCF emissions.

Data and methods are, to the extent possible, based on the official data used to calculate Danish LULUCF emissions. The model is calibrated to match the historical emissions of the NIR and the LULUCF emissions forecast of the Climate Outlook (The Danish Energy Agency, 2022), which includes a forecast of LULUCF emissions until 2035.

We do not attempt to replicate all the sub-models producing the National Emissions Inventory Report and forecast, that is, the GreenREFORM-LULUCF module is not built to replace the existing framework. Rather, the module is meant as a guiding tool, that shares the most important marginal properties of LULUCF-emissions modelling with the official methods, and works in conjunction with the rest of the GreenREFORM model system. This makes it possible to evaluate policies that affect both the macroeconomy as well as land use emissions in a coherent framework and in a single operation.

We proceed by describing our method for calculating LULUCF emissions (section 2). We follow this up with describing how the module is integrated with the rest of the GreenREFORM model (section 3). Finally (section 4), we present the emissions forecast produced by the module *before* the final calibration to the Climate Outlook, as well as the results of a shock to the module .

Before diving in we would like to extend our gratitude to the Danish Energy Agency (ENS) and the Danish Ministry for Climate, Energy and Utilities (KEFM) for their assistance in obtaining and sharing data as well as knowledge on the matter. And just as importantly the researchers at the Department of Geosciences and Natural Resource Management (IGN), who have developed the forest model, and have been generous with answering our questions and exchanging data.

1.1 Status

As mentioned in the intro; it is not the purpose of the GreenREFORM-LULUCF module to replicate all the sub-models of the National Emissions Inventory. We have however come far in making a module that produces an emissions inventory closely tracking the official historical inventory and forecast. For a comparison with the official figures we refer to section 4, figures (6) through (10).

At this point there is only a few minor discrepancies between how we model LULUCF emissions (especially when forecasting), compared to the official models used to produce the National Emissions Inventory and the Climate Outlook.

Most of these discrepancies, we do not believe the benefits, in terms of marginal model properties gained of a full scale replication, outweighs the cost of drag on computational speed. The discrepancies can be categorized as follows

1. Land-use emissions and uptakes on mineral soils.
2. Uptakes and emissions in hedgerows.
3. Emissions from peatlands.

In section 2 we will elaborate on the three items listed above.

For a few discrepancies we are working on improvements

1. Forestry emissions not related to the actual carbon stored in biomass in forests, i.e. emissions from soil-organic matter in soils in forests.
2. Unknown [sic] sources.

For forestry emissions we have a productive dialogue with the Department of Geosciences and Natural Resource Management (IGN), who produces the forestry emissions inventory.

For the unknown sources we note that the *error-term* between the emissions the model forecast on its own, and the official forecast are relatively small, but significantly not zero. It is our aim to investigate further.

1.2 Terminology and data

An emissions inventory for LULUCF is a way of accounting for changes in land carbon stocks as well as other emissions from land use. Information on land use is therefore crucial to estimate LULUCF emissions. We denote land use of type r in year t by $land_{r,t}$ and we also define matrices of gross land use changes, $\Delta land_t$, where element $\Delta land_{s,r,t}$ describes the change of land type s into land type r in year t Thus, the land use in year t is given by the land use in the previous period, plus any changes of land *to* type r, minus any changes of land *from* type r into other land types. This is summed up in the following accounting equation:

$$land_{r,t} = land_{r,t-1} + \sum_{s \neq r}[\Delta land_{s,r,t}] - \sum_{s \neq r}[\Delta land_{r,s,t}] \tag{1}$$

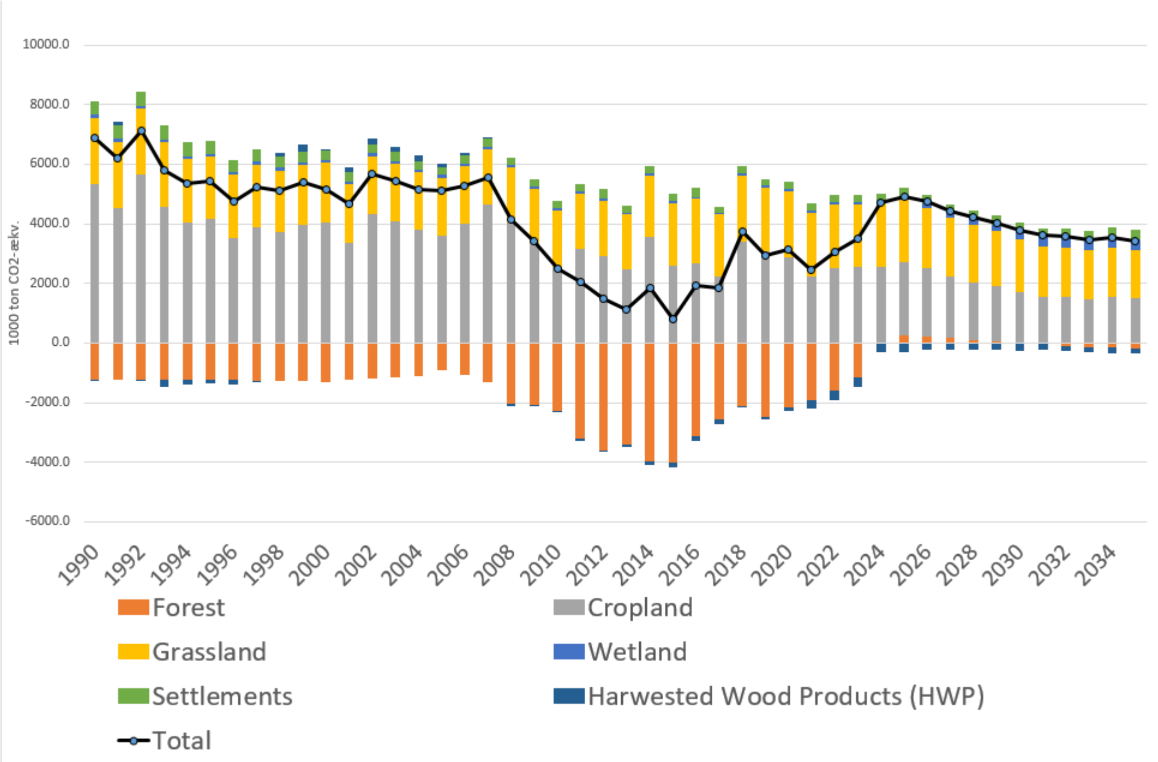
It can be useful to split LULUCF emissions into its four components:

- **Land Use (LU):** Net emissions that stem from how the land is used. As an example, when land is used for agriculture, the steady-state organic content is typically lowered. This gives rise to net emissions from agricultural land. The net emissions will be higher if the land has a high organic content in the first place. As a result, both land use and the carbon content of the land matters for emissions.
- **Land Use Change (LUC):** Net emissions that stem from changes in how land is used. As an example, land used for agriculture has a standing carbon stock. When the land use is changed to make room for e.g. roads or a forest, this carbon stock is cleared, and emissions from it ensue.
- **Forestry (F):** When trees grow, they absorb carbon from the atmosphere, which can be released to the atmosphere again when trees die or are cut down and used for various purposes.
- **Harvested Wood Products (HWP):** This is the contribution of net emissions from the creation and subsequent decomposition of differnt types of wood products (sawn wood and wood-based panels). These materials contain carbon that is released when the products reach the end of their life cycle.

The yearly net LULUCF-emissions on the five major land-categories of LULUCF-reporting, as well as the forecast up until 2035, are illustrated in figure 1. The computation of emissions are elaborated on in section 2.

Data-wise the model is based on a subset of the same data (and forecast of said data) that is used in production of the NIR and the Climate Outlook. To name a few key data inputs we use the official area-transition records and projections, records and projections for areas of organic soils (+ their emission coefficients) and input data for the official forest model.

Figure 1: Net emissions from LULUCF



Source: Climate Outlook 2022, which GreenREFORM is calibrated to in baseline.

2 Method

This section describes the method we employ for calculating LULUCF emissions. We describe methods seperately for Land Use, Land Use Change and Forestry, cf. section 1.2. For this memo, historical data is available until 2020. Reported emissions and emission coefficients after this year are projections - either our own[1] or taken from the official projection.

We denote land use stock as $land_{r,t}$, where $r = \{forest, christmas\ trees, cropland_{<6\%}, cropland_{6\%-12\%}, cropland_{>12\%}, grassland_{<6\%}, grassland_{6\%-12\%}, grassland_{>12\%}, settlements, water, wetlands\}$[2] denote the types of land that we have in the model (the subscript on cropland and grassland types denote the organic content)[3] and t is time, measured in years.

We start by discussing our modelling of land use and land use change emissions

[1]In the cases where we have chosen not to go for a full-scale replication of official models.

[2]Note that for organic soils we apply data on an even higher resolution than what comprises the set of land use-types r.

[3]The official LULUCF land categories also include an "other" category. In Denmark, this category only covers beaches and sand dunes, which are biologically inert and cover a constant area. We therefore leave it out of our model.

from land types excluding forestry. We then discuss how we calibrate this part of the model. Forestry is modelled and calibrated seperately, and we discuss this subsequently.

2.1 Land use

Emissions from land use (LU) are calculated as an emission coefficient $u_{i,t}^{LU}$, times the land stock, i.e. emissions from LU are given as:

$$\begin{aligned} CO_2e_t^{LU} = & \sum_{r \notin OC} u_{r,t}^{LU} \cdot land_{r,t} \\ & + \sum_{s \in OC} \sum_{j=1990}^{t} u^{WL} \Delta land_{s,wetland,j} \\ & + \sum_{r \in OC} \sum_{drainage} u_{r,drainage}^{LU} land_{r,t} \\ & + CO_2e_t^{Peatland} \\ & + CO_2e_t^{Hedgerows} \end{aligned} \tag{2}$$

where r is the set of land types excluding forest, OC is the subset of r containing high organic content lands. Land Use emissions consist of three terms:

1. An emission per hectar of land use of different types (the first term)
2. A term that accounts for conversions of organic soils that have been converted to wetlands, as these soils emit some amount of methane every year.
3. A term that accounts for emissions from non-wetted or partially wetted organic soils on grass- or croplands.
4. A term that accounts for emissions from peat extraction.
5. A term that accounts for emissions and uptakes in hedgerows.

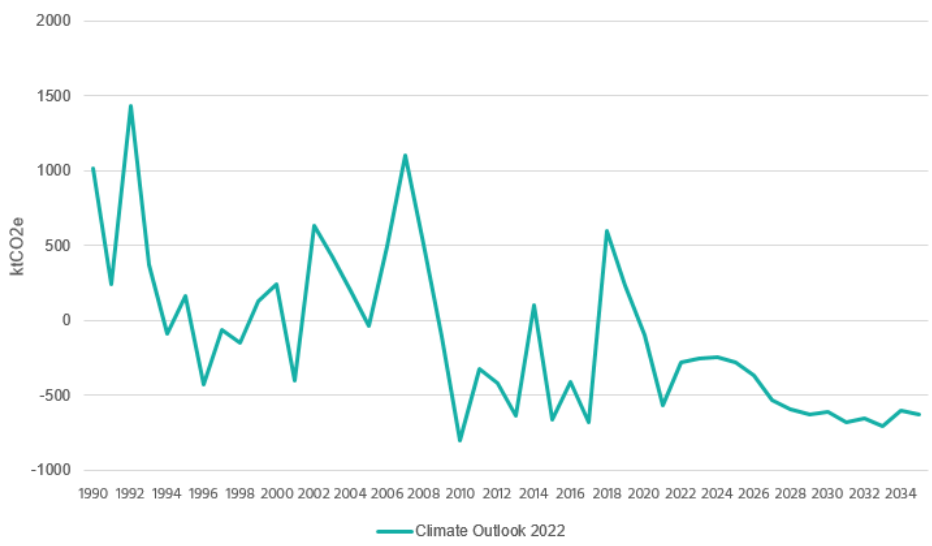
We address each of these terms

In the first term are currently only contains emissions and uptakes from mineral soils on cropland and grassland. This is the largest component of LU-emissions for which we do not pursue a full replication of the official models, as mentioned in 1.1. The uptakes and emissions on mineral soils are modelled with a modelsystem called

C-tool in the NIR/Climate Outlook. C-tool takes inputs such as crops, follw-up crops, weather and furthermore breaks "mineral soils" into an even finer resolution of different soil compositions. For more on C-tool se (Nielsen et al., 2022). As the GreenREFORM agricultural module corrently does not produce outputs of different crops and follow-up crops on a high enough resolution for C-tool, and because it must be assumed that weather is relatively constant in C-tool forecasts, our current assesment is that there would not be any gains from replicating C-tool in GreenREFORM. We note that, if, at a later point, the agricultural module is expanded with the dimensions listed above, there could be a scope for implementing C-tool in the GreenREFORM-LULUCF-module and link it to the agricultural module.

We include a figure of the emissions and uptakes on mineral soils that are produced in the Climate Outlook 2022 in 2 to illustrate the variability in this figure. We also note that fluctuations get smaller in forecast years, which one should expect when weather is removed from the equation, and data-inputs takes the form of expected values rather than measured values.

Figure 2: Emissions and uptakes on mineral soils in cropland and grassland



Source: The Climate Outlook 2022.

In the second term are emissions from converted wetlands. We include emissions from land converted to wetlands from $cropland_{>12\%}$, $cropland_{6-12\%}$, $grassland_{>12\%}$ and $grassland_{6-12\%}$ since 1990. In practice, we model a yearly methane emission of 288 kg per hectare[4] (Nielsen et al., 2020b, table 8.2).

[4]Note that from reading in the NIR one can get the impression that only $> 12\%$ are assigned this emission. After correspondance with the Danish Energy Agency we have learned that the emission is however assigned to both medium and high organic soils converted to wetland.

In the third term are emissions from organic crop- and grassland soils. We use the same areas and emission-factors as are used by the Danish Energy Agency and DCE. The emission factors are given in the table below

Table 1: Emission-coefficients on organic soils

	Fully drained				Shallow drained	
	$crop_{6-12\%}$	$crop_{>12\%}$	$grass_{6-12\%}$	$grass_{>12\%}$	$crop_{6-12\%}$	$crop_{>12\%}$
CO_2(tCO_2/ha)	21.083	42.167	15.400	30.800	6.417	12.833
CO_2-leached (tCO_2/ha)	0.568	1.137	0.568	1.137	0.568	1.137
CH_4(kg CH_4/ha)	29.125	58.250	36.725	73.450	47.650	95.300

Source: Data provided by the Danish Energy Agency.

In the fourth and fifth term emissions from peat extraction and emissions and uptakes from hedgerows are included. These are included exogenously from the historical data and the forecast in the Climate Outlook. The emissions and uptakes are rather small and we do not believe that it is of primary interest to model users to investigate policies that influence the amount of peat extraction and hedgerow area. If one wants to investigate these, we suggest simply exogenously changing the emission, eg. if one wants to investigate a full stop of peat extraction and re-wetting of peatlands, then they should just set the emission to zero in their counter-factual, and apply the emission-factors of wetlands on the area.

2.2 Land use change emissions

Emissions from land use change (LUC) use yearly transition matrices as the main input. Using the transition matrices as well as data on the stock of equilibrium carbon levels on each type of land, net emissions can be calculated. There is a distinction between the above- and below-ground biomass stock on land type i (b_i^{bm}), which is removed instantly, and the below-ground soil organic matter C-stocks (b_i^{stock}), which adjusts to the steady state value of its new land use type over a longer period.The coefficients from biomass are described in table 2. Further, we include the potential for instant oxidation of dead organic matter as $N_2O{,}oxi_{j,i}$. Currently, we only include data on emissions from forest land converted into cropland Nielsen et al. (2020a, p. 474).

Table 2: Carbon stocks by land type, kg C per hectare

	Biomass (ton C per ha)	Default C stock (ton C per ha)
Cropland	5,938	120,800
Grassland	4,560	142,000
Wetland	6,840	142,000*
Settlement	2,200	96,600
Forest	NE	142,000

Source: Nielsen et al. (2020a, , table 6.8).

Emissions from land converted into type r from type s, $\Delta land_{s,r,t}$, are in all cases except for cropland converted to forest and forest to cropland/wetland are calculated as:

$$CO_2e^{LUC}_{r,t} = \sum_s [\Delta land_{s,r,t} \cdot (b^{bm}_s - b^{bm}_r)] + \sum_{s=0}^{S} \sum_s [\Delta land_{s,r,t-s} \cdot (b^{stock}_s - b^{stock}_r) \cdot \rho^{LUC}_r] \quad (3)$$

The equation states that net emissions from land converted into type r are given as the change in biomass stock from all types of land converted into this land type (the first term), plus emissions from the gradual change of below-ground organic matter, the soil organic matter (the second term). The adjustment period varies by land type:

- For cropland, grassland and settlements, this adjustment is assumed to take 30 years (Nielsen et al., 2020a). The below-ground biomass is removed in a linear fashion, i.e:$\rho r^{LUC,t}_r = .. = \rho^{LUC,t-30}_r = \frac{1}{30}$ for $r = \{cropland_{<6\%}, cropland_{6\%-12\%}, cropland_{>12\%}, grassland_{<6\%}, grassland_{6\%-12\%}, grassland_{>12\%}, settlements, chr.trees\}$
- For wetlands, there is a no change in below-ground soil-organic matter for land converted to wetlands; this biomass stays at the initial level (Nielsen et al., 2020a, p. 482), Thus, we set $\rho^{LUC,t}_r = 0$ for all t for $r = \{wetlands\}$.
- For land converted into forests, the adjustment process of soil organic matter is set to 100 years[5] . I.e. we set $\rho^{LUC,t}_r = \rho^{LUC,t-100}_r = \frac{1}{100}$ for $r = \{forest\}$. Further, the stock of biomass in forests is handled in the forestry module.

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- For land converted away from forest land, we assume that below-ground biomass is equal to that of grassland (Nielsen et al., 2020a, table 6.8).

For cropland converted to forest slightly different dynamics apply. That is, for $r = forest$ and $j \in \{cropland_{<6\%}, cropland_{6\%-12\%}, cropland_{>12\%}\}$. LUC emissions are calculated as

$$\begin{aligned} CO_2e^{LUC}_{forest,t} &= \Delta land_{crop,forest,t} \cdot (b^{bm}_{crop} - b^{bm}_{grass}) \\ &+ \sum_{s=0}^{25}[\Delta land_{crop,forest,t-s} \cdot (b^{bm}_{grass} - b^{bm}_{forest}) \cdot 1/25] \\ &+ \sum_{s=0}^{100}[\Delta land_{crop,forest,t-s} \cdot (b^{stock}_{crop} - b^{stock}_{forest}) \cdot 1/100] \end{aligned}$$

, where the two first lines of the equations differ from 3. As trees grow slowly the initial effect in the carbon stock is dominated by wild grass that sprouts. The first term captures the initial effect of the change in biomass from that of the average carbon stock in crops to grass. The second term captures the transition from grass to forest. This transition is meant to capture that the growing trees start blocking out sunlight and the grass is replaced by a regular forest floor (the biomass of the forest floor is captured in the forest model). The third term is the conversion in below ground soil organic matter from cropland to forest, which - as mentioned - is assumed to take 100 years.

For forest converted to cropland/wetland equation (3) applies, and an additional term is added for oxidation of the forest biomass into N_2O. The emission is 5.1 kg N_2O-N per hectare ((Nielsen et al., 2020a, p. 474).bigskip

2.3 Calibration of LU and LUC emissions

The only calibration needed, in terms of LU and LUC emissions, is the calibration of the implied emission-coefficient on mineral grass- and cropland soils. This is calibrated as a per ha. emission coefficient based on the emissions data published with the Climate Outlook (The Danish Energy Agency, 2022).

– source: Background excel-sheetfrom IGN on forest emissions

2.4 Forestry

In the previous sections we advertised that the carbon stock in biomass in forests would be accounted for separately in the forest model. This section describes the biomass uptakes and emissions in forests. To be more precise, the biomass is that in the trees above-ground, below-ground plus the biomass stored in dead wood on the forest floor, and the biomass in the plants growing on the forest floor itself. The emissions and uptakes are modelled with the stock-change method, i.e. the model tracks the carbon stock in the biomass. A change in the carbon stock is then associated with an emission or an uptake.

We use the same approach to model the dynamics of net emissions from forestry as the official model used in the projections from the Climate Outlook 2022. The model input-data and output as well as an exhaustive documentation (Johannsen et al., 2022) are publically available. This primary data and documentation, as well as supplementary data[6] on organic soils and Harvested Wood Products (HWP), are the foundations of the forestry model.

We denote forest area (measured in kilohectares) at time t as, $area^{sec}_{t,f,r,a}$. The subsripts denotes the following:

1. The forest is divided into three forest types: $sec = \{frf, aff, nre\} =$ {forest-remaining-forest,afforestation, nature-reserves}.
2. Each forest type can be further divided into $f = \{b, c, p\} = \{broadleaves, conifers, perennials\}$
3. There is also a distinction about which region the forest is situated in, $r = \{Jutland, Islands\}$. The regions are a rough measure of soil quality, with Jutland being lower quality sandy loams, and the Islands being richer loams.
4. All areas are also summed up by the age of that area. The age is given by a five-year age-class: $a = \{5, 10, ..., A_f\}$.

The model iterates in 5-year periods, hence the age-classes. The forest-remaining-forest subdivison and the nature-reserves comprises all historical forest-areas up until last available data-year (2020). The afforestation areas enters the baseline of the model with the expected afforestation areas up until 2035. On top of the emissions and uptakes in the three major forest-categories comes emissions from deforestation, and - as mentioned - emissions from organic soils and harvested wood products. In the paragraphs below we describe the model in more detail before returning to deforestation, organic soils and HWP.

[6] Once again we extend our gratitude to Vivian Johannsen and her colleagues at IGN.

2.4.1 Forest-remaining forest

The forest-remaining forest model takes two key parameter-inputs namely i) the survival rate $p_{f,r,a}$, i.e. the probability that an area of trees in age-class a reaches the age-class "$a+1$"[7] and ii) the five year average carbon stock of that tree type per hectare, $C_{f,r,a}$. If an area of forest, $area_{t,f,r,a}$, does not survive, it is renewed. In the context of the model the area is transferred to age-class 0-5 . This allows for a Markov chain-style dynamic model of net emissions. The area of forest-remaining-forest of a given tree-type f in region r with an age of a is given by the three transition equations:

$$area^{frf}_{t,f,r,a} = \begin{cases} \sum_{a'} \left[area^{frf}_{t-5,f,r,a-1'} \cdot (1 - p^{frf}_{f,r,a-1'}) + area^{aff}_{t-5,f,r,a-1'} \cdot (1 - p^{aff}_{f,r,a-1'}) \right] & for\ a = 5 \\ area^{frf}_{t-5,f,r,a-1} \cdot p^{frf}_{f,r,a-1} & for\ 5 < a < A_f \\ area^{frf}_{t-5,f,r,a-1} \cdot p^{frf}_{f,r,a-1} + area^{frf}_{t-5,f,r,a} \cdot p^{frf}_{f,r,a} & for\ a = A_f \end{cases} \tag{4}$$

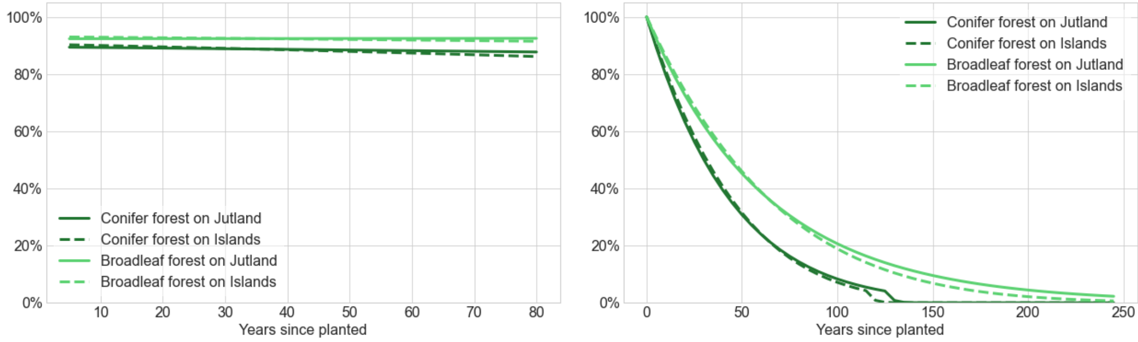
The first term is the transferring of areas that did not survive. Note that this contains both frf forest that did not survive, but also a component of afforestation areas are transferred to the frf model via this link[8]. The second term is the transition of areas from one age-class to the next, where only a fraction, $p^{frf}_{f,r,a-1}$, transitions. The last term is the final age-class that works as an end-category where the age of that forest is no longer tracked, but a fraction of that forest is renewed on every iteration.

[7] Note that the lead and lag-operator in terms of the age-classes is used to signify a shift in five-year periods. Eg. if a is the ages $0-5$ then $a+1$ is the ages $6-10$. We do this to be match the syntax of the code of the model, where the lead and lag operator, used on the age-classes, works in this exact fashion.

[8] The assumption being that the afforested areas in the long-run convergence on a tree mix resembling that of the frf-model.

Figure 3: Forest-remaining-forest Survival probabilities

(a) Survival probabilities (b) Cumulative survival probabilities



Source: Johannsen et al. (2022, Background data published withe the report) and own calculations.

2.4.2 Afforestation

The afforestation model works similarly to the frf area, with the exception that the youngest forest area, $area^{aff}_{t,f,r,5}$, is exogenous[9] . The survival rates, $s^{aff}_{f,r,a-1}$, and carbon stock coefficients, $C^{aff}_{f,r,a}$, are specific to the kind of trees being planted and can differ from the corresponding coefficients in the Forest-Remaining-Forest section. Given data on survival rates and carbon stock coefficients, any type of forest can essentially be modelled in afforestation[10]. The afforestation forest area is by the transition equations:

$$area^{aff}_{t,f,r,a} = \begin{cases} area^{aff}_{t-5,f,r,a-1} \cdot p^{aff}_{f,r,a-1} & for\ 5 < a < A \\ area^{aff}_{t-5,f,r,a-1} \cdot p^{aff}_{f,r,a-1} + area^{aff}_{t-5,f,r,a} \cdot p^{aff}_{f,r,a} & for\ a = A_f \end{cases} \tag{5}$$

2.4.3 Nature reserves and deforestation

The baseline deforestation, and nature reserves, $area^{nre}_{t,f,r,a}$, are as mentioned earlier exogenously specified. The deforestation is set to an emission of 33 $ktCO_2e$ per year. The nature reserves contributes to the total carbon stock in forests and the HWP-stock in baseline.

[9]In the baseline the afforestation is the expected afforestation in the Climate Outlook 2022. By changing the afforestation area the user can make model simulations about the implications of afforestation on emissions.

[10]A part of the data published with the IGN-documentationJohannsen et al. (2022) for the forest model also provides carbon stock coefficients for a number of afforestation models that are not in the baseline.

2.4.4 Computing forest emissions

To arrive at the total forest emissions and uptakes we firstly compute the total carbon stock in the forests at a given point in time:

$$C_t^{Forest} = \sum_{sec \in \{frf, aff\}} \sum_f \sum_r \sum_a content\_coef_{f,r,a}^{sec} \cdot area_{t,f,r,a}^{sec} + \sum_f \sum_r \sum_a C_{f,r,a,t}^{nre}$$

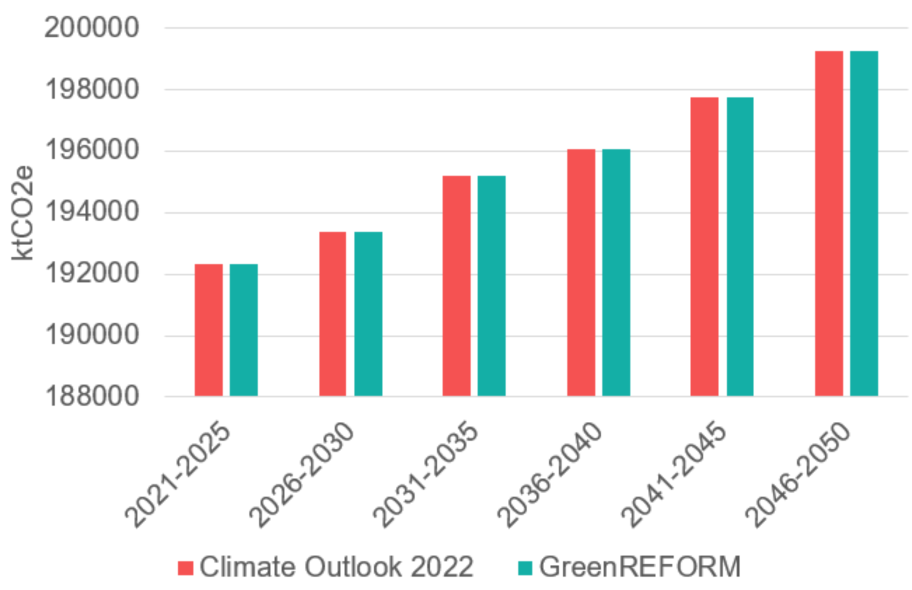
The emissions are then computed as the negative five-year average change in carbon-stock, multiplied by the relative atomic weight CO_2 and carbon of 44/12. We add deforestation to this equation as well as emissions from organic soils in forests

$$\begin{aligned} CO_2e^{Forest} = &-\frac{44}{12} \cdot \frac{C_t^{Forest} - C_{t-5}^{Forest}}{5} \\ &+33 \\ &+CO_2e_t^{OrganicSoilsInForests} \end{aligned}$$

2.4.5 Concluding remarks on the forestry model

Using the approach outlined in the sections above, our simulation of the carbon stock, should be identical to that used for the Climate Outlook. And when we look at both our carbon-stock results and our results on harvested wood products (next section) we completely reproduce the IGN model output, see fig 4 below and 5.

Figure 4: Carbon stock in forests



Source: Johannsen et al. (2022, Table 7.1 p. 54). The carbon stock is above ground biomass, below ground biomass, dead wood and litter.

Finally, when we compare total forest emissions (see figure 8) the discrepancy to the Climate Outlook is suprisingly large. The logistics of the Climate Outlook[11] makes it difficult to track why our model results are different from those reported in the Climate Outlook. We are investigating this, but are reassured in the models marginal properties by the fact that we succesfully reproduce IGN's model output.

2.5 Harvested wood products

When trees are harvested, or dies from a natural reason, the associated carbon stock is accounted for in one of three ways in the forest-model:

1. It decays naturally in the forest.
2. It is used as fuel to create energy
3. It is used in the manufacturing of wood products.

For the first two cases the lost carbon-stock will be counted as an instant emission in the forest model. In the third case a more detailed modelling is used and is referred

[11]First the projection is made by IGN who sends it to DCE (who are responsible for the rest of the NIR) in Aarhus who then sends emissions and uptakes to the Energy Agency.

to as the Harvested Wood Products (HWP). We model the harvest of wood, the inflow of the harvested wood to the HWP-stock and the gradual decay of the stock. The modelling, as is the case for the rest of the forest-model, seeks to replicate the exact method used of IGN in the projection in the Climate Outlook. The equation governing the carbon-stock in harvested wood products is given by the one below

$$C_{use,t}^{HWPstock} = C_{use,t-5}^{HWPstock} \cdot \delta_{use}^{5} + C_{use,t}^{HWPinflow}$$

This says that the total HWP-stock, split onto enduse, $use \in \{sawnwood, panels\}$, is given by the stock five-periods ago net of depreciation ($\delta_{use}^{5}$is the five-year compounded depreciation) plus any in-flow of new harvested wood-products. The inflow to the HWP-stock is given by

$$C_{use,t}^{HWPinflow} = \overbrace{s_{use}^{EndUse}}^{\text{Share going to sawn-wood/panels}} \cdot \overbrace{s_{use,f}^{Util}}^{\text{Utilization-rate}} \cdot \overbrace{\sum_{r} s_{enduse,f}^{C2V}}^{\text{Carbon per volume}} \overbrace{\sum_{sec} V_{f,r,t}^{sec,HWP}}^{\text{Volume of harvest}}$$

, where the utilization-rate denotes how much of the carbon is utilized at the saw-mill.

Table 3: Share of HWP, loss in production and depreciation

	Sawn wood	Wooden panels
Share of wood used for product, s_{use}^{EndUse}	58%	42%
Share of wood utilized for broadleaf, $s_{use,broadleaf}^{Util}$	47%	74%
Share of wood utilized for conifer, $s_{use,conifer}^{Util}$	44%	74%
1-depreciation rate, δ_{use}	0.98	0.973

Source: Johannsen et al. (2022) for utilization rates, personal correspondance with IGN for the end-use rates, and correspondance with the Danish Energy Agency providing the depreciation rates used for the Climate Outlook.

The volume of the harvest in turn links to the forest model as

$$V^{sec,HWP}_{f,r,t} = \sum_a \overbrace{\overbrace{s^{sec,Mainharvest}_{f,r,a}}^{\text{Share to saw-mill}} \cdot \overbrace{corrMainVC^{sec}_{f,r,a}}^{\text{Volume per carbon}} \cdot \overbrace{(1-p^{sec}_{f,r,a-1}) \cdot C^{sec}_{f,r,a-1} \cdot area^{sec}_{t-5,f,r,a-1}}^{\text{Carbon in renewed/harvested areas}} \cdot \delta^{2.5}_{use}}^{\text{Contribution from main harvest}}$$

$$+ \sum_a \overbrace{\overbrace{s^{sec,Thinning}_{f,r,a}}^{\text{Share to saw-mill}} \cdot \overbrace{corrThin_f}^{\text{Volume per carbon}} \cdot \overbrace{C^{Thin,sec}_{f,r,a} \times area^{sec}_{t,f,r,a}}^{\text{Carbon in thinning}} \cdot \delta^{2.5}_{use}}^{\text{Contribution from thinning}}$$

This link to the main-model begs an elaboration. Firstly, we note that the contribution from main-harvest of the forest is tied to the survival-rates of the forest-model, and the carbon associated with the areas not transferred to next age-class. Only a share of this carbon, $s^{sec,Mainharvest}_{f,r,a}$ makes it from the forest to the saw-mill. The remaining shares are, as mentioned in items (1)-(3) in the head of this section, either decaying in the forest or used as energy-fuel. The carbon inflow is a 5-year total, and it is therefore depreciated with an average depreciation of 2.5 years, $\delta^{2.5}$. Secondly the thinning of the forest is the practice of harvesting mis-growing trees, harvesting nursing trees[12] and other forest maintenance. Thinning doesn't affect the area or age of the trees. In 2026-2030 thinning is reduced with 30% on The Nature Agency's land. The official documentation Johannsen et al. (2022) states that thinning should be reduced with 20% in these years, but we can only replicate IGN's model-output by reducing thinning by 30 %.

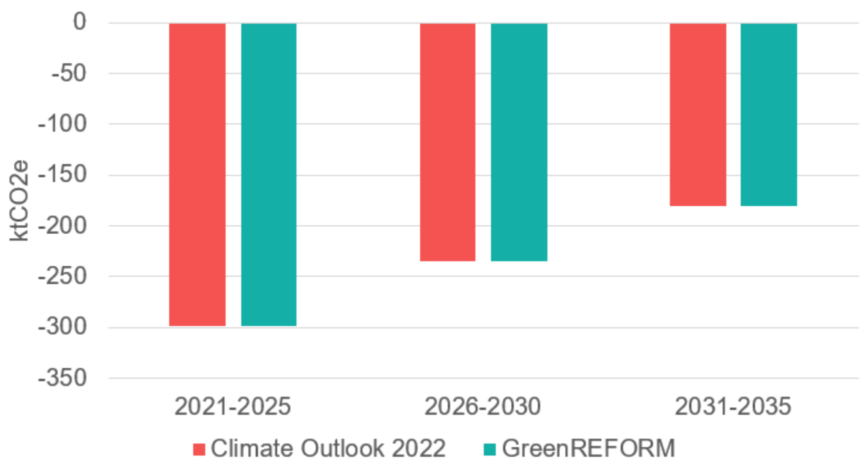
Given the above-listed transition equations of the HWP-stock we compute the HWP-emissions as the stock-change:

$$CO_e e^{HWP}_t = -\frac{44}{12} \cdot \frac{\sum_{use} C^{HWPstock}_{use,t} - C^{HWPstock}_{use,t-5}}{5}$$

Figure (5) below provides a comparison of the HWP-emissions from GrønREFORM and from the Climate Outlook 2022. The numbers are identical.

[12] Nursing trees are sometimes used as a mean of optimizing tree-growth of the main tree specie. The nursery trees are planted among the main specie to provide a sun-block for competing species. Larch and poplar are often used nursery trees.

Figure 5: Emissions and uptakes in harvested wood products



3 Integration with GreenREFORM

There are currently links between the agricultural module of GreenREFORM and the LULUCF-module in shocks to the model where agricultural land is modelled by a land-supply-function as described in Olsen (2022). The supply-function, in short, sums up how much agricultural land is in production for a given profitability of the land. The idea is that agricultural lands are only in production as long as the return on having the land in agricultural production is higher than the alternative. The alternative in Olsen (2022) being laying land fallow and cashing in the basic income per ha from the Common Agricultural Policy (CAP). When land is being laid fallow in the agricultural module this means a transfer of both mineral and organic cropland soils to grasslands in the LULUCF-module. This transfer in turn leads to lower LULUCF-emissions because grasslands have a lower per ha emission than croplands.

The link between the land-supply-function can be extended beyond just a transfer of cropland to grasslands. We are, for instance, also experimenting with a version of the land-supply function where a CO_2e-uptake subsidy is given to forests to investigate the magnitude of afforestation under such a scheme.

It is also relevant to link the forestry sector to input of forestry land in a similar way by linking the output of the forestry sector to the amount of harvested wood products produced. However, this is not currently part of the model, and will probably not have a large impact on macroeconomic results, since i) the forestry sector is small in economic terms and ii) emissions from forestry are captured by the LULUCF module, as opposed to agricultural emissions, which are mainly covered by the agricultural module. In policy scenarios where siginificant afforestation is considered, having made the link between the LULUCF-module and the forestry sector, and - just as importantly - the energy-markets of the main model, could provide insights on the effects on of energy wood crowding out fossile fuels, and imported energy-wood.

The method described in section 2 does not ensure that the emissions projection of GreenREFORM is identical to the official emissions projection. To ensure baseline consistency, we calibrate final emissions to the official projection. We do so by calibrating additive residuals to total emissions reported in the official projection. These total emissions are reported on the five main land type categories in the official projection (e.g., cropland, grassland, settlements, wetlands and forests). We therefore only calibrate emisions results at the aggregated five-type level. This ensures baseline consistency of aggregated results.

The calibration to the official emissions projection also shed an initial light at where efforts should be made to further improve the GreenREFORM-LULUCF-module. In gauging the magnitude of these differences, we start the following section by comparing the projection of the GreenREFORM model *before* this final calibration to the official projection of The Danish Climate and Energy Outlook 2022 (KF22).

4 Results

In this section we first give an overview of what raw model output the GreenREFORM yields on baseline data (before the final calibration to the Climate Outlook). We do this to document how well the model works in its own right, and as a guide to where future improvement work is needed. Secondly we walk the reader through a shock to the LULUCF-module where organic croplands are re-wetted.

4.1 Baseline

For an overview of raw model output we report emissions on an aggregate level of land-use categories: Cropland, Grassland, Forest, Wetland and Settlements. We also provide a comparison with the baseline emissions from the Climate Outlook on the same aggregate level. This i) Provides the reader with a rough idea of the modules precision, and ii) it serves as a vantage point for future work in eliminating the difference between the official emissions inventory and the GreenREFORM model projections. The model-output and comparison are provided in the figures below.

- For cropland and grassland we note that the difference between the Climate Outlook and the GR-module are larger in historic years (1990-2020) compared to forecast years (2021-2035). In fact the difference is almost eliminated in forecast years. Possible explanations for the differences are, apart from the obvious that there is an error in the GR-model, i) differences in input data, ii) differences in key-parameter inputs, iii) the possibility of ad hoc corrections in historic years for the case of the official numbers.

- For Forest emissions we should first stress to the reader that historic emissions (1990-2020) are not model-output, but based on actual sampling of the Danish forests - hence the zero-difference between GR and the Climate Outlook. For forecast years (2021-2035) we note a surprisingly large difference between official numbers and GR-forecast - surprising given how much care has gone into replicating the exact official method. We are in dialogue with IGN and the Danish Energy Agency about this.

- Wetland emissions roughly hit official numbers. For historic years there is a period of years between 2002 and 2019 where the accounts seem to diverge and then rejoin before forecacst years. The forecast years are not completely on target either. There is in other words still ground to be covered in terms of eliminating the final gap between GR-module and the Climate Outlook.

- Settlement emissions are for historic years further off than for forecast years. For forecast years it would almost seem that the difference is caused by a slight difference in a "slope"-parameter.

Figure 6: Cropland emissions

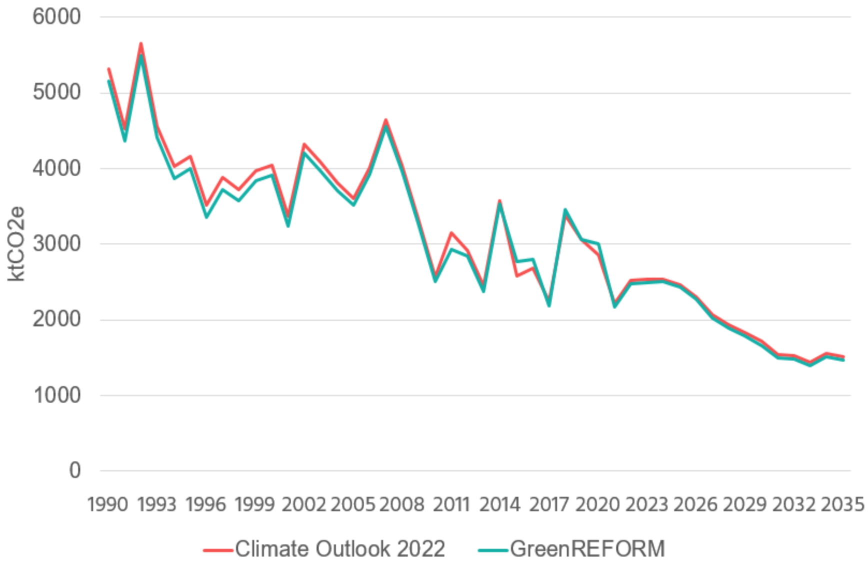


Figure 7: Grassland emissions

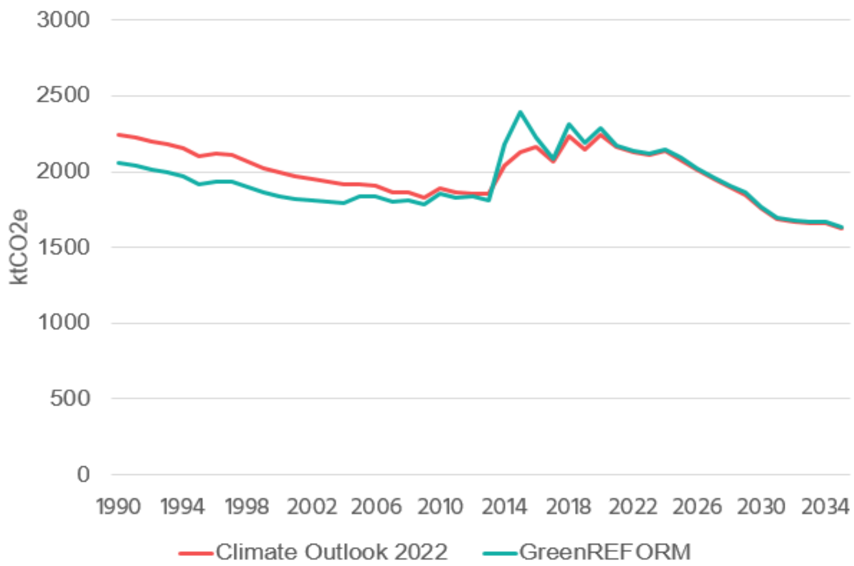


Figure 8: Forest emissions

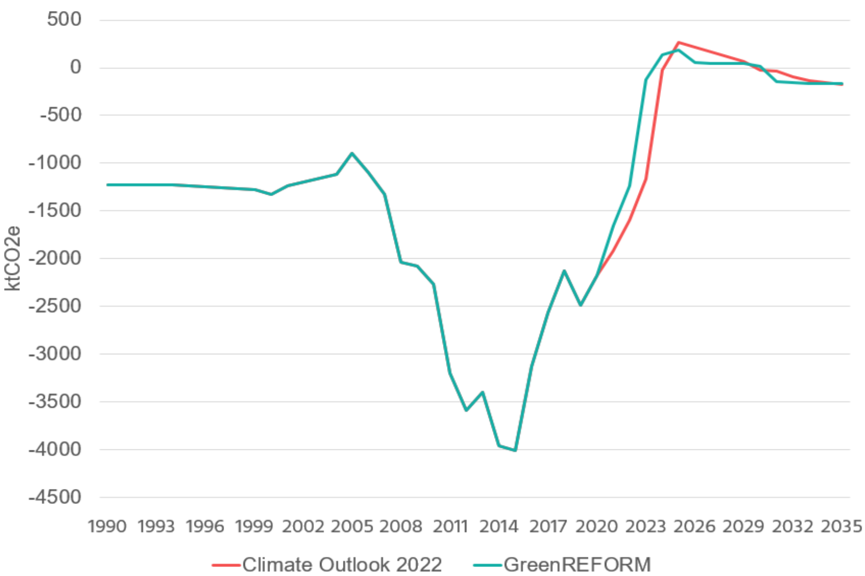


Figure 9: Wetland emissions

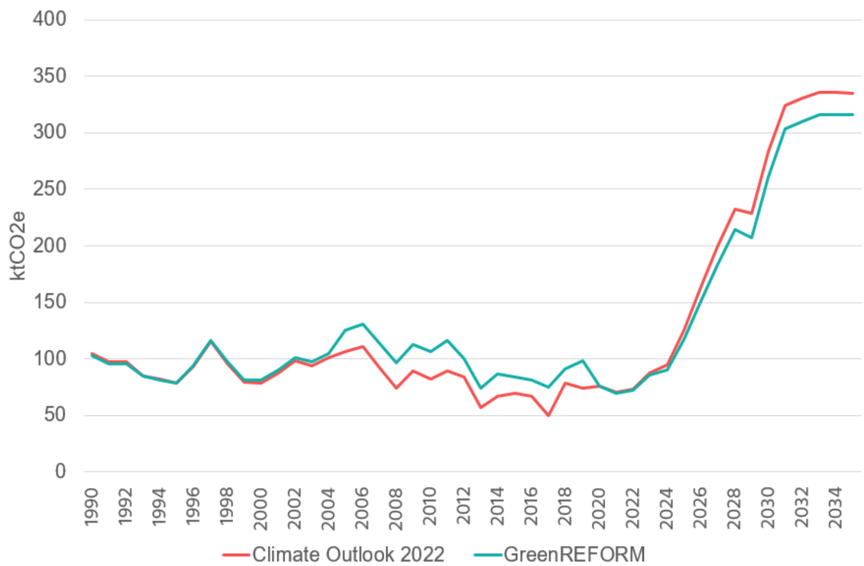
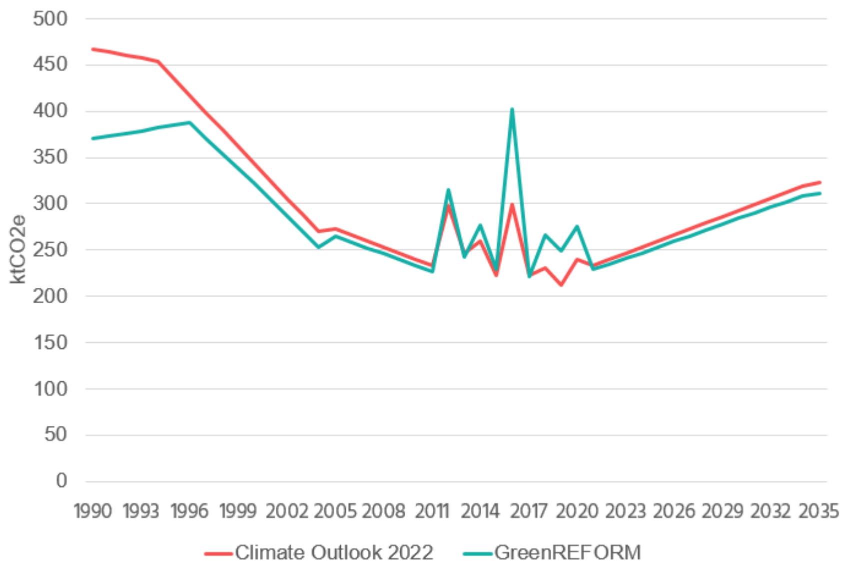


Figure 10: Settlements emissions



4.2 A shock to the module: Re-wetting of 10 000 ha. organic soils

We begin this section with an overview of the shock and after that we turn to the model results and explain the underlying mechanics.

The shock considers the re-wetting of 30 000 ha. agricultural soils. 10 000 of these are organic soils, and 20 000 are mineral soils. Because some agricultural soils, for various reasons, figure as grassland in the LULUCF-accounts we set half[13] of the 30 000 hectares as grasslands. Further we assume that it would take 5 years to convert the hectares. The change is evenly distributed on each year. In table (4) below is the total area-change over the 5-year period summed up.

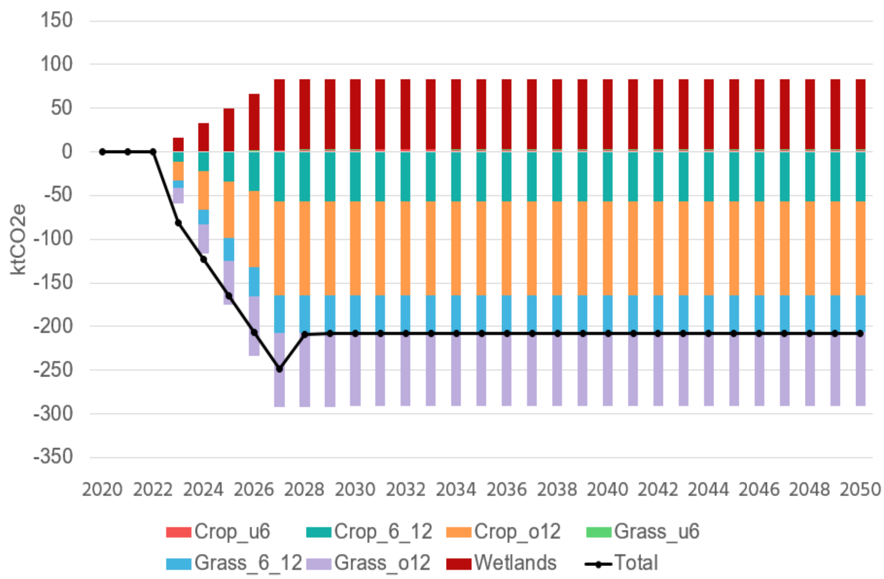
[13]Setting the proportion to a half should of course be taken with a grain of salt, as this is only s stylized shock to showcase model dynamics.

Table 4: LULUCF-shock: Re-wetting agricultural soils

Sender\Receiver (ha. converted)	$Wetlands$
$Crop_{<6\%}$	10
$Crop_{6-12\%}$	2.5
$Crop_{>12\%}$	2.5
$Grass_{<6\%}$	10
$Grass_{6-12\%}$	2.5
$Grass_{>12\%}$	2.5

After the five-years phase in of the shock the net-effect of the area-rewetting is negative emissions of 208 $ktCO_2e$ per year, or approximately 7 tCO_ee per ha. per year. The time-profile of the change compared to baseline are in figure (4) below. In the phase-in period there is a transitory negative emissions stemming from the fact that the equilibrium biomass for wetlands is higher than both grass- and cropland.

Figure 11: LULUCF-shock: Re-wetting agricultural soils



Source: Own calculations in GreenREFORM

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