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Land use and LULUCF emissions in GreenREFORM

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1 Introduction

This memo documents how the land use module of GreenREFORM works and, in particular, how so-called LULUCF-emissions are calculated. In this note we describe our current approach to modelling LULUCF emissions. We attempt to replicate the official method used for estimating emissionsin the Danish National Emissions Inventory 2020, DNEI (Nielsen et al., 2020a,b). However, as economists, LULUCF dynamics are outside our area of expertise. Improvements therefore depend on improving i) our understanding of LULUCF dynamics and ii) access to the relevant data. One purpose of the memo as it stands is to enable us to have a discussion of these issues with field experts.

Data and methods are, to the extent possible, based on the official data used to calculate Danish LULUCF emissions, namely the Danish National Emissions Inventory and the Danish National Forest Accounting Plan (Johannsen et al., 2019, DNFAP). The DNFAP is used as an input to produce the DNEI, but contains additional information on the dynamics of forestry emissions. We also use the LULUCF emissions forecast of the Danish Energy Outlook (The Danish Energy Agency, 2020), which includes a forecast of LULUCF emissions up until and including 2030.

Our attempt at replicating the 2020 Danish National Emissions Inventory is in some ways outdated, as a new Emissions Inventory for 2021 has been released. The 2021 inventory feeds into the latest official Danish emissions projection, the Climate Outlook 2021, published by the Danish Energy Agency. It is relevant to update our methods to the methods and baseline data used in the Climate Outlook 2021.

After this introductory section, 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, we show some results to give an idea of how the model works (section 4).

1.1 Status

There are currently discrepancies between how we model LULUCF emissions effects, compared to the official models used to produce the National Emissions Inventory and the Danish Energy Outlook. Reasons for these discrepancies include lack of access to detailed model data, as well as a limited understanding of the underlying models. The underlying models are documented in various places, and at various levels of detail.

Currently, the differences compared to the official LULUCF method mean that effects on the margin of e.g., changes in land will differ. This means that, for a given change in land use, the GreenREFORM module will not predict the same changes in LULUCF emissions as the change that will be apparent in next year's official Emissions Inventory. The magnitude of such differences can be tested - it would indeed be useful to do so. Given better data, additional time and resources, and expert guidance, we believe that the current module can be improved.

From the results presented in this mem, the main differences between the GreenREFORM LULUCF model and the official method appear to stem from two sources, namely:

1. Emissions from cropland with high levels (>12%) of organic content (OC)
2. Forestry emissions

Moving forward, our top priority is to improve these two parts of the model.

Given the caveats outlined above, it should be clear that the GreenREFORM LULUCF module is not built to replace the existing, more detailed model frameworks. Rather, the module is meant as a guiding tool that 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 in a coherent framework and in a single operation.

1.2 Terminology and data

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 i in year t by $land_{i,t}$ and we also define matrices of gross land use changes, $\Delta land_t$, where element $\Delta land_{j,i,t}$ describes the change of land type j into land type i 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 i, minus any changes of land *from* type i into other land types. This is summed up in the following accounting equation:

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

It can be useful to split LULUCF emissions in 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 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.[1]

- **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, wood-based panels and paper, and paper products). These materials contain carbon that is released when the products reach the end of their life cycle.

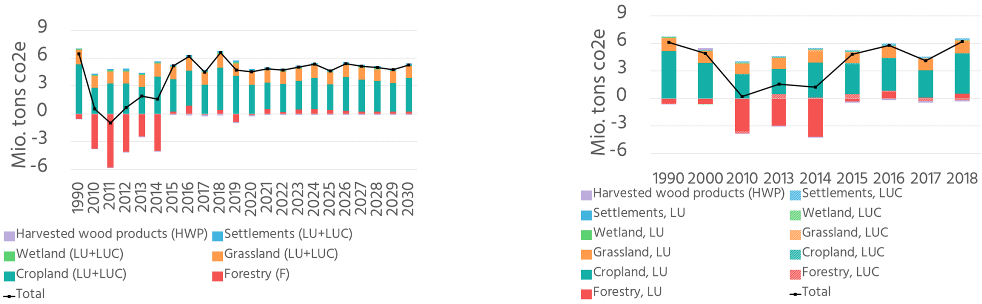
Yearly net emissions, as well as the forecast up until 2030, from these components are illustrated in figure 2a. Detailed information on land use emissions of cropland and grassland by organic content is also available in DNEI. We note that the Energy Otlook forecast does not distinguish between LU and LUC emissions, but it does break down emissions according to land types (cropland, grassland, wetland and settlements). Detailed information on LU and LUC emissions are available in the yearly emissions inventories, cf. figure 2b. Emissions split by carbon content categories are only available in select historic years (Nielsen et al., 2020a, table 6.18 and 6.20) and not in forecast years.

We also have information on land use and land use changes from the forecast of The Danish Energy Agency (2020), cf. figure 2.[2]

[1] Formally, we classify LULUCF emissions from the line item "forest land remaining forest land" as belonging to this category. Emissions from "land converted to forest land" is covered under Land Use Change.

[2] There is a typo in the land use data in the background material for LULUCF accompanying the energy outlook. We have recieved the correct data from personal correspondence with Steen Gyldenkærne, Danish Centre For Environment And Energy, University of Aarhus.

Figure 1: Net emissions from LULUCF

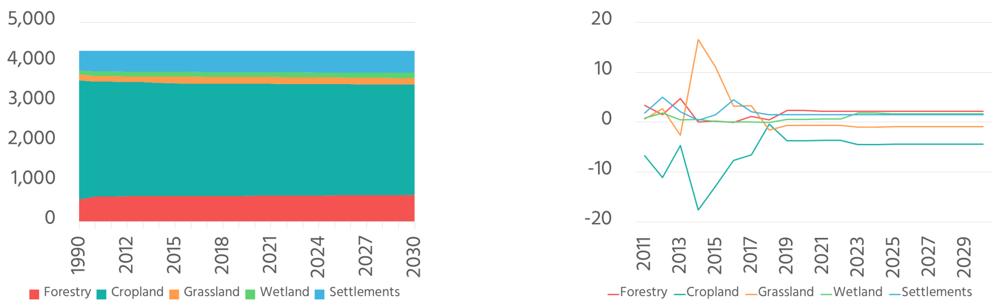


(a) Net emissions, 1990-2030 (b) Detailed net emissions, 1990-2018

Source: Figure a: Background datasheet of The Danish Energy Agency (2020). Figure b: Nielsen et al. (2020a, table 6.3)

Note: Figure a shows yearly net emissions for 1990 and each year from 2010 to 2030. Figure b shows yearly net emissions for 1990 and 200 and each year from 2013 to 2018.

Figure 2: Land use and land use changes



(a) Land use, 1990-2030 (b) Land use changes, 2010-2030

Source: Background datasheet of The Danish Energy Agency (2020) and own calculations

Note: The reported grassland reduction in 2019 is 118.000 hectares.

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. They all take available land use and emissions data as key inputs. Where data is unavailable, we fill in with assumptions and calibrated values that are described in more detail in this section. The main idea is to set up the best possible model based on available reports and historical data. For this memo, historical data is available until 2018. Reported emissions and emission coefficients after this year are projections - either our own or taken from the official projection.

We denote land use stock as $land_{i,t}$, where $i = \{forest, cropland_{<6\%}, cropland_{6\%-12\%}, cropland_{>12\%}, grassland_{<6\%}, grassland_{6\%-12\%}, grassland_{>12\%}, settlements, wetlands\}$ 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 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:

$$CO_2e_t^{LU} = \sum_i u_{i,t}^{LU} * land_{i,t} + \sum_{i,j} \sum_{s=1990}^{t} u_{i,j,s}^{LU-conv} \Delta land_{i,j,s} + \sum_i u_{i,t}^{other} * land_{i,t} \quad (2)$$

where i is the set of land types excluding forest. Land Use emissions consist of three terms:

1. A emission per hectar of land use of different types (the first term)
2. A term that accounts for conversions of high-carbon soils that have been converted to wetlands, as these soils emit some amount of methane every year (the second term).

[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.

3. A term that accounts for emissions that are nominally not related to neither land use nor land use change, but that we include here for now.

We address each of these terms in reverse order:

In the third term - emissions that are not related to land use nor land use change - we include emissions that are described as "Emissions and removals from drainage and rewetting and other management of organic and mineral soils" (Nielsen et al., 2020a, table 4.ii). We calibrate emission factors, $u_{i,t}^{other}$, to the official emissions projection and let emissions be proportional to land use during simulations.

In the second term - emissions from converted wetlands - we include emissions from land converted to wetlands from $cropland_{>12\%}$ and $grassland_{>12\%}$ since 1990. In practice, we model a yearly methane emission of 288 kg per hectare (Nielsen et al., 2020b, table 8.2). For all other types of conversions, the $u_{i,j,s}^{LU-conv}$ coefficients are set to zero.

In the first term - emission coefficients on land use - we calibrate the $u_{i,t}^{LU}$ coefficients in order to replicate land use stocks as well as land use-related emissions for each land use category. However, for high-carbon grass and cropland, we use the values reported by Nielsen et al. (2020b, table 8.2). Calibrated values as well as values used are illustrated in table 1. There is a substantial degree of consistency between the coefficients calibrated from data and coefficients from Nielsen et al. (2020b) except for $cropland_{>12\%}$, where the coefficient of Nielsen et al. (2020b) is about 20% higher. Understanding this discrepancy is important for future work.

Table 1: Calibrated land use emission, ton CO_2e per hectare

	Calibrated 1990	Calibrated 2018	Nielsen et al. (2020)	Olesen et al. (2018)	MFVM (2020)
$cropland_{>12\%}$	42.1	39.7	48.3	35.0	
$cropland_{6\%-12\%}$	21.0	19.7	24.0	21.1	15.0
$cropland_{<6\%}$	0.2	0.3		N/A	
$grassland_{>12\%}$	41.3	36.1	35.1	30.8	
$grassland_{6\%-12\%}$	4.4	19.9	17.5	15.4	N/A
$grassland_{<6\%}$	0.1	0.3		N/A	
Wetland	1.0	0.4		N/A	N/A
Settlements	0	0		N/A	N/A

Source: "1990" and "2018" columns are own calibrated values based based on Nielsen et al. (2020a) and The Danish Energy Agency (2020). The column "Nielsen et al. (2020a)" are own calculations based on Nielsen et al. (2020a), table 8.2. MFVM (2020) is Miljø- og Fødevareministeriet (2020)
Note: OC is organic content. The figure of Miljø- og Fødevareministeriet (2020) is weighted average, based on practical experiences with reducing high-OC cropland.

Full data including land use split by carbon content is (only) available for the years

1990 and 2018. We can therefore only calibrate the $u_{i,t}^{LU}$ coefficients directly for these two years.[4] The land use coefficients reflect annual emissions from each type of land. The annual effect of e.g. stopping drainage on cropland with high organic content (high-OC) and converting it to wetland is determined by the land use coefficient. It is therefore reassuring to note that the calibrated coefficients are close to available estimates of such effects in the Danish context (Olesen et al., 2018), cf. table 1. In practice, the effects of reducing high-OC cropland are often thought to be smaller, since it is not possible in practice to target only high-OC land, and the effect per hectare is therefore a weighted average of high- and low-OC emission factors (Miljø- og Fødevareministeriet, 2020). Such an average emission factor can be achieved by designing a model shock where some combination of cropland types are removed simultaneously. When the model is used to evaluate changes in land use compared to the baseline, marginal effects are calculated using the calibrated coefficients. It is in principle possible to achieve complete consistency with the emission factors of Olesen et al. (2018). However, this would require an additional assumption that the marginal high-OC hectares that can be removed have a different land use emission factor than the average high-OC hectare.

2.2 Land use change emissions

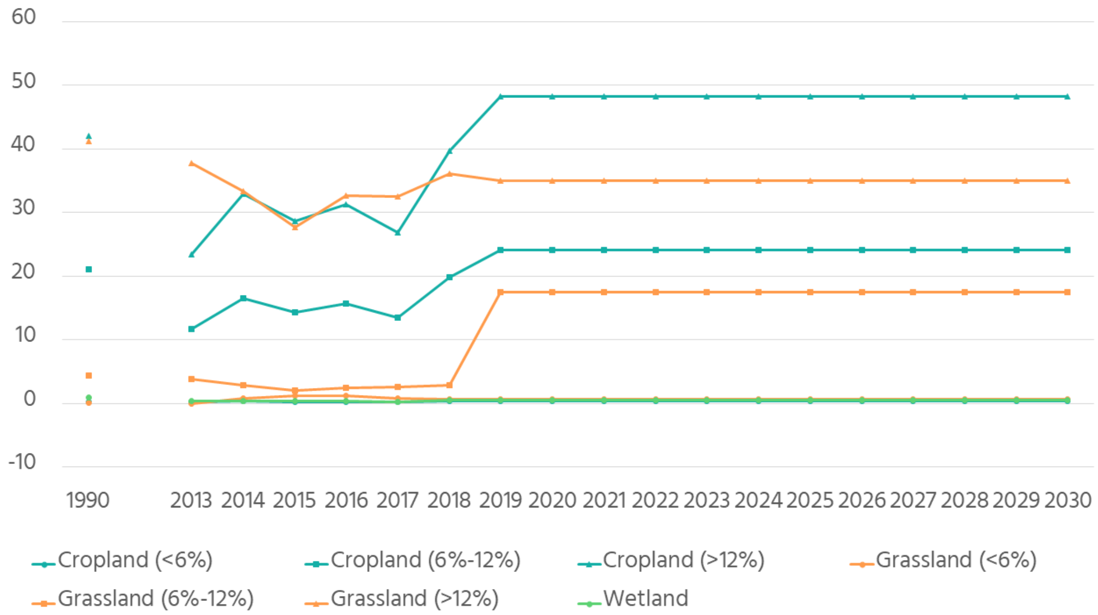
Emissions from land use change (LUC) use yearly transition matrices as the main input. Using these as well as data on the stock of carbon on each type of land, net emissions can be calculated. There is a distinction between the above- and below-ground biomass stock on land type i (b_i^{bm}), which is removed instantly, and below-ground default C-stocks (b_i^{stock}), which adjusts to the steady state value of its new land use type over a longer period.[5] 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) More information could be included here, if available.

Thus, emissions from land converted into type i from type j, $\Delta land_{j,i,t}$, can be caluclated as:

[4] Using an interpolation procedure, we do also calibrate coefficients for the years between 1990 and 2018 in order to replicate emissions aggregates. These are part of the model database, but do not impact model results.

[5] Coefficients on above and below-ground biomass are taken directly from Nielsen et al. (2020a) (table 6.8). We note that the stock of below-ground biomass on wetlands differs from table 6.8 (10.080 kg dry matter per hectare) and the description in the text (1.200 kg dry matter per hectare (Nielsen et al., 2020a, p. 482)). We are not in a position to determine which number is correct.

Figure 3: Land Use emission coefficients used in the GreenREFORM module, ton CO_2e per hectare



Source: Nielsen et al. (2020a); The Danish Energy Agency (2020) and own calculations.
Note: Values up until 2018 are calibrated based on historical data and own imputations. Values from 2019 and forward are used in projections. For projections, calibrated 2018-values are used for low-OC cropland and grassland as well as wetlands, whereas reported emissions coefficients from Nielsen et al. (2020b) are used for medium- and high-OC cropland and grassland.

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

	Biomass	Default C stock
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) and own assumptions.

$$CO_2e^{LUC}_{i,t} = \sum_j [\Delta land_{j,i,t} * (b^{bm}_j - b^{bm}_i) + oxi_{j,i}] \quad (3)$$

$$+ \sum_t^T \sum_j [\Delta land_{j,i,t} * (b^{stock}_j - b^{stock}_i) * \rho^{LUC,t}_i] \quad (4)$$

The equation states that net emissions from land converted into type i are given as the change in above-ground biomass from all types of land converted into this land type (the first term), plus emissions from the gradual change of below-ground biomass (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). We assume, in the absence of more detailed informaton, that below-ground biomass is removed in a linear fashion, i.e., that $\rho^{LUC,t}_i = .. = \rho^{LUC,t-30}_i = \frac{1}{30}$ for $i = \{cropland_{<6\%}, croppland_{6\%-12\%}, cropland_{>12\%}, grassland_{<6\%}, grassland_{6\%-12\%}, grassland_{>12\%}, settlements\}$
- For wetlands, there is a change in below-ground biomass for land converted to wetlands; this biomass stays at the initial level (Nielsen et al., 2020a, p. 482), Thus, we set $\rho^{LUC,t}_i = 0$ for all t for $i = \{wetlands\}$.
- For land converted into forestry, the adjustment process is assumed to take 100 years. Further, the stock of below-ground biomass in forests is handled by the forestry module. Therefore, we set $\rho^{LUC,t}_i = \rho^{LUC,t-100}_i = \frac{1}{100}$ for $i = \{forest\}$.
- 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). We assume the same is true for wetlands.

The method described above requires land use change transition matrices ($\Delta land_{j,i,t}$) going back 30 years for non-forest land types and 100 year for forest land. In accordance with the official methodology, we employ a "broken-stick" method, where we assume that there are changes in land use prior to 1990, which is the first year where data is available.

Nothing in this framework is calibrated to emissions data. Thus, one way of testing whether this framework is reasonable is to test against historic LUC emissions data. However, using the method described above, it is possible to do for the years closest to 2018 without a major error from this. When we do so, wetland LUC emissions (where there is no adoption of below-ground biomass) are fairly close to their historical averages; however, this is not the case for cropland, grassland and settlements. This is a strong indication that the method requires improvement, and that the modeling of below-ground biomas is causing issues.

2.3 Calibration of LU and LUC emissions

For land use emisisons, emissions coefficients are already calibrated to replicate historic data as well as our interpolations of historic data. Thus, no further calibration is required. For Land Use Changes, we calibrate a set of year- and land type specific coefficients to ensure that we replicate data in historic years.

2.4 Forestry

We use the same approach to model the dynamics of net emissions from forestry as the official model used in the emissions inventory for trees older than 30 years. This model, which is used for the so-called Danish National Forest Accounting Plan (DNFAP), is well-documented and detailed model data is publically available (Johannsen et al., 2019).[6] For young trees, DNFAP use a separate method.

The model for older trees separates the total forest area (measured in hectares) at time t, $area_{t,f,r,a}$ into tree types, $f = \{broadleaves, conifers, christmas\ trees\}$ and regions, $r = \{Jutland, Islands\}$ as well as age classes, $a = \{0, 1, ..., A\}$. For each tree type, region and age class, two pieces of information are known, namely i) the survival rate $s_{f,r,a}$, i.e. the probability that the tree achieves age $a + 1$ in the next period and ii) the carbon stock of that tree type per hectare, $C_{f,r,a}$. If trees don's survive, they are renewed, which means they reenter the model as age zero trees. This allows for a Markov chain-style dynamic model of net emissions: For a given age class, a forest area either survives into the next age class, is renewed, or the forest area is removed. Deforestation (def) is exogenously specified. For the oldest age class, A, trees have a fixed probability of being renewed; if they are not renewed, they stay in that age class in the next period. Finally, new forest areas can be introduced due to aforestation (aff). New forest areas enter the model as age class zero trees. To be specific, the stock equations for forest areas are:

[6] Model data is available at https://www.doi.org/10.17894/ucph.96be1df6-a26e-4d8c-aeb0-7f516d7148dd and https://www.doi.org/10.17894/ucph.96be1df6-a26e-4d8c-aeb0-7f516d7148dd

$$area_{t,f,r,a} = \begin{cases} area_{t-1,f,r,a-1} * s_{f,r,a-1} - \text{def}_{t,f,r,a} & for\ 0 < a < A \\ \sum_{a'} area_{t-1,f,r,a'} * (1 - s_{f,r,a'}) + \text{aff.}_{t,f,r} - \text{def}_{t,f,r,a} & for\ a = 0 \\ (area_{t-1,f,r,a} + area_{t-1,f,r,a-1}) * s_{f,r,a-1} - \text{def}_{t,f,r,a} & for\ a = A \end{cases} \tag{5}$$

The NFAP-model uses five-year periods and age classes. We calculate yearly areas as a backward-looking weighted average between the previous five-year period and the next five-year period.

Using this, net emissions can be calculated as the total change in carbon stock from last period. We also add a constant level of soil emissions of CO_2, CH_4 and N_2O, for a total of 158 kt CO_2e per year (Johannsen et al., 2019, p. 48):

$$emissions_t^F = \sum_f \sum_r \sum_a [(area_{t-1,f,r,a} - area_{t,f,r,a}) * C_{f,r,a} * 3,67] + 158 \tag{6}$$

Where the change in the carbon stock is multiplied with 3,67 to account for the atomic weight of CO_2 being 3,67 times that of the carbon atom. This method is identical to the method used by (Johannsen et al., 2019) to estimate the so-called Forest Reference Level. The Forest Reference level (FRL) is used as an input in the calculation of forestry-related net emissions in the Danish Emissions Inventory and the emissions forecast of the Energy Outlook. The forest reference level relies on the method described above and assumes a constant forest arrea, i.e., zero deforestation and afforestation.

Using the approach described above, our simulation of the carbon stock is very similar to the offically reported figures for the FRL (cf. section 4.1.2 and figure 6 below). This validates our approach, although we should investigate why there are any differences, given that the input data should be identical. One potential issue concerns the survival rates $s_{f,r,a}$ of the detailed model data. Some survival rates must be imputed for the model to run, and when we we follow Johannsen et al. (2019) and conduct linear imputation, our results differ from the survival rates used in FRL results. This issue is described in more detail in appendix A.

The FRL assumes that the forest area has been constant constant since 1990, whereas in reality, the area has increased, cf. figure 2. Johannsen et al. (2019) describe how net emissions from forestry consist of the sum of the FRL and afforestation as well as deforestation effects since 1990. A separate model is used to model afforested land for the first 30 years of the forests' lifetime, after which it enters the model framework described above. We do not currently include a separate model for young trees. Further, we lack information on the how afforested trees enter the framework of 5 when they reach 30 years of age.

Importantly, we also lack information about the distribution of historic afforestation and deforestation as well as assumptions about future afforestation and deforestation.[7]

For now, we simply assume that gross afforestation since 2015 is 2105 hectares per year and deforestation is 205 hectares per year, which gives a net increase in forest area of 1900 hectares per year, and that afforestation and deforestation in year t is proportional to the existing forest. This is consistent with assumptions used in the DNFAP, but may differ from what is used in the DNEI.

We note that there are additional emissions from forestry that occurs on drained land (Nielsen et al., 2020b, table 8.2). Since we do not currently have access to data on how much forest land that is drained, we ignore these emissions for now.

2.5 Harvested wood products

Forest products can be used as harvested wood products (HWP). The lifetime of HWP depends on the type of wood product, and the emissions inventory split HWP into three categories, namely sawn wood, wood-based panels and paper, and paper products with half-lives of 35, 25 and 2 years, respectively. We do not currently model the production and decomposition of HWP; instead, we currently assume that net emisions from HWP are constant. This is consistent with the Energy Outlook forecast. This, combined with the relative small share of HWP net emissions, cf. figure 1, we do not believe this omission in our model constitutes a major source of error.

However, given time and resources, we hope to be able to include a model of HWP net emissions.

3 Integration with GreenREFORM

There is currently a single point of connection between the land use module an the rest of the GreenREFORM model system, namely that cropland is linked to input

[7] Since the carbon stock of forests increases with age, we need "gross flows" of both afforestation and deforestation. Further, the age and type distribution of deforested areas matter.

of land in the agricultural module. This means that when cropland is removed and changed to e.g. forest, this has implications in the agricultural module.

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 coverd by the agricultural module.

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 multiplicative scalars 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), but not on a more detailed level (e.g. seperately for LU and LUC emissions or for low-, medium- and high-OC land). We therefore only calibrate emisions results at the aggregated five-type level. This ensures baseline consistency of aggregated results. Since only five-type results are calibrated to the official figures, the module as it stands should not be used to investigate changes in emissions on a finer level.

However, the calibration to the official emissions projection also hides differences between the underlying models. In gauge 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 2020 (BF20).

4 Results

In this section, we first present baseline projection results before calibration. We conlude the paper by illustrating the results in our calibrated module to a change in land use.

4.1 Baseline results before calibration

Results are summarized in figure 4, which shows the total emissions of the Danish Energy Outlook forecast and forecasted emissions of our model. For reference, we

Figure 4: Net emissions from LULUCF, 1.000 tons CO_2e

Source: Nielsen et al. (2020a); The Danish Energy Agency (2020) and own calculations.
Note: BF20 is The Danish Climate and Energy Outlook (2020). KF21 is The Danish Climate Outlook (2021).

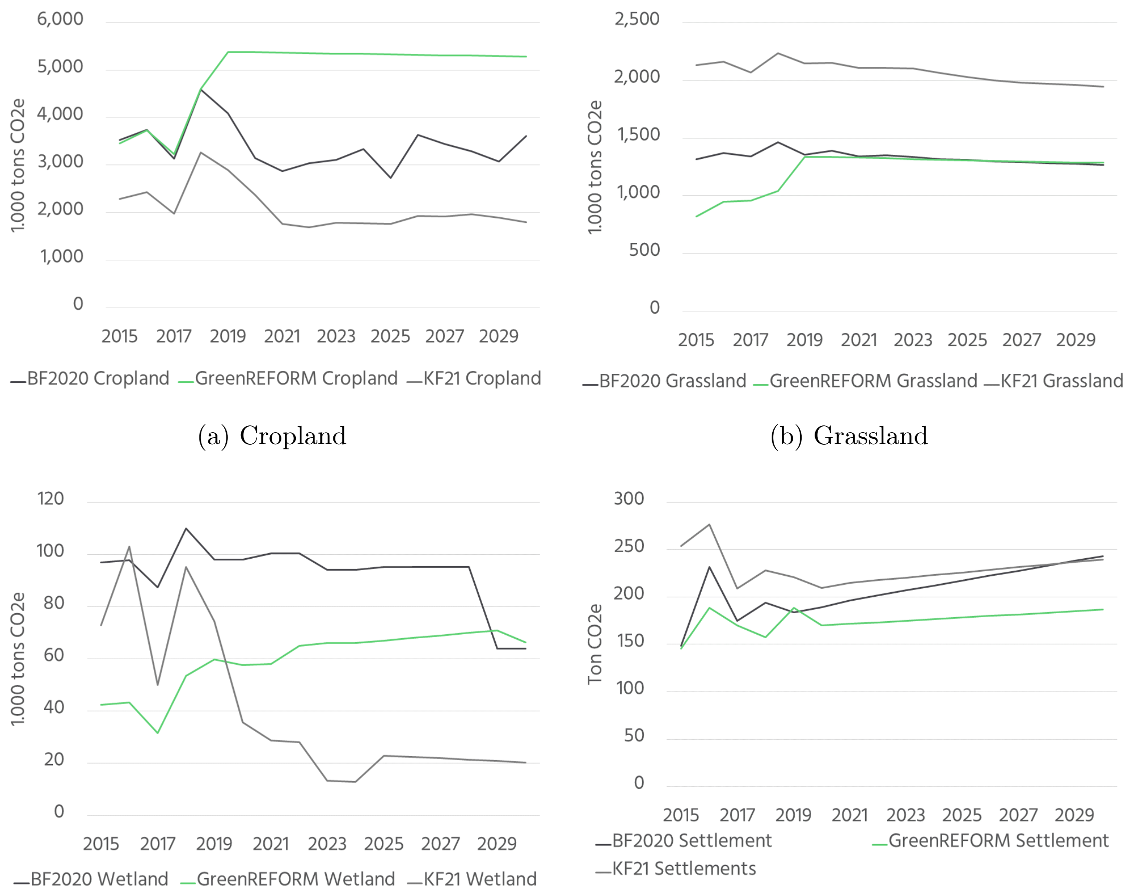
also include the most recent results of the Danish Climate Outlook 2021 (KF21), although we do not discuss these projectons in detail, as the current model is based on data from The Danish Climate and Energy Outlook 2020 (BF20). Overall emissions levels are relatively similar to BF20, although our model has somewhat higher emissions in future years.

4.1.1 Emissions from Land Use and Land Use Change

- For cropland, Energy Outlook emissions are substantially lower than in our model. This is an artifact of the relatively high cropland land use emission coefficent that we employ $cropland_{>12\%}$, as illustrated in figure 1. The discrepancy would be significantly lower if we used the calibrated coefficient rather than the one we can find in the official documentation. In fact, This difference makes up the majority of the discrepancy in total emmissions.
- Grassland emissions are very close to the official BF20 projection.
- For wetlands and settlements, absolute emissions are much lower. This means that these differences are not very important for the total differences between the models, even though the relative differences for wetlands are substantial.

In conclusion, we believe expert guidance is needed in order to improve the modeling

Figure 5: Land Use and Land Use Change net emissions, 1.000 tons CO_2e



(a) Cropland

(b) Grassland

(c) Wetlands

(d) Settlements

Source: Nielsen et al. (2020a); The Danish Energy Agency (2020) and own calculations.
Note: BF20 is The Danish Climate and Energy Outlook (2020). KF21 is The Danish Climate Outlook (2021).

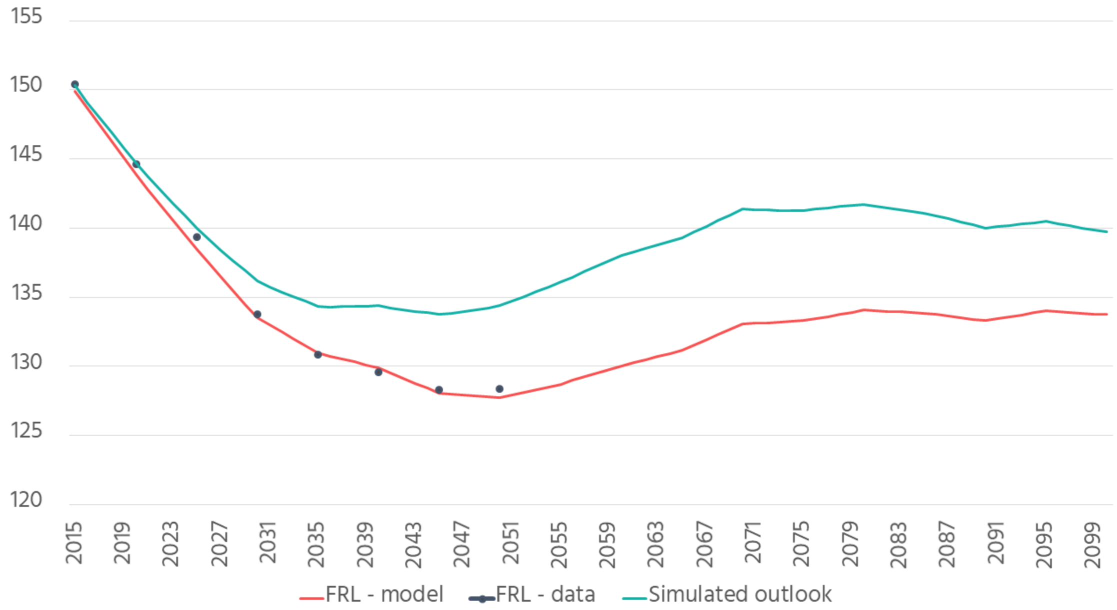
of each of the components above.

4.1.2 Forestry emissions

As described in section 2.4, forecasted emissions are made op of a markov-chain model and a separate model for young trees. Currently, we only model the markov-chain model. Further, we do not have detailed information on afforestation and deforestation of the forecast years. The cleanest comparison is therefore to the results of of Johannsen et al. (2019), where the markov-chain model is used on a constant forest area to establish the so-called Forest Reference Level (FRL). We see that our simulation of the FRL is fairly close to the reported FRL results. We also see that the afforestation increases the carbon pool substantially, but mostly after 2030, as the additional afforested area accumulates.

Net forest emissions are illustrated in figure 7. The overall level of emissions in

Figure 6: Carbon stock projections



Source: Johannsen et al. (2019) and own calculations.

forecast years is similar, although the forecasted emissions profile has some kinks that our model does not currently capture. Some of the kinks appear to have disappeared in the newest official projection ("Klimafremskrivning 2021"). A key area for future work is to understand the drivers of the differences between official projections and the GreenREFORM model.

4.2 Effects of changes in land use

To illustrate the effects of the GreenREFORM module, we have simulated the effects of an exogenous change in land use. The shock consists of a takeout of high-carbon agricultural land. The shock is a crude attempt to a substantial share of the potential for takeout of high-OC agricultural land as described by The Danish Council on Climate Change (2020) Since it is in practice difficult to take out only high-OC agricultural land, the shock also removes some low-OC land. To be concrete, we model the effect of a land use change of 15.000 hectares each year for the ten-year period from 2021-2030. The land use changes are as follows:

- 70% cropland - of this:
  - 1/3 is $cropland_{>12\%}$, which is converted into wetlands
  - 1/3 is $cropland_{6\%-12\%}$, which is converted into wetlands

  - 1/3 is $cropland_{<6\%}$, which is converted into forest

- 30% grassland - of this:
  - 1/3 is $grassland_{>12\%}$, which is converted into wetlands
  - 1/3 is $grassland_{6\%-12\%}$, which is converted into wetlands
  - 1/3 is $grassland_{<6\%}$, which is converted into forest

The newly planted forest is assumed to have the same composition on regions and tree types as the existing stock of forest area. This shock will have spill-over effects on agricultural production, which also generates significant emissions. These effects are captured by the GreenREFORM model framework, but in this section we consider only the partial effects on LULUCF emissions.

Figure 8 illustrates the main results. The changes in land use leads to a decrease in emissions, the size of which is increasing over time. For the period 2021-2030 this is driven by an ever-increasing change in land use. After 2030 it is driven by the continued adjustment of below-ground biomass as well as the carbon capture of the newly planted forests. For the period 2021-2030, the shock reduces cumulated emissions by 12.9 mio. tons CO_2e.

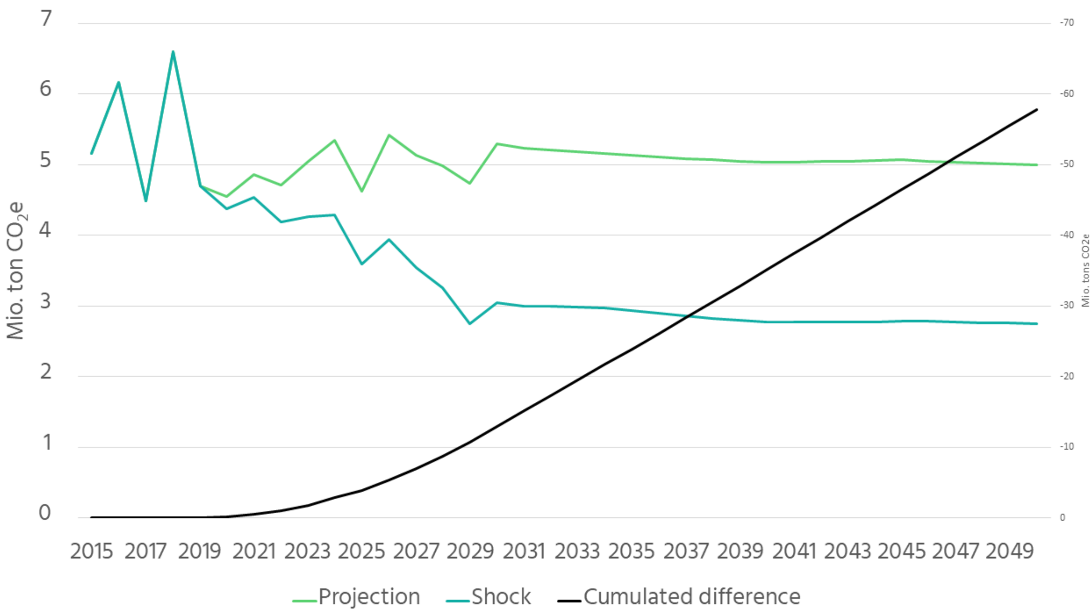
Figure 9 decomposes emisisons in the calibrated baseline as well as in the shock scenario by the five main land use types. It is evident that there is a decrease in emissions from cropland and grassland in the shock scenario. Further, net emissions from forestry decrease and turn into net negative emissions in 2038. The emissions decreases are partly offset by an increase in wetland emissions, which are the methane emissions from converting high-OC soils to wetlands, which are captured by the second term of equation (2).

Since the model does not perfectly replicate the effects used in the official projection, the results of this shock will also vary from the results that would be obtained from using the official method. A comparison of the effects with the same effects computed on the official model could be a fruitful way to gauge the magnitude of the error introduced by the current modelling approach used in the GreenREFORM module.

Figure 7: Net emissions from forestry, 1.000 tons CO_2e

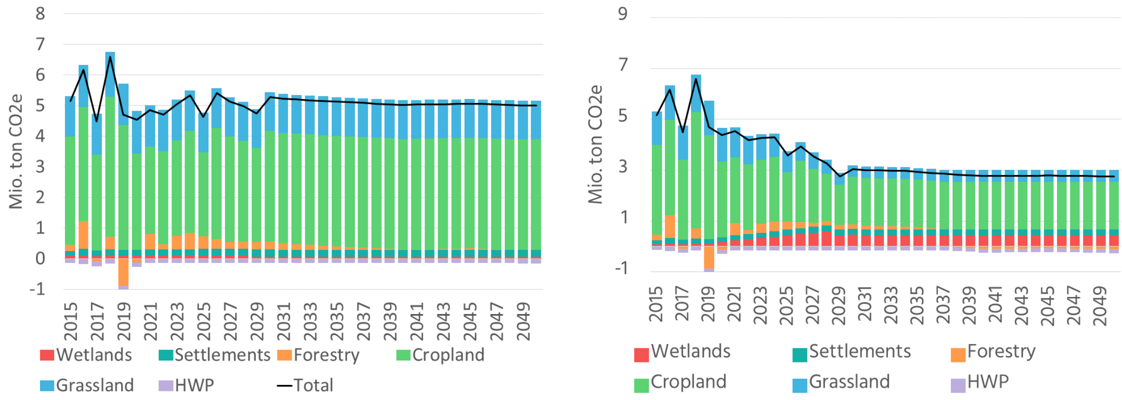
Source: Nielsen et al. (2020a), The Danish Energy Agency (2020) and own calculations.
Note: BF20 is The Danish Climate and Energy Outlook (2020). KF21 is The Danish Climate Outlook (2021).

Figure 8: Emissions in projection and in shock scenario



Source: Own calculations.

Figure 9: Emissions by category in projection and in shock scenario



(a) Projection (b) Shock

Source: Own calculations.
Note: HWP is Harvested Wood Products.

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Appendix A: Imputed forest survival rates

As part of the Danish National Forest Accounting Plan (Johannsen et al., 2019), forest survival rates were estimated. It was not possible to estimate forest survival rates for all age classes for broadleave trees. Therefore, some survival rates need to be imputed. The report states that missing survival rates were obtained by interpolating between known survival rates.

Using the output data from the model of the Danish National Forest Accounting Plan, it is possible to calculate implicit survival rates by using the fact that the area in year t of age class a is the survival rate times the area in year $t-1$ of age class $a-1$, i.e.:

$$area_{t,f,r,a} = area_{t-1,f,r,a-1} * s_{f,r,a-1} \Rightarrow \quad (7)$$

$$s_{f,r,a-1} = \frac{area_{t,f,r,a}}{area_{t-1,f,r,a-1}} \quad (8)$$

When we do this, we can replicate the estimated survival rates. However, implicit survival rates for broadleave trees where survival rates were imputed do not appear to be interpolations between known values. Instead, it appears that the survival rate for the final period has been used. The implicit survival rates calculated using (8) are shown in figure 10.

Figure 10: Implicit survival rates by age classes