Journal of Environmental Management 325 (2023) 116474

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Climate change mitigation potentials of biofuels produced from perennial crops and natural regrowth on abandoned and degraded cropland in Nordic countries

Jan Sandstad Næss *, Xiangping Hu, Maren Haug Gvein, Cristina-Maria Iordan, Otavio Cavalett, Martin Dorber, Baptiste Giroux, Francesco Cherubini

Norwegian University of Science and Technology. Industrial Ecology Programme, Department of Energy and Process Engineering, Høgskoleringen 1, 7011, Trondheim, Norway

A R T I C L E I N F O

Keywords:
Bioenergy
Nature-based solutions
Abandoned cropland
Soil erosion
Land management
Negative emissions

A B S T R A C T

Bioenergy expansion is present in most climate change mitigation scenarios. The associated large land use changes have led to concerns on how bioenergy can be sustainably deployed. Promising win-win strategies include the production of perennial bioenergy crops on recently abandoned cropland or on cropland prone to land degradation, as perennial crops typically reduce soil erosion rates. Natural vegetation regrowth is an alternative nature-based solution that can also co-deliver negative emissions and other environmental benefits. In this study, we explore the potential to deploy bioenergy crops in Nordic countries (Norway, Sweden, Finland, and Denmark) on abandoned cropland and on cropland threatened by soil erosion and compare the achievable climate change mitigation benefits with natural regrowth. We found 186 thousand hectares (kha) of abandoned cropland and 995 kha of cropland threatened by soil erosion suitable for bioenergy crop cultivation. The primary bioenergy potential in the region is 151 PJ (PJ) per year, corresponding to 67–110 PJ per year of liquid biofuels depending on biorefinery technology. This has a climate change mitigation potential from −6.0 to −17 megatons of carbon dioxide equivalents ($MtCO_{2eq}$) per year over the first 20 years (equivalent to 14–40% of annual road transport emissions), with high-end estimates relying on bioenergy coupled to carbon capture and storage (BECCS). On the same area, natural regrowth can deliver negative emissions of −10 $MtCO_{2eq}$ per year. Biofuel production outperforms natural regrowth on 46% of abandoned cropland with currently available biorefinery technologies, 83% with improved energy conversion efficiency, and nearly everywhere with BECCS. For willow windbreaks, improved biorefinery technology or BECCS is necessary to ensure the delivery of larger negative emissions than natural regrowth. Biofuel production is preferable to natural regrowth on 16% of croplands threatened by soil erosion with the current biorefinery technology and on 87% of the land area with BECCS. Without BECCS, liquid biofuels achieve larger climate benefits than natural regrowth only when bioenergy yields are high. Underutilized land and land affected by degradation processes are an opportunity for a gradual and more sustainable bioenergy deployment, and local considerations are needed to identify case-specific solutions that can co-deliver multiple environmental benefits.

1. Introduction

A large-scale bioenergy deployment is essential in most future emission pathways consistent with ambitious temperature stabilization targets (Rogelj et al., 2018b). In top-down global econometric models, global primary bioenergy supply is projected to increase from 57 EJ year^{-1} (IEA, 2017) to a median of 222–412 EJ year^{-1} in 2100 for 1.5 °C scenarios across different Shared Socio-economic Pathways (SSPs) (Riahi et al., 2017; Rogelj et al., 2018a). Agricultural and forest residues will not be sufficient to meet this demand, and extensive deployment of bioenergy plantations growing dedicated lignocellulosic bioenergy crops will be needed (Daioglou et al., 2019; Hanssen et al., 2020). The mean projected land requirement for dedicated bioenergy crops in 1.5 °C scenarios by 2100 is 430–760 Mha across SSPs (IPCC, 2019), equal to 27–48% of the current cropland area extent (FAO, 2011).

These massive land use changes have led to concerns on how

* Corresponding author.
E-mail address: jan.s.nass@ntnu.no (J.S. Næss).

https://doi.org/10.1016/j.jenvman.2022.116474
Received 23 December 2021; Received in revised form 4 October 2022; Accepted 5 October 2022

environmental trade-offs and risks to food security can be avoided (Anderson and Peters, 2016; Calvin et al., 2021; IPCC, 2019; Vaughan and Gough, 2016). Two promising win-win strategies for near-term deployment are the cultivation of bioenergy crops on abandoned cropland (Campbell et al., 2008; Næss et al., 2021, 2022) and croplands threatened by soil erosion (Englund et al., 2020b, 2021a, 2021b). Abandoned cropland has already been impacted by human activities as it was until recently used to produce food or feed, and is usually located near existing infrastructure (Lasanta et al., 2017; Li and Li, 2017). Croplands threatened by soil erosion can benefit from the deployment of bioenergy crops, as soil erosion by water is reduced under perennial crops (Englund et al., 2021a; Ferrarini et al., 2017; Kort et al., 1998; Wang et al., 2020), and the deployment of short-rotation woody crops as windbreaks can substantially reduce soil erosion by wind with benefits to crop yields in the sheltered areas (Englund et al., 2021b; Osorio et al., 2019; Smith et al., 2021). Over time, high soil erosion rates risk to compromise agricultural productivity (Kaiser, 2004), and targeting these areas for land-based climate change mitigation measures is an opportunity to co-deliver reduced environmental impacts and renewable energy production. A switch from food crops to bioenergy crops can also enhance a variety of other ecosystem services (Robertson et al., 2017). Perennial crops typically increase soil carbon stocks thanks to their deep roots, thereby providing benefits to soil quality and climate change mitigation (Ledo et al., 2019, 2020; Qin et al., 2016). Converting cropland to bioenergy crops has also been shown to induce a local biophysical cooling effect during the growth season, which can support climate change adaptation (Georgescu et al., 2011; Wang et al., 2016, 2021). In addition, perennials also boost multiple indicators related to local biodiversity and species richness (Donnison et al., 2021; McCalmont et al., 2017; Robertson et al., 2017).

Natural vegetation regrowth is another option for both land-based climate change mitigation and soil erosion control. Abandoned croplands have already started to accumulate carbon since abandonment (Crawford et al., 2022), a process that will continue without human interference. Soil erosion rates by water are also lower in forested ecosystems relative to croplands (Borrelli et al., 2017, 2020; Hu et al., 2021; Zhou et al., 2021), and trees can be established as windbreaks (Weninger et al., 2021). Understanding where and under which conditions the establishment of bioenergy crops can achieve larger climate benefits than natural regrowth is vital to design optimal land management strategies for abandoned and degraded croplands.

Fossil fuels currently represent about half of the Nordic (Norway, Sweden, Finland, and Denmark) final energy demand, and a rapid decarbonization of the energy system is needed to achieve the net zero emissions needed for climate stabilization. Increasing bioenergy supply is seen as a key option for this ambition, especially in sectors that are hard to electrify or in combination with carbon capture and storage (CCS). While the Nordic region has one of the highest adoption rates of electric vehicles in the world, the ongoing process of replacing the conventional combustion engine vehicle stock will take decades due to the long lifetime of vehicles (Fridstrøm et al., 2016). Recent studies have highlighted the benefits of ramping-up the supply of liquid biofuels for road transport towards the 2030s for shorter-term mitigation (Cavalett and Cherubini, 2022; Wråke et al., 2021). Previous studies focusing on bioenergy resource potentials in the Nordic region have explored biomass streams from domestic managed forest woody biomass (Forbord et al., 2012) and forestry residues (Cavalett and Cherubini, 2018), but the sustainable potential is limited. Further mitigation can be achieved by growing dedicated bioenergy crops (Field et al., 2020), but near-term sustainable Nordic resource potentials are still unclear. A high resolution approach is necessary to identify optimal short-term deployment strategies, which co-delivers multifunctionality across agricultural, land and energy systems.

Previous studies have addressed energy potentials from bioenergy crops on abandoned cropland at the global level (Campbell et al., 2008; Leirpoll et al., 2021; Næss et al., 2021), but they lacked country specific insights and did not quantify climate change mitigation potentials. Likewise, previous studies have identified areas threatened by soil erosion at the EU level which could benefit from a strategic deployment of bioenergy plantations (Englund et al., 2020a, 2021b). However, these studies did not include Norway, they did not spatially quantify bioenergy potentials at a grid level, nor they assessed the effects of biorefinery technology alternatives for bioenergy with CCS (BECCS) on climate change mitigation estimates. There is also a need to assess how mitigation through liquid biofuel production and BECCS compares to natural vegetation regrowth and to identify optimal land management strategies locally.

Here we performed a spatially explicit comparison of the climate change mitigation benefits of liquid biofuel production from bioenergy crops and natural regrowth on abandoned cropland and cropland threatened by soil erosion in Nordic countries. We performed a bottom-up analysis by integrating multiple datasets and methods. We combined two consistent land cover datasets (European Space Agency's Climate Change Initiative Land Cover (ESA CCI-LC) (Defourny et al., 2017) and Copernicus Climate Change Service climate data store (C3S-CDS) (Defourny et al., 2019) to quantify current cropland extent and historical cropland abandonment in the Nordic region between 1992 and 2018. Croplands threatened by soil erosion and suitable for beneficial land use change through bioenergy crop deployment were mapped by integrating the C3S-CDS (Defourny et al., 2019) with datasets on soil erosion by wind (Borrelli et al., 2016) and water (Borrelli et al., 2017). We used the parameterized crop yield model Global Agro-Ecological Zones v4.0 (Fischer et al., 2021) and a high-resolution dataset on willow yields (Mola-Yudego et al., 2016) to quantify bioenergy potentials from cultivating reed canary grass, switchgrass and willow under a modern and highly intensive agricultural management system. The climate change mitigation potential of biofuels were estimated considering three biorefinery technologies: a currently commercial biorefinery (Laser et al., 2009a), a future improved biorefinery (Laser et al., 2009b) and a future improved biorefinery coupled with CCS (Field et al., 2020; Laser et al., 2009b; Liu et al., 2011), Supply chain life-cycle emissions (Krzyżaniak et al., 2016), soil carbon accumulation (Ledo et al., 2020), and fossil fuel displacement were included in the analysis. Using a high-resolution dataset of natural regrowth rates (Cook-Patton et al., 2020), we quantified historical aboveground carbon accumulation on abandoned cropland and future carbon accumulation potentials on abandoned and degraded croplands. Mitigation potentials of natural regrowth were compared with those from biofuels and BECCS.

2. Material and methods

2.1. Abandoned cropland

We used the ESA CCI-LC (Defourny et al., 2017) and the C3S-CDS (Defourny et al., 2019) products to quantify abandoned cropland between 1992 and 2018. The ESA CCI-LC maps provides a dynamic representation of land cover at ten arcseconds spatial resolution using 37 unique land cover classes. There are six land cover classes that represent different cropland types, out of which four describe fully cropland cover and two describe cropland mosaics with a mix of cropland and natural vegetation cover. The dataset was originally developed to improve land use change detection for use in climate models, achieving an average global detection accuracy of 71% when compared to independent validation datasets (Defourny et al., 2017, 2019). The highest accuracy was found for cropland classes.

We quantified abandoned cropland by comparing individual pixels of the ESA CCI-LC and C3S-CDS datasets for all years between 1992 and 2018. Abandoned cropland was mapped as any changes from the six cropland classes to non-cropland classes (entire pixel). This included transitions to 30 different classes, such as to forests, grasslands, shrublands, barren lands, and sparse vegetation, but excluded cropland pixels transitioning to urban areas. Additionally, pixels transitioning from complete cropland cover (four classes) to cropland mosaics (two classes) were considered as abandoned cropland. For improved consistency, the land cover datasets require a land cover transition to be visible for 3 consecutive years before a pixel change classification (Defourny et al., 2017, 2019). Based on this information, we quantified the area extent of cropland abandonment per year since 1992, as it affects the current naturally regrown aboveground carbon stock. We applied a national identified grid (Center for International Earth Science Information Network - CIESIN et al., 2016) to mask out country-specific cropland abandonment in the Nordic region.

2.2. Cropland under soil erosion by wind and water

The Nordic cropland cover in 2018 was identified according to the C3S-CDS data. We used a dataset of soil erosion by water to map Nordic croplands under unsustainable water erosion (Borrelli et al., 2020). This dataset was produced through the Global Soil Erosion Modelling platform (GloSEM), which relies on the Revised Universal Soil Loss Equation (RUSLE) to quantify spatially explicit soil erosion rates. The RUSLE methodology accounts for rainfall runoff erosivity, soil erodibility, slope length and steepness, land cover characteristics and soil conservation measures. We integrated the soil erosion by water dataset (Borrelli et al., 2020) with the cropland maps to quantify erosion rates for each cropland grid cell with the nearest neighbor method. As soil erosion rates exceeding 5 ton ha^{-1} $year^{-1}$ typically requires mitigation measures (Panagos et al., 2015), we filtered out the cropland areas above this threshold to be targeted for bioenergy deployment. We defined croplands under soil erosion by water rates between 5 and 10 and above 10 ton ha^{-1} $year^{-1}$ as under "moderate" or "high" soil erosion by water, respectively. All the available land under soil erosion by water was converted to bioenergy production, as a measure to reduce soil erosion.

Cropland threatened from soil erosion by wind was identified using a European dataset (Borrelli et al., 2016). The dataset considers the most important wind erosion factors, such as climatic erosivity, soil erodibility, vegetation cover and landscape roughness. Through a fuzzy logic technique an Index of Land Susceptibility to Wind Erosion (ILSWE) was created and land areas were spatially ranked into five different levels of wind erosion susceptibility. The ILSWE dataset is provided in ETRS89 Lambert Azimuthal Equal Area projection (500 × 500 m). We used ESRI ArcGIS Pro 2.9.0 (Environmental Systems Research Institute (ESRI), 2021) to project the dataset to WGS84 at 30 arcseconds. We considered cropland under moderate and high wind erosion susceptibility (ILSWE categories 4 and 5, respectively) as areas where woody bioenergy crops deployed as wind barriers can contribute to reduce wind erosion. We aggregated the cropland (2018) from the C3S-CDS database from 10 arcseconds to 30 arcseconds to match the resolution of the ILSWE dataset. We identified croplands under moderate and high susceptibility and used country masks to quantify the country level extent. Establishing woody bioenergy crops in these areas as windbreaks can co-deliver both biomass production and mitigation of soil erosion by wind. Following Englund et al. (2021b), we assumed a willow windbreak design with a width of 50 m, a height of 5 m, rotation periods of 3 years, and a distance between windbreaks of twenty times windbreak height. This means that one third of all croplands threatened from soil erosion by wind was covered by willow crops, while the remaining croplands were retained for food crops sheltered by the new windbreaks. Half of the windbreak is harvested at a time to keep a sustained windbreak functionality.

2.3. Bioenergy yields

Two perennial grasses, reed canary grass (*Phalaris arundinacea)* and switchgrass (*Panicum virgatum*), and the woody crop willow (*Salix* sp.) were the biomass species considered for deployment in the Nordic region (Supplementary Text 1). They have shown promising yields and suitability as bioenergy crops, and they thrive under different climatic conditions (Lewandowski et al., 2003; Nordborg et al., 2018; Usťak et al., 2019).

The parameterized Global Agro-Ecological Zones (GAEZ) v4 model (Fischer et al., 2021) at 5 arcminutes was used to obtain dry mass yields of perennial grasses on the identified available land (Supplementary Fig. 1a and b). Previous versions of GAEZ has been used to assess the productivity of bioenergy crops (Leirpoll et al., 2021; Næss et al., 2021; Staples et al., 2017, 2018; Zhang et al., 2020), and it has been validated against observational field data for perennial grasses (Næss et al., 2022). GAEZ models yields using a variety of site-specific parameters, such as climatic conditions, soil quality, terrain, agricultural management, and water supply. Climatic parameters considered are local surface irradiation, temperature, and precipitation throughout the year. Yield losses from pests, soil workability constraints and frosts are also considered (Fischer et al., 2021). GAEZ models three different levels of agricultural management, and Nordic agriculture is closer to high management intensity (Næss et al., 2021), representative of a market-oriented and mechanized production system where yield gaps are closed, with high yielding varieties, optimal fertilizer use, and optimal pesticide use. We considered present day climatic conditions (multi-ensemble mean of 2011–2040, Representative Concentration Pathway 4.5 (Van Vuuren et al., 2011)) from the NorESM (Tjiputra et al., 2013) model which was downscaled to 0.5° (Hempel et al., 2013).

For willow, we used a spatially explicit yield dataset at 1 km resolution specifically developed for Northern Europe (Supplementary Figure 1c) (Mola-Yudego et al., 2016). Dry mass yields were modelled based on Swedish harvesting records from 1790 willow plantations (Mola-Yudego, 2010), by applying the boosted regression trees approach to combine both statistical and machine learning techniques (Mola-Yudego et al., 2016). The willow model identifies three categories based on agricultural performance at a municipality basis so that variance mainly reflects non-climatic parameters such as management. Consistent with high management intensity from GAEZ, we used the high-performance category from the willow model (based on the top ten percent performing willow plantations per municipality). We used ESRI ArcGIS Pro 2.9.0 (Environmental Systems Research Institute (ESRI), 2021) to project the willow yield data from UTM zone 33 N (1 × 1km) to WGS84 at 30 arcseconds for consistency with the land cover data. We then integrated the willow dataset with land availability maps of abandoned cropland and cropland threatened by soil erosion at 30 arcseconds. Spatially quantified dry mass potentials of willow were upscaled to 5 arcminutes to match the resolution from GAEZ perennials.

We converted dry mass yields to bioenergy yields using lower heating values of 18.06, 17.82, and 18.49 GJ tdm^{-1} for reed canary grass, switchgrass, and willow, respectively (ECN.TNO, 2019). The carbon yield was quantified using carbon content of dry mass ratios of 0.4526, 0.4632 and 0.4882 tC tdm^{-1} for the respective three crops (ECN.TNO, 2019).

2.4. Crop distributions

We allocated the three bioenergy crops to the available land according to the following criteria:

i) Cropland and abandoned cropland under moderate or high levels of soil erosion by wind were allocated to willow to create wind barriers perpendicular to the dominant wind direction, thereby co-delivering reduced wind erosion and biomass production.
ii) Cropland and abandoned cropland under moderate and high levels of soil erosion by water were allocated to the highest yielding crop by maximizing energy production, as soil erosion by water is reduced with both perennial grasses and woody bioenergy crops.
iii) Cropland and abandoned cropland subject to both soil erosion by water and wind was allocated to willow to mitigate both soil erosion types.

iv) Abandoned cropland not subject to soil erosion was allocated to the highest yielding crop to maximize energy production.

While results are mainly shown at 5 arcminutes for improved visualization, the same pixel can contain shares of both perennial grasses and willow, as ESA CCI-LC and the ILSWE datasets were integrated at a higher resolution of 30 arcseconds. Fractional crop allocations were used in the calculations of gridded yields and potentials, while only the dominant crop is shown in the crop distribution maps.

2.5. Biorefineries and CCS

We considered three different cases of biorefinery with and without implementation of CCS technology (following ref (Field et al., 2020) Biorefinery efficiencies for energy conversion and CCS are shown in Supplementary Table 1.

First, we considered a biorefinery producing cellulosic ethanol consistent with present day available technologies (Laser et al., 2009a). This conversion pathway includes dilute acid pretreatment, saccharification and fermentation. Wastewater was treated with a sequence of anaerobic and aerobic digesters to recover organic material that is used to generate electricity through a Rankine cycle. In total, 40.4% of biomass primary energy was converted to ethanol and 2.9% to exported electricity.

We also considered a future design with a hybrid biochemical-thermochemical pathway (Laser et al., 2009b) as a potential future biorefinery. It applies an innovative pretreatment of ammonia fiber expansion and a consolidated bioprocessing to ethanol. Syngas from gasification of fermentation residues (mostly lignin) is additionally converted to Fischer-Tropsch (FT) liquids through single-pass FT conversion. This future biorefinery returned 54.1%, 9.7% and 6.1% of biomass primary energy as ethanol, FT diesel and FT gasoline, respectively. Residual syngas not converted to biofuels was used to produce electricity, with electricity exports equaling 1.3% of biomass primary energy. This process had a CCS efficiency of 1.7% (captured input carbon) due to the production of a char by-product which was assumed to be applied to soil at a 80% long-term carbon retention (Roberts et al., 2010).

Finally, we considered another future biorefinery design with CCS (BECCS) (Field et al., 2020), where CO_2 streams from the conversion process (Laser et al., 2009b) were subject to CCS (Liu et al., 2011). The fermentation produces CO_2 at a 1:1 stoichiometric ratio with ethanol, where 17.9% of the input biomass carbon is captured. Another 30.2% of input carbon is captured from two other streams of CO_2 (a stream of CO_2 during syngas cleanup and from unconverted syngas downstream of the FT reactor). CCS is associated with increased electricity use and turns the future BECCS biorefinery into a net importer of grid electricity equal to 2.3% of the primary energy in the biomass.

2.6. Biofuel climate change mitigation

We quantified the climate change mitigation potential of biofuels using Global Warming Potential with the time horizon of 100 years (GWP100) as climate metric (Forster et al., 2021). Life cycle impacts were quantified for activities of the supply chain, energy substitution of fossil fuels and grid electricity, and soil carbon change due to changing land cover. For abandoned land, we also considered the initial implications of clearing aboveground carbon from natural regrowth after abandonment.

Supply chain emissions considered were on-farm agricultural activities and biomass transportation. Spatially explicit life cycle emissions related to agricultural inputs and energy use needed to produce perennial grasses were based on Giroux (2020). System boundaries were set to include all processes related to biomass planting, cultivation and harvesting up to the farm gate. Processes considered in the foreground system included mowing, ploughing, planting, weeding, fertilizer application, harvesting and bailing (see Supplementary Tables 2–6). The background system covered all the material and energy inputs used during production. Our study assumed a crop cycle of 15 years. We considered country-specific electricity emission factors (Supplementary Table 7) and produced life cycle climate impacts for each country at 5 arcminutes. For willow, agricultural life cycle emissions were based on Krzyżaniak et al. (2016). Spatially explicit climate impacts were quantified using a fitted model as a function of willow yields (tCO_2-eq. tdm^{-1}) (Supplementary Figs. 2 and 3). Transportation of biomass between farm gate and the biorefinery was assumed to be 200 km for all bioenergy crops, a conservative estimate based on a previous study (Cavalett and Cherubini, 2018). We calculated transportation impacts considering fossil diesel energy use in trucks as of 0.811 MJ ton km^{-1} (Etiope, 2009).

Mitigation of climate change was computed by considering emission savings from fossil fuel substitution, CCS, and soil carbon accumulation. Biofuels were assumed to replace fossil fuels at a 1:1 energy ratio. We considered fossil fuel climate impacts to be 84.2 gCO_2eq MJ^{-1} for fossil diesel and 87.1 gCO_2eq MJ^{-1} for fossil gasoline (Wernet et al., 2016). The climate impacts of each country specific electricity mix (Wernet et al., 2016) (Supplementary Table 7) were used to quantify the effect of electricity substitution for the current and future biorefinery, as well as the added impacts from electricity imports to biorefinery operations (in the future BECCS case). Negative emissions from BECCS were calculated as the product between land availability, carbon yields and CCS efficiencies.

Soil carbon sequestration after establishment of bioenergy crops was estimated using a semi-empirical model that predicts the changes in soil organic carbon stocks from conversion of croplands and fallow land to bioenergy crops (Ledo et al., 2020). It is based on a state-of-the-art open access dataset of soil organic carbon change under perennial crops (Ledo et al., 2019) and applies generalized linear mixed modelling techniques with a Gaussian distribution as identity link function (Ledo et al., 2020). A range of parameters related to climatic conditions, topography, soil characteristics, and land use were considered to produce multiple fitted models. The best fitted model can explain 20% of soil carbon dataset variance, a non-neglectable share due to the heterogeneity in available data (Ledo et al., 2019, 2020). Here, we applied the best fitted model parameterized with gridded data on annual mean temperature (°C), crop age (years since the switch to bioenergy crops), soil depth (cm), clay content (%), soil bulk density (g cm^{-3}), and coefficients for previous and current land use.

The ratio of soil carbon change was quantified for 100 cm soil depth over a period of 20 years at 5 arcmin resolution. We used mean annual surface temperature data for the years 2021–2040 and scenario SSP2-4.5 from NorESM2-MM (Seland et al., 2020) at a resolution of $0.9 \times 1.25°$, downscaled to 5 arcminutes with the nearest neighbor method. Spatial datasets of soil bulk density and clay contents were taken from the World Soil Information from the International Science Council (ISC) World Data System (Batjes, 2012). For cropland and abandoned cropland conversion to bioenergy crops we used previous land use coefficients for annual crops and fallow land, respectively (Ledo et al., 2020). The current land use coefficient was set to bioenergy grass for land converted to reed canary grass and switchgrass, and agroforestry for willow deployment. The obtained ratios of soil carbon change were spatially multiplied with present soil carbon stock data from the European Soil Data Center (Hiederer and Köchy, 2011), thereby quantifying total soil carbon accumulation (tC ha^{-1}) over the 20-year period. As it is not recommended to use the method for longer time horizons, we conservatively assumed that soil carbon accumulation due to a switch to bioenergy crops saturates after 20 years.

The climate mitigation benefits or trade-offs of clearing secondary vegetation to make land available for bioenergy crop production depends both on how much carbon has been accumulated and the fate of the cleared biomass. We assumed that aboveground carbon on abandoned cropland (see Natural vegetation regrowth section) was collected and fed to the same bioenergy supply chain for biofuel production as bioenergy crops. We considered a carbon content of 0.487 tC tdm^{-1} and a lower heating value of 18.27 GJ ton_{dm}^{-1}, which for simplicity was assumed equal to birch (ECN.TNO, 2019). Climate impact from secondary vegetation harvesting was taken as 0.0132 tCO_2eq ton_{dm}^{-1} based on the use of a harvesting machine (Wernet et al., 2016). Otherwise, we considered the same parameterization and conversion pathways as for bioenergy crops. As an additional test, we also explored a scenario where aboveground carbon is instead cleared through combustion and released completely to the atmosphere as CO_2, thereby providing an increased initial carbon penalty.

2.7. Natural vegetation regrowth

To compare the climate change mitigation potential of biofuels from bioenergy crops and natural regrowth, a state-of-the-art spatial dataset of carbon accumulation of natural forest regrowth at 30 arcseconds (Cook-Patton et al., 2020) was used to quantify carbon sequestration. The dataset was produced with machine-learning techniques based on 13,112 georeferenced measurements of natural vegetation regrowth from 1400 different studies. A set of 66 environmental covariates including climate, soil nutrient, soil chemical, soil physical, radiation, topography, and nitrogen deposition variables were considered. Out of 16 different applied combinations of machine learning and feature selections, a random forest algorithm with no feature selection performed the best.

Yearly cropland abandonment maps were upscaled from 10 to 30 arcseconds to match the natural regrowth dataset and historical aboveground carbon accumulation per cell was calculated as the product between abandoned land, carbon accumulation rate and the number of years since abandonment. Likewise, future carbon accumulation from natural regrowth was calculated based on land availability and considered time horizon.

We also considered soil organic carbon accumulation from natural regrowth based on mean soil carbon accumulation rates among biomes from a literature review (Cook-Patton et al., 2020). The 14 defined biomes are proxies to divide the Earth's terrestrial ecosystems into areas with similar climatic and environmental conditions (Olson et al., 2001). Soil carbon accumulation rates per biome were based on 5762 field measurements from 3058 unique plots taken from 227 different studies. We quantified abandoned cropland and cropland under soil erosion in each of the four biomes located in the Nordic region at the country level using country (Center for International Earth Science Information Network - CIESIN et al., 2016) and biome (Olson et al., 2001) masks (Supplementary Tables 8 and 9). Using biome-specific mean soil carbon accumulation rates (Cook-Patton et al., 2020) we obtained country specific rates of soil carbon change (Supplementary Table 10).

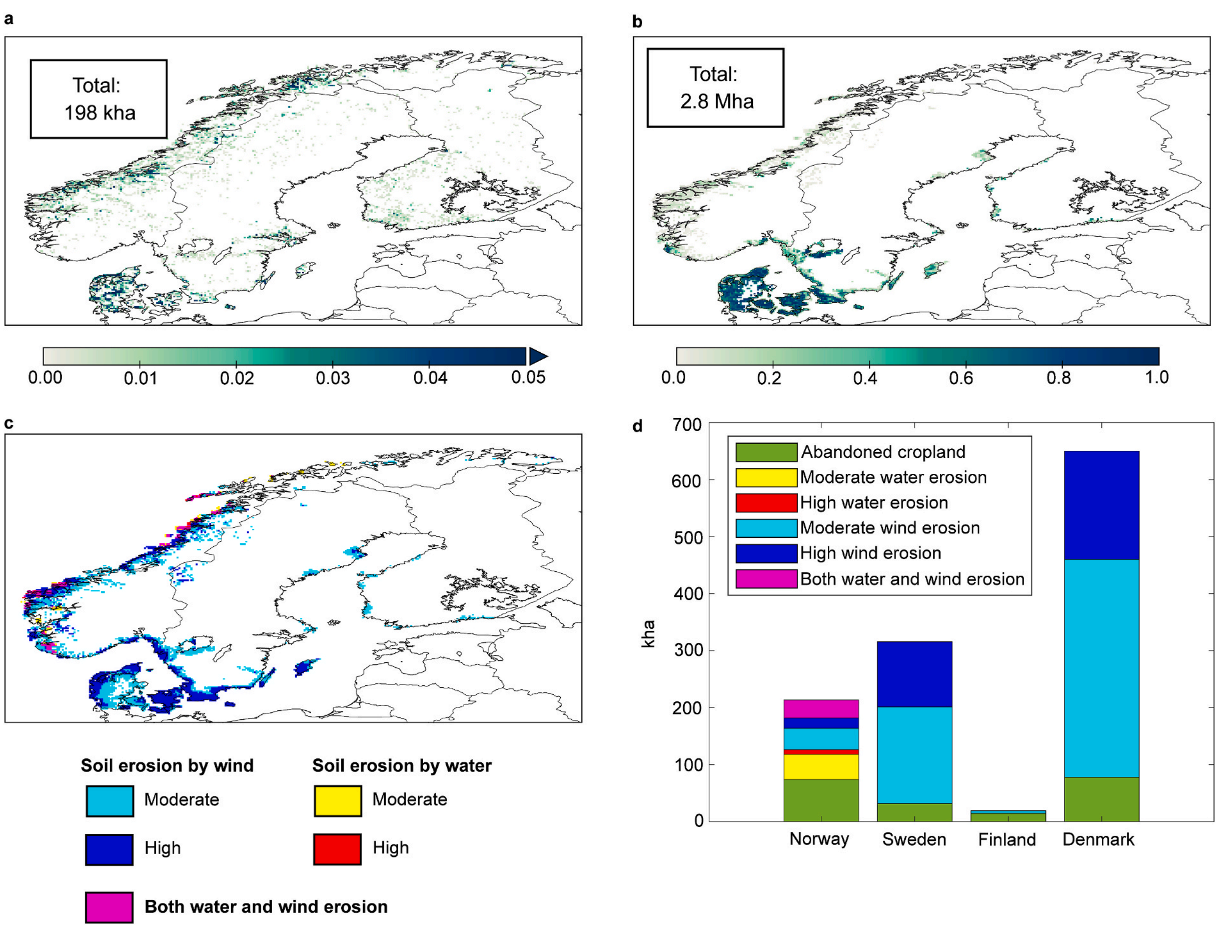

Fig. 1. Land availability for bioenergy production in Nordic countries. Maps of (a) Nordic cropland abandonment (1992–2018) as fraction of grid cell, (b) current croplands under land degradation by soil erosion as fraction of grid cell, and (c) cropland threatened by soil erosion categorized after moderate and high levels of soil erosion by wind and water (or both). (d) Country level distribution of potential land availability for bioenergy crops (kha), made by all abandoned croplands (a), all croplands threatened from soil erosion by water (b) and one third of the cropland threatened from soil erosion by wind (b). Maps are shown at a resolution of 5 arcminutes. Note: Different scales on color bars in (a) and (b). A grid box in (c) is completely colored if there is any land inside the grid box allocated to bioenergy (>0 ha). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Results and discussion

3.1. Abandoned cropland and cropland threatened by soil erosion

We have found 198 kha of cropland abandonment between 1992 and 2018 (Fig. 1a). Cropland abandonment is most intense in Denmark, Southeastern Sweden, and the Central and Northern parts of Norway. A total of 74, 32, 14 and 78 kha of abandoned cropland was found in Norway, Sweden, Finland, and Denmark, respectively.

A total of 2.8 Mha of Nordic croplands were under moderate and high levels of soil erosion by wind and water (Fig. 1b). Out of this, 1000 kha was considered for bioenergy deployment, as only one third of the land under soil erosion by wind should be deployed with windbreaks. About 927 kha was allocated to bioenergy production through a windbreak system. Croplands under soil erosion by water was 84 kha, with 32 kha under simultaneous pressure from soil erosion by water and wind. Cropland at high risk of degradation from soil erosion by water was mainly located in the coastal areas of the Nordic region (Fig. 1c). Large parts of Denmark were under moderate and high levels of wind erosion, giving a bioenergy land availability of 382 kha and 190 kha, respectively. The southern coastline of Sweden and large parts of the Norwegian coastline was also under moderate and high wind erosion levels. There was a potential for wind break deployment of 284 kha and 66 kha in Sweden and Norway, respectively. Norway was the only country with cropland under unsustainable levels of soil erosion by water, especially in coastal and mountainous areas (70 kha and 14 kha

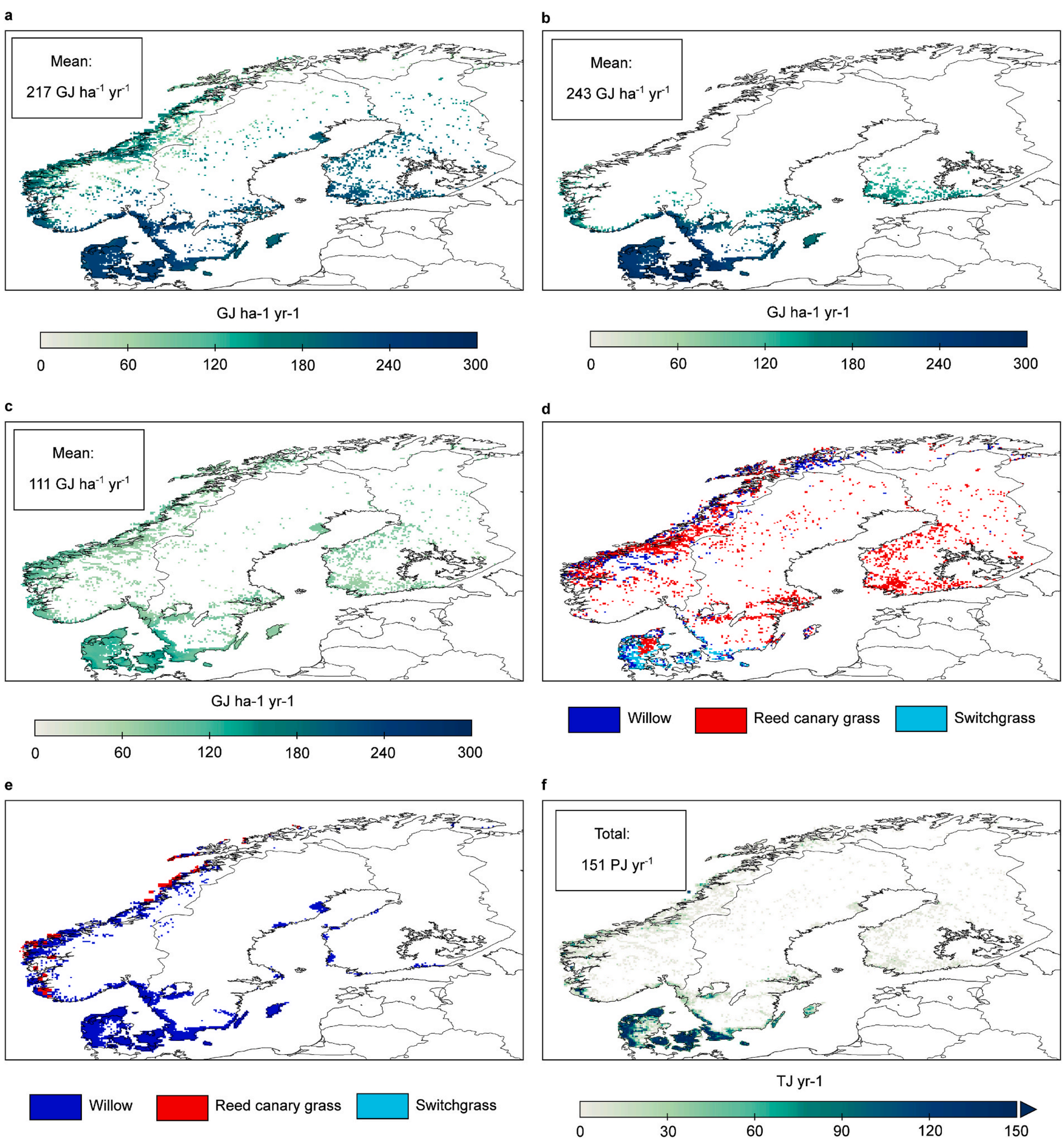

Fig. 2. Primary bioenergy yields (GJ ha^{-1} year^{-1}), crop allocations, and primary bioenergy potentials (PJ year^{-1}) on abandoned cropland and cropland threatened by soil erosion in Nordic countries. Bioenergy yields are shown for (a) reed canary grass, (b) switchgrass, (c) willow for the grid cell where each of these crops achieve the highest yield. Crop distribution maps refer to (d) abandoned cropland and (e) cropland under moderate and high levels of soil erosion by wind and water. (f) Annual bioenergy potentials of deploying both available abandoned cropland and cropland under moderate and high soil erosion by wind and water. Map resolutions are 5 arcminutes.

under moderate and high levels, respectively).

The total considered land for bioenergy crops (Fig. 1d) was the highest in Denmark (650 kha), followed by Sweden (316 kha), Norway (213 kha), and Finland (19 kha). This equaled 25%, 12%, 13% and 1% of the current arable land extent in each country, respectively (Natural Resources Institute Finland, 2021; Statistics Denmark, 2021; Statistics Norway, 2021; Statistics Sweden, 2021). Cropland under wind erosion contributed to 90% and 88% of the total land availability in Denmark and Sweden, respectively. Cropland threatened from soil erosion by water covered the largest share of land availability in Norway (39%). In Finland, abandoned cropland was the major contributor with 75% of its total land availability.

3.2. Bioenergy productivity and energy potential

Fig. 2 shows bioenergy yields of the individual bioenergy crops, crop allocations on the identified land, and the bioenergy potentials. The mean primary bioenergy yield of reed canary grass on productive land was 217 GJ ha^{-1} year^{-1}, with yields higher than 200 GJ ha^{-1} year^{-1} in Denmark and the southern coastline of Norway and Sweden (Fig. 2a). Reed canary grass yields decreased at higher latitudes, but most of the land stayed productive (>98%). Switchgrass showed a 12% higher mean bioenergy yield on productive land (243 GJ ha^{-1} year^{-1}) than reed canary grass but was mostly unproductive above 60 °N due to unfavorable climatic conditions (Fig. 2b). Willow was also productive nearly everywhere (98% of the land), but with a mean bioenergy yield of 111 GJ ha^{-1} yr^{-1} (Fig. 2c). Willow had higher productivity than the two perennial grasses only in mountainous areas or at high latitudes (34 kha).

Most of the abandoned cropland was allocated to crops based on maximal energy production (156 kha), except abandoned croplands under soil erosion by wind which were forced to willow for windbreaks deployment to provide environmental benefits through reduced wind erosion (30 kha). On abandoned cropland, 48 kha, 91 kha and 47 kha were allocated to switchgrass, reed canary grass and willow, respectively (Fig. 2d), while 12 kha was unproductive. Switchgrass was the dominant crop on abandoned croplands in Denmark due to superior productivity (42 kha), followed by reed canary grass (20 kha) and willow windbreak deployment (16 kha). In Sweden, 18, 7, and 4 kha were allocated to reed canary grass, switchgrass, and willow, respectively. Reed canary grass covered nearly everything in Finland (14 kha). Norwegian abandoned cropland had 40 kha allocated to reed canary grass and 26 kha to willow. For croplands threatened by soil erosion (Fig. 2e), all areas in Denmark (572 kha), Sweden (287 kha) and Finland (47 kha) were allocated to willow for windbreaks deployment. In Norway, 76 and 59 kha were allocated to reed canary grass and willow, respectively.

In total across both abandoned croplands and croplands threatened by soil erosion, 965 kha, 168 kha and 47 kha were allocated to willow, reed canary grass and switchgrass, respectively (Supplementary Fig. 4). This gave a total primary energy potential of 151 PJ year^{-1} in the Nordic region (Fig. 2f). About 22% came from biomass produced on abandoned cropland and 78% from biomass from cropland threatened by soil erosion. With the given crop allocation, 98% of the available land was productive and utilized for bioenergy production. Most of the primary potential was in Denmark (86 PJ year^{-1}), followed by Sweden (35 PJ year^{-1}), Norway (27 PJ year^{-1}) and Finland (3.3 PJ year^{-1}).

The net final energy produced was 67, 110, and 105 PJ year^{-1} with the current, future, and BECCS biorefinery, respectively (Fig. 3). Cropland threatened by wind erosion was the major contributor to potentials in Denmark (78%) and Sweden (84%), whilst abandoned cropland dominates in Finland (93%). Norway was the only country with croplands experiencing unsustainable levels of soil erosion simultaneously by both water and wind (21% of the potential), and these areas may be especially beneficial to target for deployment. Final energy supply was mostly cellulosic ethanol, with additional co-production of electricity, Fischer-Tropsch diesel, and Fischer-Tropsch gasoline depending on the biorefinery (Supplementary Table 11). Notably, with BECCS, the biorefinery turned from an electricity producer (4.6 and 2.0 PJ year^{-1} for the current and future refinery, respectively) into an importer (−4 PJ year^{-1}).

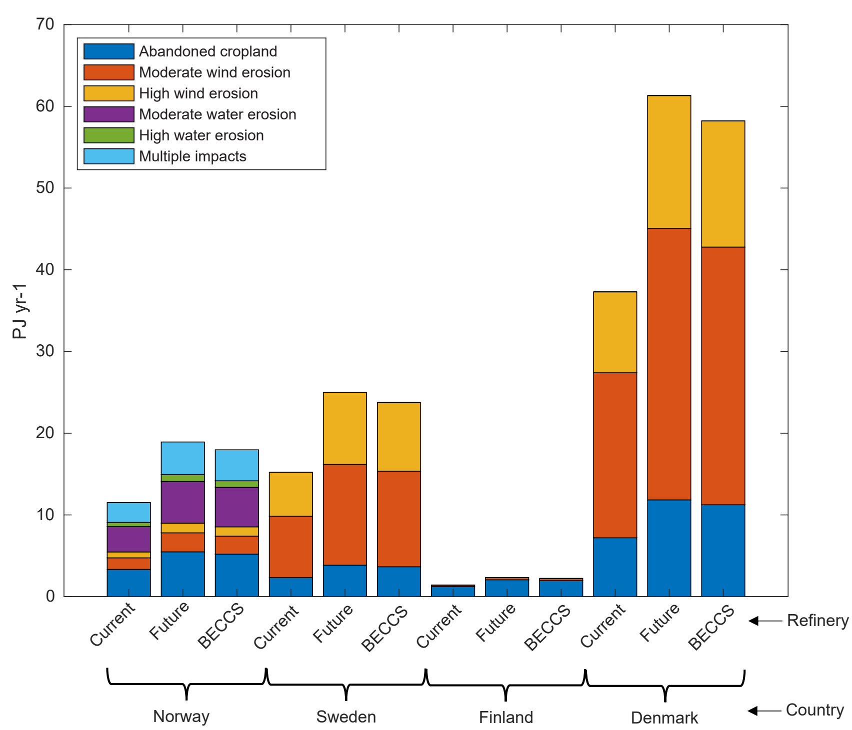

Fig. 3. Final energy potential achieved with different biorefinery technologies per country (PJ year^{-1}). Contributions from abandoned cropland and cropland under moderate and high levels of soil erosion by wind and water are shown in the stacked bars. Multiple impacts refer to areas threatened from soil erosion by both wind and water.

Biofuels from biomass produced on abandoned cropland and cropland under soil erosion could meet between 8 and 15% of the current Nordic demand in the road transport sector (which was 722 PJ year^{-1} in 2020), depending on biorefinery technology (Supplementary Table 12). The potential was especially large in Denmark, where biofuels could meet between 23 and 38% of the demand in the road transport sector (160 PJ year^{-1}). In Norway and Sweden, biofuels met up to 14% and 9% of the demand, respectively.

3.3. Climate change mitigation

The average and breakdown of the individual contributions to climate change mitigation per hectare are shown in Fig. 4. For biofuels produced from abandoned cropland, the average net annual mitigation was −6.2 ± 4.4 tCO_2eq ha^{-1} year^{-1} with current biorefinery, −11.8 ± 4.7 tCO_2eq ha^{-1} year^{-1} with the future biorefinery, and −21 ± 6.9 tCO_2eq ha^{-1} year^{-1} with the BECCS technology (ranges refers to one standard deviation of spatial variability weighted by productive area of bioenergy crops). For comparisons, natural regrowth achieved a lower average of −5.9 ± 3.5 tCO2eq ha^{-1} year^{-1} on abandoned cropland. The predicted carbon yields of harvested aboveground biomass from bioenergy crops were on average about three times higher than the predicted natural regrowth rates (Supplementary Fig. 5). On croplands under soil erosion (Fig. 4), biofuels achieved an average annual net mitigation of −4.9 ± 2.3, −8.0 ± 2.6 and −13 ± 3.4 tCO_2eq ha^{-1} year^{-1} for the current, future and BECCS biorefinery, respectively. In these areas, biofuel mitigation intensities were relatively lower than those from abandoned cropland due to the allocation of low yielding willow for windbreak deployment on croplands threatened by wind erosion. For this reason, natural regrowth was generally a more competitive option on croplands threatened by soil erosion with a sequestration potential of −9.3 ± 3.1 tCO_2eq ha^{-1} year^{-1}. As areas under soil erosion were mainly located in Denmark and the southern areas of Norway and Sweden, average natural regrowth rates were higher relative to abandoned cropland which is more evenly spread out across the Nordic region.

On average, for abandoned cropland the ranges due to spatial variability of mitigation from natural regrowth overlapped with those from biofuels under the current and future biorefinery technology. For cropland threatened by soil erosion, the standard deviation range of the net mitigation of natural regrowth overlapped with those from all biorefinery technologies. Notably, for interpretation, the gridded mitigation intensities of liquid biofuels were negatively skewed around the mean (skewness range between −1.19 and −2.50) spreading towards stronger mitigation, whilst the natural regrowth data was more symmetrical (skewness of −0.66 and −0.06 for abandoned cropland and cropland threatened by soil erosion, respectively) (Supplementary Table 13). Biofuels provided the largest mitigation on 46% of abandoned cropland with the current technology, 83% with the future, and 100% with the BECCS technology (Supplementary Fig. 6 and Supplementary Fig. 7). Biofuels outperformed natural regrowth on 16%, 24% and 87% of cropland threatened by soil erosion for the current, future and BECCS biorefinery, respectively. A two-sample *t*-test confirmed that the natural regrowth and liquid biofuels (all refineries) have unequal means at a 5% significance level for both abandoned cropland and cropland threatened by soil erosion (Supplementary Table 14). Natural regrowth was preferred over willow windbreaks in Denmark and southern coastal areas of Sweden and Norway with the current biorefinery. Biorefinery efficiency gains and BECCS is key to providing higher negative emission with biofuel production from willow windbreak deployment in these areas.

Mitigation contributions from the different components varied between abandoned cropland and cropland under soil erosion, due to the changing spatial patterns of land availability, crop allocations, and emission inventories (Supplementary Text 2). For example, we found that the mean soil organic carbon sequestration following land use change to bioenergy crops (Supplementary Fig. 8) was relatively lower on croplands under soil erosion than abandoned cropland, reflecting that soil carbon change following a switch to bioenergy crops is typically weaker in warmer climates than colder (Ledo et al., 2019, 2020).

Cumulative net mitigation over time is shown in Fig. 5 for the first 30 years. Average cumulative net mitigation intensity of biofuels production on abandoned cropland (Fig. 5a) was −169 ± 93, −329 ± 119, and −591 ± 192 tCO2eq ha^{-1} for the current, future and BECCS biorefinery, respectively (ranges refer to one standard deviation of spatial variability weighted by productive area) (Fig. 5a). For comparisons, natural regrowth achieved −183 ± 137 tCO2eq ha^{-1}, with variability ranges which overlap with the current and future biorefinery. For biofuels produced with cropland threatened by soil erosion (Fig. 5b), average cumulative net mitigation intensities were −125 ± 51, −219 ± 65, and −377 ± 92 tCO2eq ha^{-1} for the current, future and BECCS biorefinery, respectively. Variability ranges of natural regrowth (−270 ± 115 tCO2eq ha^{-1}) overlapped with those of biofuels for cropland threatened by soil erosion, independently of the refinery. Willow deployed as windbreaks had relatively lower yields than perennial grasses, making

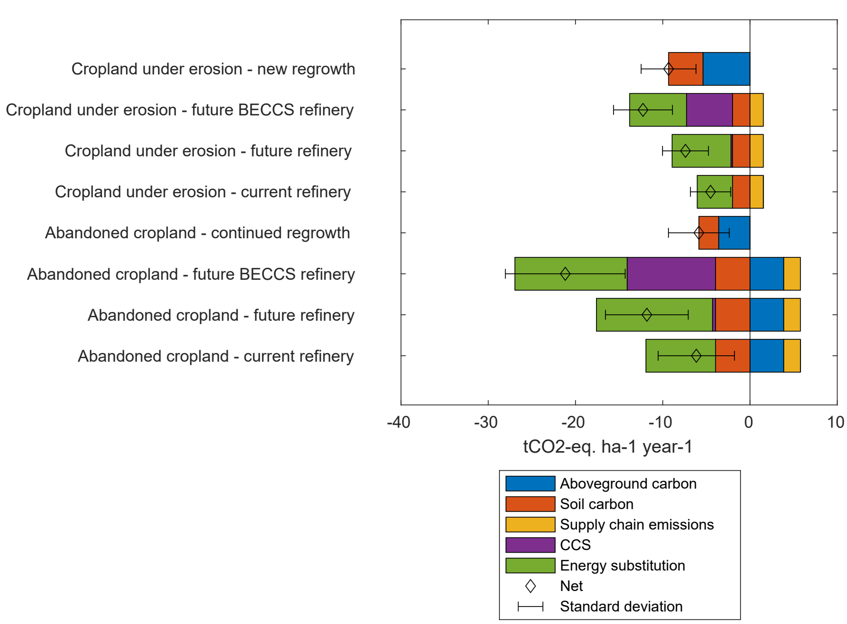

Fig. 4. Net GHG mitigation potential of biofuel on abandoned cropland and cropland under soil erosion in Nordic countries (tCO2eq ha-1 year^{-1}). Results are averaged over the first 20 years. Individual contributions from different components are changes in aboveground carbon (due to natural regrowth or clearing abandoned cropland), soil carbon changes following land use change, supply chain emissions (on-farm activities and biomass transport), CCS (biorefinery carbon capture and storage, including a smaller contribution of a char by-product applied to soils), and energy substitution (mainly fossil fuel displacement, plus a smaller contribution from additional displacement of grid electricity). Error bars represent spatial variability in terms of one standard deviation around the mean (weighted by productive land).

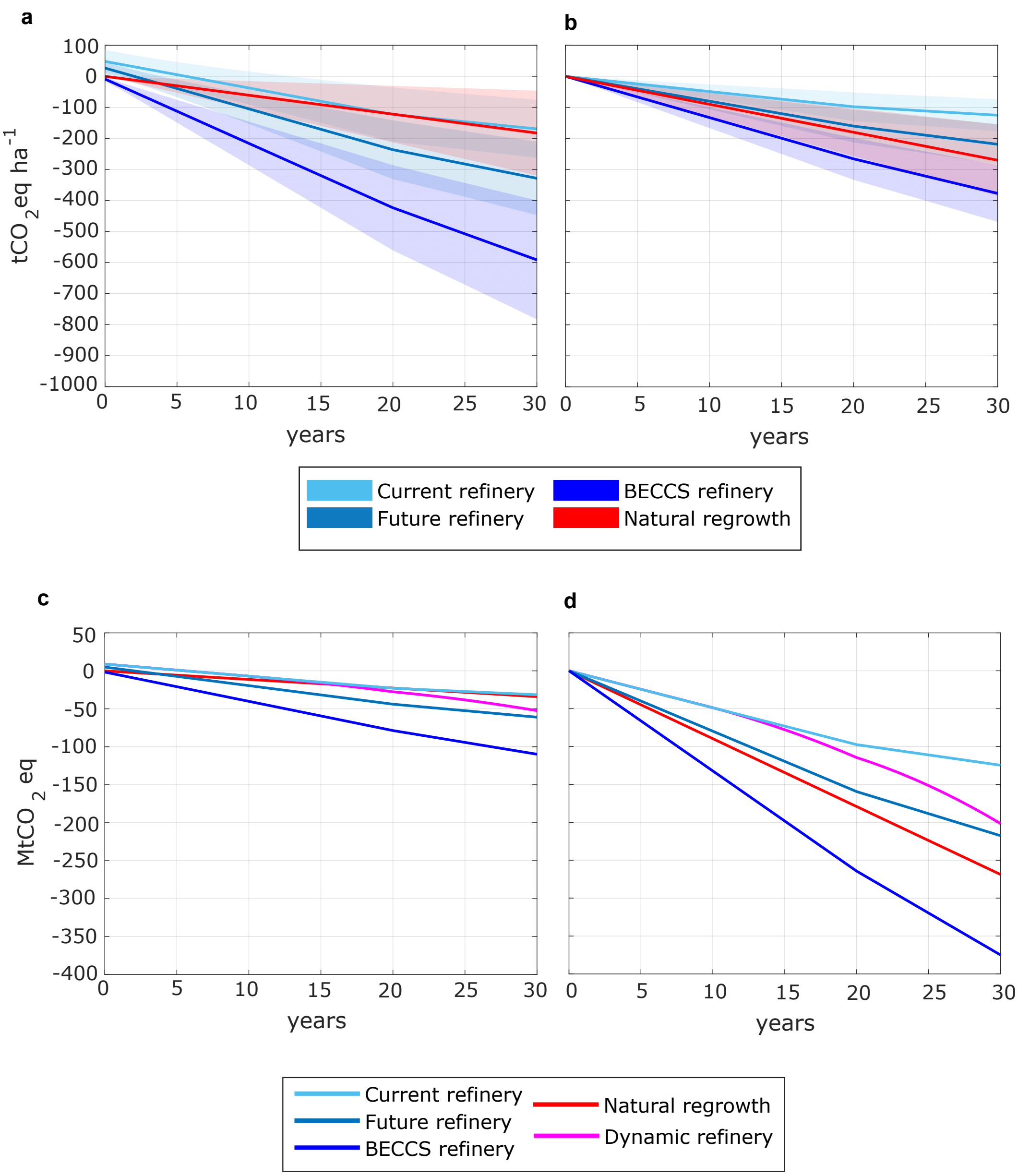

Fig. 5. Cumulative GHG mitigation potential over time in Nordic countries. Cumulative mitigation intensity (tCO2eq ha^{-1}) for (a) abandoned cropland and (b) cropland threatened by soil erosion. Cumulative mitigation (MtCO2eq) for (c) abandoned cropland and (d) cropland threatened by soil erosion. Shaded bands in (a) and (b) refer to one standard deviation of spatial variability weighted by land area. Dynamic biorefinery in (c) and (d) refers to a gradual switch in technology over time from current biorefinery to future biorefinery and BECCS. Current biorefinery is assumed for the first ten years, a gradual linear change from current to future biorefinery between year eleven and twenty (10% increase every year), and a gradual linear change from future biorefinery to BECCS biorefinery between year 21 and 30 (10% increase every year).

natural regrowth more competitive in areas threatened by wind erosion.

Cumulative mitigation of bioenergy production on all considered lands were −156, −279 and −485 $MtCO_2eq$ for the current, future and BECCS biorefinery, respectively (Fig. 5c–d). Natural regrowth (−304 $MtCO_2eq$) outperformed the future biorefinery case (+9%), mainly due to our conservative assumption that soil carbon changes after conversion to perennial crops saturate after 20 years. We also considered a scenario with a dynamic biorefinery deployment with gradually improved technology (the current biorefinery was assumed for the first ten years, before a gradual linear change from current to future biorefinery occurred between year 11 and 20 (10% increase every year), and a further change from future biorefinery to BECCS biorefinery occurred between year 21 and 30 (10% increase every year)). In this dynamic case, a cumulative mitigation of −254 $MtCO_2eq$ was achieved through biofuel production, which was 16% lower than natural regrowth.

The considered time horizon is important when assessing optimal land-based mitigation strategies on abandoned cropland (Fig. 5c). Bioenergy crops provided a 15-year cumulative mitigation from −15 to −59 Mt CO_2eq depending on technology, and improved refinery technology or BECCS is necessary to outperform the −17 $MtCO_2eq$ achievable through continued natural regrowth on abandoned cropland (Fig. 5c). After 30 years, cumulative mitigation was between −31 and −110 $MtCO_2eq$ for biofuels and −34 $MtCO_2eq$ for natural regrowth. Most of the abandoned cropland in the Nordic region was abandoned in the 1990s (96 kha), while 55 kha and 48 kha were abandoned during the 2000s and 2010s, respectively (Supplementary Fig. 9). Natural regrowth on abandoned cropland has led to an accumulated aboveground carbon stock at present day of 3.9 MtC equal to 14 $MtCO_2eq$ if combusted (Supplementary Fig. 10). A clearing and collection of regrown aboveground carbon biomass for biofuel production thus caused an initial carbon penalty of 9 and 5 $MtCO_2eq$ for the current and future biorefinery, respectively, and a smaller initial benefit with BECCS of −2 $MtCO_2eq$ (Fig. 5c). Most of the abandoned cropland was allocated to the highest yielding crop for maximized energy production, and the carbon penalty was paid back after 6 and 3 years for the current and future biorefinery, respectively. If instead the standing aboveground carbon stock was burned at site and released as atmospheric CO_2 the initial carbon penalty would be 14 $MtCO_2eq$ for all refineries, which would be paid back after 9, 6 and 4 years of biofuel production (Supplementary Fig. 11). For this case, natural regrowth was preferable to biofuels produced with the current refinery throughout the full 30 years. With improved refinery technology or BECCS, the cumulative climate benefits of liquid biofuel production became stronger than natural regrowth after 11 and 5 years, respectively.

For cropland under soil erosion (Fig. 5d), the 30-year cumulative mitigation potential of biofuel production ranged between −125 and −375 $MtCO_2eq$, while it is −269 $MtCO_2eq$ for natural regrowth. Willow had lower average productivity (113 GJ ha^{-1} yr^{-1}) than the perennial grasses in the Nordic region (274 and 222 GJ ha^{-1} $year^{-1}$ for switchgrass and reed canary grass on their respective productive areas), and while it delivered the benefit of reduced wind erosion by slowing down surface wind speed, it also led to lower climate change mitigation relative to perennials. For example, considering a pure energy optimized crop allocation on these areas increased 30-year cumulative mitigation to between −286 and −786 Mt CO_2eq across biorefinery technologies as willow got largely replaced by grasses (Supplementary Fig. 12), but this also removed the environmental benefit of windbreaks (for example, reduced soil erosion rates (Weninger et al., 2021) and potential yield gains in surrounding areas (Osorio et al., 2019)). The yield of the bioenergy crop is thus key to secure larger climate benefits than natural regrowth without BECCS, and there is a trade-off between energy potential and mitigation of soil erosion with willow.

Comparing the mitigation potential from biofuels with today's annual road transport emissions in the Nordic region (Supplementary Table 15), we found that 14–40% of the emissions could be mitigated, depending on technology. The mitigation potential of biofuels with the current biorefinery was equal to 29%, 15%, 9% and 2% of the road transport emissions in Denmark, Norway, Sweden, and Finland, respectively. In Denmark, biofuel production with BECCS had the potential to mitigate nearly all emissions (84%). Large mitigation could also be achieved with BECCS in Norway and Sweden (39% and 27%, respectively).

3.4. Limitations and uncertainties

The results of this study rely on the integration of a variety of models, methods and datasets which are subject to different limitations and uncertainties. We used the ESA CCI-LC (Defourny et al., 2017) and C3S-CDS products to estimate cropland abandonment between 1992 and 2018 and the current cropland extent in the Nordic region. The products have an overall global accuracy of 71%, with cropland classes user and producer accuracies ranging between 85-94% and 76–92% across the datasets, respectively. Previous validation attempts of ESA CCI-LC in the Arctic region showed a 62% overall accuracy (north of the arctic circle only) (Liang et al., 2019). ESA CCI-LC also achieved a 64% consistency when compared with the European land cover product CORINE in Finland (Karvonen et al., 2018). Non remotely sensed country-level land use inventories from the Food and Agricultural Organization (FAO) of the United Nations and national statistics confirm cropland contraction in the region over the last three decades (Supplementary Table 16). Our estimate of abandoned land (198 kha) is conservative relative to FAO reported cropland contraction in the Nordic region (466 kha from 1992 to 2018), and higher land availability would increase climate change mitigation potentials. More refined satellite-based estimates combined with on-field observations would allow a more accurate estimate of abandoned cropland extent (Olofsson et al., 2014).

Most of the abandoned cropland considered here was in 2018 classified by the land cover dataset as either forests (72%), grasslands (17%), or sparse vegetation (6%) (Supplementary Table 17). Parts of the abandoned cropland may be committed to other uses that prevent bioenergy crop deployment. For example, the land cover dataset used here does not distinguish between natural and managed forests or grasslands. Site-specific evaluations are needed to assess actual land availability.

We relied on spatially explicit soil erosion data to quantify cropland areas under unsustainable soil erosion by wind and water. The spatial distribution of erodible croplands found here generally aligns with previous studies (Englund et al., 2020a, 2021b; Zhou et al., 2021). When comparing the wind erosion dataset to 155 locations described in local and regional studies, areas predicted to be susceptible to wind erosion coincided well with the literature (95.5% accuracy) (Borrelli et al., 2016). For example, wind erosion is well documented as an important ongoing process in western Denmark, with incentives already in place to deploy windbreaks (Veihe et al., 2003). Our study used the ILSWE indicator to identify croplands that can benefit from windbreak construction, but a strategic implementation should integrate this indicator with site-specific evaluations of feasibility and need. For simplicity, we considered a specific willow windbreak design with a fixed width of 50 m, a height of 5 m, rotation periods of 3 years, and a distance between windbreaks of twenty times windbreak height. The optimal design of windbreaks at each site will vary with changing wind erosion rates and wind speed, with shorter distances between windbreaks at sites experiencing higher impacts (Englund et al., 2021b). The water erosion dataset relies on data-driven assumptions that have a variety of limitations, such as no simulation of soil deposition and inability to predict soil removal along drainage lines (Alewell et al., 2019; Borrelli et al., 2017). The water erosion dataset also has a coarser resolution than the other datasets, leading to additional uncertainty when coupled to high-resolution land cover data. Future soil erosion rates by wind and water will be affected not only by climate change, but also by land management choices and priorities (e.g., food-only approach vs. a more ecosystem service wide management) (Borrelli et al., 2017; Gawith and Hodge, 2019; Giovanni et al., 2021). More research is needed to understand how bioenergy crops can be efficiently deployed within a context that maximizes the co-delivery of multiple ecosystem services from land management under a changing climate and the interlinkages with different socio-economic pathways.

While the GAEZ model is widely used in literature, it relies on many assumptions, such as those related to yield losses from frosts, moisture stress and excess air humidity (Fischer et al., 2021). Our GAEZ yield estimates referred to present day climatic conditions, but climate change is projected to lead to increased crop yields throughout the Nordic region, and to potentially increase the productive area of bioenergy crops that require warmer growing conditions (Næss et al., 2021). Extreme events such as droughts or floods can also periodically affect yields of bioenergy crops (Lesk et al., 2016). We considered high management intensities both from the GAEZ model and the willow yield dataset in the main analysis, thereby assuming high-performance production systems and closed yield gaps. As an additional test, we therefore repeated the entire analysis for willow deployed on abandoned cropland with less intensive agricultural management (Supplementary Table 18). Energy potential decreased by −45% and the associated mitigation declined by −35% to −43% depending on biorefinery technology with an average performing management system relative to a high performing management system. Type of agricultural management is thus an important factor to achieve high energy and climate change mitigation potentials.

Reduction in food production from reducing agricultural land to establish woody crops as windbreaks can be expected, although it will be (partly) compensated for by yield gains between windbreaks (Supplementary Fig. 13), and it will be more sustainable in the long term by reducing irreversible soil losses. Typically, studies report yield losses close to the windbreaks (horizontal distance of about 0–3 times windbreak height) due to sunlight shading and increased competition for water and nutrients with the windbreaks themselves (Weninger et al., 2021). At the same time, there has been substantial average yield gains observed in the range of 8–25% for wheat growing in most of the sheltered zone (up to 20 times in horizontal distance of windbreak height) (Campi et al., 2009; Osorio et al., 2019; Smith et al., 2021). We considered 995 kha of croplands threatened by soil erosion for land-based climate change mitigation, out of which 927 kha were allocated to windbreak deployment. Nordic agriculture is dominated by cereal production (FAO, 2022). Using wheat yields modelled by GAEZ as a proxy, we found that potential food production losses from a complete windbreak deployment is likely in the range of −5.6 to −3.4 million tons depending on the achieved mean yield increase between windbreaks (Supplementary Fig. 14). This equals about 11–17% of the annual crop production in the Nordic region (FAO, 2022). Consequently, potential indirect land use change could occur elsewhere to replace the lost production and meet food demand. We did not attempt to quantify carbon penalties (indirect deforestation) from those here as indirect land use changes are highly uncertain and controversial (Daioglou et al., 2020). Yield response to windbreak shelters is also crop-specific and windbreaks can be especially beneficial for vegetables and fruits, with strawberry yield increases reported above 50% (Peri and Bloomberg, 2002; Smith et al., 2021). Furthermore, the strategic introduction of perennials may in fact reduce or even stop ongoing land degradation processes by soil erosion and secure long-term agricultural productivity, despite some possible yield declines in the short-term. It will also decrease the risks of larger yield losses and future land abandonment, with associated deforestation to make space for new agricultural land.

We used a commercially available biorefinery technology as a baseline for the analysis, while also exploring the potential future gains due to the implementation of innovative technologies based on previous modelling efforts. BECCS is vital in most climate change mitigation scenarios (Rogelj et al., 2018a). BECCS technology is relatively mature (Baik et al., 2018), and could theoretically be introduced to biorefineries at a faster pace than we considered in our dynamic refinery case. However, large-scale BECCS deployment is still uncertain because of its dependency economic and social factors, such as lack of incentives and low social acceptance (Fridahl and Lehtveer, 2018). Successful BECCS deployment in Nordic countries will require supporting policies, such as state guarantees, quota obligations for selected sectors, or allowing the trade of BECCS negative emission credits to compensate for emissions elsewhere in the European Union's Emission Trading System (Fuss and Johnsson, 2021; Zetterberg et al., 2021). Additionally, captured CO_2 must be transported and injected into reservoir infrastructure for long term storage, and the offshore oil and gas infrastructure and used reservoirs in the North Sea offer possibilities. Two full-scale Nordic demonstration geological reservoir projects for CO_2 storage are currently under development with expected capacities of 1.5 and 4–8 $MtCO_2$ $year^{-1}$ in Norway (Northern lights, 2021) and Denmark (Project Greensand, 2021), respectively. In comparison, annual BECCS storage requirements in our study were 7.4 $MtCO_2$ $year^{-1}$, with 1.3 and 4.3 $MtCO_2$ $year^{-1}$ from production based on plantations in Norway and Denmark, respectively. BECCS deployment beyond the planned capacity would require opening new storage sites or transporting CO_2 over longer distances to utilize other European sites (Rosa et al., 2021).

Estimating soil carbon changes associated with natural regrowth on abandoned cropland is challenging due to a lack of harmonization of data and large variance of measurements even within biomes and with similar soil texture (Cook-Patton et al., 2020). Likewise, while a switch to bioenergy crops typically leads to soil carbon accumulation, field data also show large variance (Ledo et al., 2020). Predicted crop yields showed no clear correlation (Pearson correlation coefficient of 0.06) with the predicted soil carbon change after land use conversion to bioenergy crops (Supplementary Fig. 15). The soil carbon change method used here produced generic rates for all bioenergy crops, and future work should consider using processed-based land surface models to assess the effect of individual crop characteristics. There is also a need for more field work and increased standardization of reporting to improve our understanding of soil carbon accumulation following land use change (Ledo et al., 2019).

4. Conclusion

Utilizing abandoned cropland and cropland threatened by soil erosion for bioenergy production can ramp-up Nordic bioenergy supply (up to 110 PJ $year^{-1}$ of final energy), with reduced impacts on food production and by providing environmental co-benefits through reduced soil erosion. Such an integrated strategy for bioenergy deployment can make a substantial contribution to reaching climate change mitigation targets and moving towards net zero emissions while co-delivering improved ecosystem services. There is a potential to mitigate 14% of the current Nordic land-based transport emissions with a commercially available biorefinery technology, and up to 40% if production is combined with BECCS technology.

Achievable bioenergy crop yields, biorefinery technology, and CCS are important for the relative climate change mitigation performance of biofuel production when compared to natural regrowth. Targeting abandoned cropland for liquid biofuel production (−31 Mt CO_2eq) is competitive with continued natural regrowth (−34 Mt CO_2eq) in Nordic countries after the first 30 years. Future gains in biorefinery efficiency and the introduction of BECCS can potentially triple climate benefits of liquid biofuel production (up to −110 Mt CO_2eq), thereby outperforming natural regrowth on abandoned cropland. It is important to make efficient use of any aboveground biomass cleared during the recultivation of abandoned cropland to maximize mitigation. There is also a substantial potential for annual mitigation through a windbreak system (−3.7 to −11 Mt CO_2eq $year^{-1}$), equal to 9–26% of annual emissions from Nordic land-based transport. For willow windbreaks, yields are lower than for perennial grasses, and improvements in energy conversion efficiencies or BECCS are typically necessary to ensure larger climate benefits than natural regrowth.

Deployment strategies for bioenergy production need to be comprehensive to ensure food security and protect biodiversity. Local assessments should aim to identify what global challenges can be better addressed by the given local context, considering both bioenergy production and nature-based solutions. Our study asserts that targeting abandoned cropland and cropland prone to soil erosion for bioenergy is a promising near-term option to increase biomass supply, and they are an example of sustainable land management strategies that can co-deliver multiple benefits (for climate, nature, and soil quality) and may minimize environmental trade-offs.

Credit author statement

Jan Sandstad Næss: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Validation, Writing – original draft, Writing – review & editing, Visualization. **Xiangping Hu:** Conceptualization, Methodology, Investigation, Software, Writing – review & editing. **Maren Haug Gvein:** Conceptualization, Methodology, Writing – review & editing. **Cristina Maria Iordan:** Methodology, Software, Investigation, Writing – review & editing. **Otavio Cavalett:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Martin Dorber:** Software, Resources, Writing – review & editing. **Baptiste Giroux:** Methodology, Investigation, Writing – review & editing. **Francesco Cherubini:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Otavio Cavalett, Xiangping Hu, Francesco Cherubini reports financial support was provided by the Research Council of Norway.

Data availability

Custom code used in this analysis is available at https://github.com/janjsn/cc_mit_ac_se.git. Data supporting the findings of this study will be made available upon reasonable request.

Acknowledgements

The support of the Research Council of Norway is acknowledged through the projects Bio4Fuels (project no. 257622), BioPath (project no. 293434) and MitiStress (project no. 286773).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116474.

References

Alewell, C., Borrelli, P., Meusburger, K., Panagos, P., 2019. Using the USLE: chances, challenges and limitations of soil erosion modelling. Int. Soil Water Conserv. Res. 7, 203–225. https://doi.org/10.1016/j.iswcr.2019.05.004.

Anderson, K., Peters, G., 2016. The trouble with negative emissions. Science 84 354, 182. https://doi.org/10.1126/science.aah4567. LP – 183.

Baik, E., Sanchez, D.L., Turner, P.A., Mach, K.J., Field, C.B., Benson, S.M., 2018. Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. Proc. Natl. Acad. Sci. USA 115, 3290–3295. https://doi.org/10.1073/pnas.1720338115.

Batjes, N.H., 2012. ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid (ver. 1.2). ISRIC-World Soil Information, pp. 1–56. No. 2012/01.

Borrelli, P., Panagos, P., Ballabio, C., Lugato, E., Weynants, M., Montanarella, L., 2016. Towards a pan-European assessment of land susceptibility to wind erosion. Land Degrad. Dev. 27, 1093–1105. https://doi.org/10.1002/ldr.2318.

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., 2017. An assessment of the global impact of 21st century land use change on soil erosion. Nat. Commun. 8, 1–13.

Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C., Wuepper, D., Montanarella, L., Ballabio, C., 2020. Land use and climate change impacts on global soil erosion by water (2015-2070). Proc. Natl. Acad. Sci. USA 117, 21994–22001. https://doi.org/10.1073/pnas.2001403117.

Calvin, K., Cowie, A., Berndes, G., Arneth, A., Cherubini, F., Portugal-Pereira, J., Grassi, G., House, J., Johnson, F.X., Popp, A., Rounsevell, M., Slade, R., Smith, P., 2021. Bioenergy for climate change mitigation: scale and sustainability. GCB Bioenergy 13, 1346–1371. https://doi.org/10.1111/gcbb.12863.

Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. The global potential of bioenergy on abandonded agricultural lands. Environ. Sci. Technol. 42, 5791–5794. https://doi.org/10.1021/es800052w.

Campi, P., Palumbo, A.D., Mastrorilli, M., 2009. Effects of tree windbreak on microclimate and wheat productivity in a Mediterranean environment. Eur. J. Agron. 30, 220–227. https://doi.org/10.1016/j.eja.2008.10.004.

Cavalett, O., Cherubini, F., 2018. Contribution of jet fuel from forest residues to multiple Sustainable Development Goals. Nat. Sustain. 1, 799–807. https://doi.org/10.1038/s41893-018-0181-2.

Cavalett, O., Cherubini, F., 2022. Unraveling the role of biofuels in road transport under rapid electrification. Biofuels, Bioprod. Biorefining. https://doi.org/10.1002/bbb.2395 n/a.

Center for International Earth Science Information Network - CIESIN, 2016. Columbia University, Centro internacional de Agricultura tropical - CIAT. Version 4 Gridded Population of the World. https://doi.org/10.7927/H4TD9VDP (GPWv4): National Identifier Grid.

Cook-Patton, S.C., Leavitt, S.M., Gibbs, D., Harris, N.L., Lister, K., Anderson-Teixeira, K.J., Briggs, R.D., Chazdon, R.L., Crowther, T.W., Ellis, P.W., Griscom, H.P., Herrmann, V., Holl, K.D., Houghton, R.A., Larrosa, C., Lomax, G., Lucas, R., Madsen, P., Malhi, Y., Paquette, A., Parker, J.D., Paul, K., Routh, D., Roxburgh, S., Saatchi, S., van den Hoogen, J., Walker, W.S., Wheeler, C.E., Wood, S.A., Xu, L., Griscom, B.W., 2020. Mapping carbon accumulation potential from global natural forest regrowth. Nature 585, 545–550. https://doi.org/10.1038/s41586-020-2686-x.

Crawford, C.L., Yin, H., Volker, R.C., Wilcove, D.S., 2022. Rural land abandonment is too ephemeral to provide major benefits for biodiversity and climate. Sci. Adv. 8, eabm8999 https://doi.org/10.1126/sciadv.abm8999.

Daioglou, V., Doelman, J.C., Wicke, B., Faaij, A., Vuuren, D.P. Van, 2019. Integrated assessment of biomass supply and demand in climate change mitigation scenarios. Global Environ. Change 54, 88–101. https://doi.org/10.1016/j.gloenvcha.2018.11.012.

Daioglou, V., Woltjer, G., Strengers, B., Elbersen, B., Barberena Ibañez, G., Sánchez Gonzalez, D., Gil Barno, J., Vuuren, D.P., 2020. Progress and barriers in understanding and preventing indirect land-use change. Biofuels, Bioprod. Biorefining 14, 924–934. https://doi.org/10.1002/bbb.2124.

Defourny, P., Santoro, M., Schlerf, M., Lamarche, C., Bontemps, S., Peters, M., Boettcher, M., Brockmann, C., Kirches, G., 2017. Land Cover CCI Product User Guide, version 2.0.

Defourny, P., Lamarche, C., Marissiaux, Q., Brockmann, C., Boettcher, M., Kirches, G., 2019. Product User Guide and Specification ICDR Land Cover 2016–2019.

Donnison, C., Holland, R.A., Harris, Z.M., Eigenbrod, F., Taylor, G., 2021. Land-use change from food to energy: meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services. Environ. Res. Lett. 16, 113005 https://doi.org/10.1088/1748-9326/ac22be.

Ecn.TNO, 2019. Phyllis2, database for (treated) biomass, algae, feedstocks for biogas production and biochar [WWW Document]. URL. https://phyllis.nl/.

Englund, O., Börjesson, P., Berndes, G., Scarlat, N., Dallemand, J.-F., Grizzetti, B., Dimitriou, I., Mola-Yudego, B., Fahl, F., 2020a. Beneficial land use change: strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. Global Environ. Change 60, 101990. https://doi.org/10.1016/j.gloenvcha.2019.101990.

Englund, O., Dimitriou, I., Dale, V.H., Kline, K.L., Mola-Yudego, B., Murphy, F., English, B., McGrath, J., Busch, G., Negri, M.C., Brown, M., Goss, K., Jackson, S., Parish, E.S., Cacho, J., Zumpf, C., Quinn, J., Mishra, S.K., 2020b. Multifunctional perennial production systems for bioenergy: performance and progress. WIREs Energy Environ 9, e375. https://doi.org/10.1002/wene.375.

Englund, O., Börjesson, P., Mola-Yudego, B., Berndes, G., Dimitriou, I., Cederberg, C., Scarlat, N., 2021a. Beneficial Land-Use Change in Europe: Deployment Scenarios for Multifunctional Riparian Buffers and Windbreaks.

Englund, O., Börjesson, P., Mola-Yudego, B., Berndes, G., Dimitriou, I., Cederberg, C., Scarlat, N., 2021b. Strategic deployment of riparian buffers and windbreaks in Europe can co-deliver biomass and environmental benefits. Commun. Earth Environ. 2, 176. https://doi.org/10.1038/s43247-021-00247-y.

Environmental Systems Research Institute (ESRI), 2021. ArcGIS Pro 2.9.0.

Etiope, G., 2009. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2009.

FAO, 2011. The State of the World's Land and Water Resources for Food and Agriculture: Managing Systems at Risk. Earthscan.

FAO, 2022. FAOSTAT Database [WWW Document]. http://www.fao.org/faostat/en.

Ferrarini, A., Serra, P., Almagro, M., Trevisan, M., Amaducci, S., 2017. Multiple ecosystem services provision and biomass logistics management in bioenergy buffers: a state-of-the-art review. Renew. Sustain. Energy Rev. 73, 277–290. https://doi.org/10.1016/j.rser.2017.01.052.

Field, J.L., Richard, T.L., Smithwick, E.A.H., Cai, H., Laser, M.S., LeBauer, D.S., Long, S.P., Paustian, K., Qin, Z., Sheehan, J.J., Smith, P., Wang, M.Q., Lynd, L.R., 2020. Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. Proc. Natl. Acad. Sci. USA 117, 21968–21977. https://doi.org/10.1073/pnas.1920877117.

Fischer, G., Nachtergaele, F.O., van Velthuizen, H.T., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D., Tramberend, S., 2021. Global Agro-Ecological Zone V4 – Model Documentation. FAO. https://doi.org/10.4060/cb4744en.

Forbord, M., Vik, J., Hillring, B.G., 2012. Development of local and regional forest based bioenergy in Norway – supply networks, financial support and political commitment. Biomass Bioenergy 47, 164–176. https://doi.org/10.1016/j.biombioe.2012.09.045.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D., Mauritsen, T., Palmer, M., Watanabe, M., Wild, M., Zhang, H., 2021. Chapter 7: the Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. https://doi.org/10.25455/wgtn.16869671.v1.

Fridahl, M., Lehtveer, M., 2018. Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers. Energy Res. Social Sci. 42, 155–165. https://doi.org/10.1016/j.erss.2018.03.019.

Fridstrøm, L., Østli, V., Johansen, K.W., 2016. A stock-flow cohort model of the national car fleet. Eur. Transp. Res. Rev. 8, 22. https://doi.org/10.1007/s12544-016-0210-z.

Fuss, S., Johnsson, F., 2021. The BECCS implementation gap–A Swedish case study. Front. Energy Res. https://doi.org/10.3389/fenrg.2020.553400.

Gawith, D., Hodge, I., 2019. Focus rural land policies on ecosystem services, not agriculture. Nat. Ecol. Evol. 3, 1136–1139. https://doi.org/10.1038/s41559-019-0934-y.

Georgescu, M., Lobell, D.B., Field, C.B., 2011. Direct climate effects of perennial bioenergy crops in the United States. Proc. Natl. Acad. Sci. USA 108, 4307–4312. https://doi.org/10.1073/pnas.1008779108.

Giovanni, T., Riccardo, B., Cherico, W.T., Claire, K., A van der, H.M.G., Matt, L., Sara, H., 2021. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. 6, eaba1715. https://doi.org/10.1126/sciadv.aba1715.

Giroux, B., 2020. Bioenergy Feedstock Production on Abandonned Agricultural Land in Europe-A Spatially Explicit Life Cycle Analysis. Master thesis. NTNU.

Hanssen, S.V., Daioglou, V., Steinmann, Z.J.N., Frank, S., Popp, A., Brunelle, T., Lauri, P., Hasegawa, T., Huijbregts, M.A.J., Van Vuuren, D.P., 2020. Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models. Clim. Change 163, 1569–1586. https://doi.org/10.1007/s10584-019-02539-x.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., Piontek, F., 2013. A trend-preserving bias correction - the ISI-MIP approach. Earth Syst. Dyn. 4, 219–236. https://doi.org/10.5194/esd-4-219-2013.
Hiederer, R., Köchy, M., 2011. Global soil organic carbon estimates and the harmonized world soil database. EUR 79, 10–2788.
Hu, X., Næss, J.S., Iordan, C.M., Huang, B., Zhao, W., Cherubini, F., 2021. Recent global land cover dynamics and implications for soil erosion and carbon losses from deforestation. Anthropocene 34, 100291. https://doi.org/10.1016/j.ancene.2021.100291.
IEA, 2017. Energy technology perspectives 2017. Catal. Energy Technol. Transform.
IPCC, 2019. Summary for policymakers. In: Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.
Kaiser, J., 2004. Wounding Earth's fragile skin. Science 304, 1616. https://doi.org/10.1126/science.304.5677.1616. LP – 1618.
Karvonen, V., Ribard, C., Sädekoski, N., Tyystjärvi, V., Muukkonen, P., 2018. Comparing ESA land cover data with higher resolution national datasets. Creat. Manag. Anal. geospatial data databases Geogr. themes 26–45.
Kort, J., Collins, M., Ditsch, D., 1998. A review of soil erosion potential associated with biomass crops. Biomass Bioenergy 14, 351–359. https://doi.org/10.1016/S0961-9534(97)10071-X.
Krzyżaniak, M., Stolarski, M.J., Szczukowski, S., Tworkowski, J., 2016. Life cycle assessment of new willow cultivars grown as feedstock for integrated biorefineries. BioEnergy Res 9, 224–238. https://doi.org/10.1007/s12155-015-9681-3.
Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, M.P., Lana-Renault, N., 2017. Space–time process and drivers of land abandonment in Europe. Catena 149, 810–823. https://doi.org/10.1016/j.catena.2016.02.024.
Laser, M., Jin, H., Jayawardhana, K., Lynd, L.R., 2009a. Coproduction of ethanol and power from switchgrass. Biofuels, Bioprod. Biorefining 3, 195–218. https://doi.org/10.1002/bbb.133.
Laser, M., Larson, E., Dale, B., Wang, M., Greene, N., Lynd, L.R., 2009b. Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios. Biofuels, Bioprod. Biorefining 3, 247–270. https://doi.org/10.1002/bbb.136/.
Ledo, A., Hillier, J., Smith, P., Aguilera, E., Blagodatskiy, S., Brearley, F.Q., Datta, A., Diaz-Pines, E., Don, A., Dondini, M., Dunn, J., Feliciano, D.M., Liebig, M.A., Lang, R., Llorente, M., Zinn, Y.L., McNamara, N., Ogle, S., Qin, Z., Rovira, P., Rowe, R., Vicente-Vicente, J.L., Whitaker, J., Yue, Q., Zerihun, A., 2019. A global, empirical, harmonised dataset of soil organic carbon changes under perennial crops. Sci. Data 6, 57. https://doi.org/10.1038/s41597-019-0062-1.
Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente-Vicente, J.L., Qin, Z., McNamara, N.P., Zinn, Y.L., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., Hillier, J., 2020. Changes in soil organic carbon under perennial crops. Global Change Biol. 26, 4158–4168. https://doi.org/10.1111/gcb.15120.
Leirpoll, M.E., Næss, J.S., Cavalett, O., Dorber, M., Hu, X., Cherubini, F., 2021. Optimal combination of bioenergy and solar photovoltaic for renewable energy production on abandoned cropland. Renew. Energy 168, 45–56. https://doi.org/10.1016/j.renene.2020.11.159.
Lesk, C., Rowhani, P., Ramankutty, N., 2016. Influence of extreme weather disasters on global crop production. Nature 529, 84–87.
Lewandowski, I., Scurlock, J.M.O., Lindvall, E., Christou, M., 2003. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy 25, 335–361. https://doi.org/10.1016/S0961-9534(03)00030-8.
Li, S., Li, X., 2017. Global understanding of farmland abandonment: a review and prospects. J. Geogr. Sci. 27, 1123–1150. https://doi.org/10.1007/s11442-017-1426-0.
Liang, L., Liu, Q., Liu, G., Li, H., Huang, C., 2019. Accuracy evaluation and consistency analysis of four global land cover products in the arctic region. Rem. Sens. 11, 1396.
Liu, G., Larson, E.D., Williams, R.H., Kreutz, T.G., Guo, X., 2011. Making Fischer−Tropsch fuels and electricity from coal and biomass: performance and cost analysis. Energy Fuels 25, 415–437. https://doi.org/10.1021/ef101184e.
McCalmont, J.P., Hastings, A., McNamara, N.P., Richter, G.M., Robson, P., Donnison, I.S., Clifton-Brown, J., 2017. Environmental costs and benefits of growing Miscanthus for bioenergy in the UK. GCB Bioenergy 9, 489–507.
Mola-Yudego, B., 2010. Regional potential yields of short rotation willow plantations on agricultural land in Northern Europe. Silva Fenn. 44, 63–76.
Mola-Yudego, B., Rahlf, J., Astrup, R., Dimitriou, I., 2016. Spatial yield estimates of fast-growing willow plantations for energy based on climatic variables in northern Europe. GCB Bioenergy 8, 1093–1105. https://doi.org/10.1111/gcbb.12332.
Næss, J.S., Cavalett, O., Cherubini, F., 2021. The land–energy–water nexus of global bioenergy potentials from abandoned cropland. Nat. Sustain. 4, 525–536. https://doi.org/10.1038/s41893-020-00680-5.
Næss, J.S., Iordan, C.M., Muri, H., Cherubini, F., 2022. Energy potentials and water requirements from perennial grasses on abandoned land in the former Soviet Union. Environ. Res. Lett. 17, 45017 https://doi.org/10.1088/1748-9326/ac5e67.
Natural Resources Institute Finland, 2021. Official Statistics of Finland (OSF): Utilised Agricultural Area [e-publication]. [WWW Document]. URL. https://stat.luke.fi/en/utilised-agricultural-area.
Nordborg, M., Berndes, G., Dimitriou, I., Henriksson, A., Mola-Yudego, B., Rosenqvist, H., 2018. Energy analysis of willow production for bioenergy in Sweden. Renew. Sustain. Energy Rev. 93, 473–482.
Northern lights, 2021 [WWW Document]. https://northernlightsccs.com/.
Statistics Norway, 2021. Statistikkbanken. Gardsbruk, Jordbruksareal Og Husdyr. 05982: Jordbruksareal (Dekar), Etter Vekst, Statistikkvariabel Og År [WWW Document]. URL. https://www.ssb.no/statbank/table/04496/tableViewLayout1/.
Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E., Wulder, M.A., 2014. Good practices for estimating area and assessing accuracy of land change. Remote Sens. Environ. 148, 42–57. https://doi.org/10.1016/j.rse.2014.02.015.
Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial Ecoregions of the World: a New Map of Life on Earth: a new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. Bioscience 51, 933–938. https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2.
Osorio, R.J., Barden, C.J., Ciampitti, I.A., 2019. GIS approach to estimate windbreak crop yield effects in Kansas–Nebraska. Agrofor. Syst. 93, 1567–1576. https://doi.org/10.1007/s10457-018-0270-2.
Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. Environ. Sci. Pol. 54, 438–447. https://doi.org/10.1016/j.envsci.2015.08.012.
Peri, P.L., Bloomberg, M., 2002. Windbreaks in southern Patagonia,Argentina: a review of research on growth models, windspeed reduction, and effects oncrops. Agrofor. Syst. 56, 129–144. https://doi.org/10.1023/A:1021314927209.
Project Greensand, 2021 [WWW Document]. https://projectgreensand.com/.
Qin, Z., Dunn, J.B., Kwon, H., Mueller, S., Wander, M.M., 2016. Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. GCB Bioenergy 8, 66–80. https://doi.org/10.1111/gcbb.12237.
Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Samir, K.C., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Silva, L.A. Da, Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ. Change 42, 153–168.
Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R., Lehmann, J., 2010. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ. Sci. Technol. 44, 827–833. https://doi.org/10.1021/es902266r.
Robertson, G.P., Hamilton, S.K., Barham, B.L., Dale, B.E., Izaurralde, R.C., Jackson, R.D., Landis, D.A., Swinton, S.M., Thelen, K.D., Tiedje, J.M., 2017. Cellulosic biofuel contributions to a sustainable energy future: choices and outcomes. Science 80, 356. https://doi.org/10.1126/science.aal2324.
Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D.P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlík, P., Humpenöder, F., Stehfest, E., Tavoni, M., 2018a. Scenarios towards limiting global mean temperature increase below 1.5 °C. Nat. Clim. Change 8, 325–332.
Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Seferian, R., Vilarino, M.V., Calvin, K., Edelenbosch, O., Emmerling, J., Fuss, S., Gasser, T., Gillet, N., He, C., Hertwich, E., Isaksson, L.H., Huppmann, D., Luderer, G., Markandya, A., McCollum, D., Millar, R., Meinshausen, M., Popp, A., Pereira, J., Purohit, P., Riahi, K., Ribes, A., Saunders, H., Schadel, C., Smith, C., Smith, P., Trutnevyte, E., Xiu, Y., Zickfeld, K., Zhou, W., 2018b. Chapter 2: mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global Warming of 1.5 °C an IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change. Intergovernmental Panel on Climate Change.
Rosa, L., Sanchez, D.L., Mazzotti, M., 2021. Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. Energy Environ. Sci. 14, 3086–3097. https://doi.org/10.1039/D1EE00642H.
Seland, Ø., Bentsen, M., Olivié, D., Toniazzo, T., Gjermundsen, A., Graff, L.S., Debernard, J.B., Gupta, A.K., He, Y.-C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Aas, K.S., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., Karset, I.H.H., Landgren, O., Liakka, J., Moseid, K.O., Nummelin, A., Spensberger, C., Tang, H., Zhang, Z., Heinze, C., Iversen, T., Schulz, M., 2020. Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. Geosci. Model Dev. (GMD) 13, 6165–6200. https://doi.org/10.5194/gmd-13-6165-2020.
Smith, M.M., Bentrup, G., Kellerman, T., MacFarland, K., Straight, R., Ameyaw, Lord, 2021. Windbreaks in the United States: a systematic review of producer-reported benefits, challenges, management activities and drivers of adoption. Agric. Syst. 187, 103032 https://doi.org/10.1016/j.agsy.2020.103032.
Staples, M.D., Malina, R., Barrett, S.R.H., 2017. The limits of bioenergy for mitigating global life-cycle greenhouse gas emissions from fossil fuels. Nat. Energy 2, 16202. https://doi.org/10.1038/nenergy.2016.202.
Staples, M.D., Malina, R., Suresh, P., Hileman, J.I., Barrett, S.R.H., 2018. Aviation CO2 emissions reductions from the use of alternative jet fuels. Energy Pol. 114, 342–354. https://doi.org/10.1016/j.enpol.2017.12.007.

Statistics Denmark, 2021. Cultivated Area by Crop, Region, Unit and Time [WWW Document]. URL. https://www.dst.dk/en/Statistik/emner/erhvervsliv/landbrug-gartneri-og-skovbrug/det-dyrkede-areal.
Statistics Sweden, 2021. Type of Land Area by County/country. Year 1981-1999, 2003-2007 [WWW Document]. URL. https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START_JO_JO0104/AgoslagArealL/.
Tjiputra, J.F., Roelandt, C., Bentsen, M., Lawrence, D.M., Lorentzen, T., Schwinger, J., Seland, Ø., Heinze, C., 2013. Evaluation of the carbon cycle components in the Norwegian Earth system model (NorESM). Geosci. Model Dev 6, 301–325.
Usťak, S., Šinko, J., Muñoz, J., 2019. Reed canary grass (Phalaris arundinacea L.) as a promising energy crop. J. Cent. Eur. Agric. 20, 1143–1168.
Vaughan, N.E., Gough, C., 2016. Expert assessment concludes negative emissions scenarios may not deliver. Environ. Res. Lett. 11, 95003 https://doi.org/10.1088/1748-9326/11/9/095003.
Veihe, A., Hasholt, B., Schiøtz, I.G., 2003. Soil erosion in Denmark: processes and politics. Environ. Sci. Pol. 6, 37–50. https://doi.org/10.1016/S1462-9011(02)00123-5.
Van Vuuren, D.P., Stehfest, E., den Elzen, M.G.J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Goldewijk, K.K., Hof, A., Beltran, A.M., 2011. RCP2. 6: exploring the possibility to keep global mean temperature increase below 2 C. Clim. Change 109, 95–116.
Wang, M., Wagner, M., Miguez-Macho, G., Kamarianakis, Y., Mahalov, A., Moustaoui, M., Miller, J., VanLoocke, A., Bagley, J.E., Bernacchi, C.J., Georgescu, M., 2016. On the long-term hydroclimatic sustainability of perennial bioenergy crop expansion over the United States. J. Clim. 30, 2535–2557. https://doi.org/10.1175/JCLI-D-16-0610.1.
Wang, E., Cruse, R.M., Sharma-Acharya, B., Herzmann, D.E., Gelder, B.K., James, D.E., Flanagan, D.C., Blanco-Canqui, H., Mitchell, R.B., Laird, D.A., 2020. Strategic switchgrass (Panicum virgatum) production within row cropping systems: regional-scale assessment of soil erosion loss and water runoff impacts. GCB Bioenergy 12, 955–967. https://doi.org/10.1111/gcbb.12749.
Wang, J., Li, W., Ciais, P., Li, L.Z.X., Chang, J., Goll, D., Gasser, T., Huang, X., Devaraju, N., Boucher, O., 2021. Global cooling induced by biophysical effects of bioenergy crop cultivation. Nat. Commun. 12, 7255. https://doi.org/10.1038/s41467-021-27520-0.
Weninger, T., Scheper, S., Lackóová, L., Kitzler, B., Gartner, K., King, N.W., Cornelis, W., Strauss, P., Michel, K., 2021. Ecosystem services of tree windbreaks in rural landscapes—a systematic review. Environ. Res. Lett. 16, 103002 https://doi.org/10.1088/1748-9326/ac1d0d.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.
Wråke, M., Karlsson, K., Kofoed-Wiuff, A., Folsland Bolkesjø, T., Lindroos, T.J., Hagberg, M., Bosack Simonsen, M., Unger, T., Tennback, B., Ogner Jåstad, E., Lehtilä, A., Putkonen, N., Koljonen, T., 2021. Nordic clean energy scenarios: solutions for carbon neutrality. Nordic Energy Research. https://doi.org/10.6027/NER2021-01.
Zetterberg, L., Johnsson, F., Möllersten, K., 2021. Incentivizing BECCS—a Swedish case study. Front. Clim. 3, 99. https://doi.org/10.3389/fclim.2021.685227.
Zhang, B., Hastings, A., Clifton-Brown, J.C., Jiang, D., Faaij, A.P.C., 2020. Modeled spatial assessment of biomass productivity and technical potential of Miscanthus × giganteus , Panicum virgatum L., and Jatropha on marginal land in China. GCB Bioenergy 12, 328–345. https://doi.org/10.1111/gcbb.12673.
Zhou, N., Hu, X., Byskov, I., Næss, J.S., Wu, Q., Zhao, W., Cherubini, F., 2021. Overview of recent land cover changes, forest harvest areas, and soil erosion trends in Nordic countries. Geogr. Sustain. 2, 163–174. https://doi.org/10.1016/j.geosus.2021.07.001.