Integrated spatiotemporal modelling of bioenergy production potentials, agricultural land use, and related GHG balances; demonstrated for Ukraine

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Abstract: This study shows how bioenergy potential and total greenhouse gas (GHG) balances of land-use change and agricultural intensification can be modeled in an integrated way. The modeling framework is demonstrated for first- and second-generation ethanol production in Ukraine for the timeframe 2010–2030 for two scenarios: a business as usual (BAU) scenario in which current trends in agricultural productivity are continued; and a progressive scenario, which projects a convergence of yield levels in Ukraine with Western Europe. The spatiotemporal development in land for food production is analyzed making use of the PCRaster Land Use Change (PLUC) model. The land-use projections serve as input for the analysis of the CO₂, N₂O, and CH₄ emissions related to changes in land use and agricultural management, as well as the abatement of GHG emissions by replacing fossil fuels with bioethanol production from wheat and switchgrass. This results in annual maps (1 km² resolution) of the different GHG emissions for the modeled timeframe. In the BAU scenario, the GHG emissions increase over time, whereas in the progressive scenario, a total cumulative GHG emission reduction of 0.8 Gt CO₂-eq for wheat and 3.8 Gt CO₂-eq for switchgrass could be achieved in 2030. When the available land is used for the re-growth of natural vegetation, 3.5 Gt CO₂-eq could be accumulated. These emission reductions could increase when appropriate measures are taken. The spatiotemporal PLUC model + GHG module allows for spatiotemporal and integrated modeling of total GHG emissions of bioenergy production and intensification of the agricultural sector.
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Key words: bioethanol; agricultural intensification; land-use change; GHG emissions, modeling; GIS
Introduction

Competition between food, feed, and fuel, and therefore indirect land-use change (iLUC), could be avoided if the increased production of biomass for energy is balanced by improvements in agricultural management. Therefore, the bioenergy potential that can be realized without expanding the total agricultural land-use area depends on the rate of intensification of the agricultural sector and the suitability of the land that becomes available for energy crop production. However, both intensification of the agricultural sector and land-use conversion can have adverse environmental effects such as increased greenhouse (GHG) emissions related to carbon stock losses and N2O emissions from increased fertilizer use which could reduce the GHG mitigation potential. Therefore, the development in bioenergy potential and agricultural intensification should be assessed in an integrated way.

Potential yield levels and environmental impacts of the intensification of agricultural production and energy crop cultivation are strongly related to the biophysical conditions which are spatially heterogenous. For that reason, bioenergy potential and potential impacts of agricultural intensification should be assessed spatially explicitly, taking into account the variability in land use, soil, and climate. Therefore, the aim of this study is to develop a modeling framework that enables the spatially and temporally specific assessment LUC and related emissions of bioenergy potential and agricultural intensification.

Studies on global and European bioenergy potential have indicated large techno-economic production potential for Eastern Europe and for Ukraine specifically. Ukraine is considered to be a promising region for bioenergy production because of favorable climate conditions, rich agricultural resources, access to abundant water resources, and the proximity to major foreign markets. The decreasing population, the stable dietary intake, and the low productivity of current agriculture provide opportunities to reduce the required area for food and feed production, and thereby increasing the potential land available for bioenergy crop production. Although there are quite a few studies that have assessed the biomass production potential in Europe, just a few studies have done this spatially explicitly. Only the studies of Fischer et al. and De Wit and Faaij have included Ukraine in their assessments. However, as these studies were done on a spatially aggregated level, little information is available on the exact amount and location of available land for energy crops in Ukraine. In this study, the PCRaster Land Use change (PLUC) model is used to assess the potential LUC developments and related land availability for energy crops in Ukraine on a detailed spatial level (1 km²).

Some studies have integrally assessed the impacts of agricultural and use and LUCs on GHG emissions. Popp et al. and De Wit et al. assessed the GHG emissions of bioenergy production including the emissions from agricultural intensification spatially explicitly. Due to the scope of these studies (global, European), the assessments were made on an aggregated spatial level, which partly disregard the high spatial heterogeneity biophysical factors. In addition, these assessments are not temporally explicit and therefore ignore the development of carbon sequestration and GHG emissions over time.

In this study, a dynamic model is developed to assess the developments in CO₂, N₂O, and CH₄ emissions temporally and spatially explicitly for the period 2010–2030, taking into account the emissions related to agricultural intensification and LUC. The GHG model is developed as an additional module of the PLUC model. The emissions are differentiated for biophysical factors such as land use, climate, and soil, making use of the best quality spatial data available. The model is demonstrated for a case study in Ukraine in which agricultural production is intensified and the abandoned agricultural land is used for energy crops.

Wheat and switchgrass are selected as typical first- and second-generation bioethanol crops, respectively. As re- and afforestation could offer high potential for carbon sequestration, too, re-growth of natural vegetation is also considered as an alternative use of abandoned farmland.

Method

The conducted analysis consists of four methodological steps:

1. Projections are made for the development in domestic production of food, feed, and livestock products.
2. Scenarios are constructed on the developments in agricultural productivity.
3. LUCs are modeled temporally and spatially explicitly making use of the PLUC model.
4. GHG emissions due to changes in land use and management are analyzed temporally and spatially explicitly.

The four methodological steps are described in detail below.

Projections of domestic production

The demand for domestically produced food and feed is related to developments in population size, Gross Domestic
Product (GDP), food intake per capita, and self-sufficiency ratio (SSR, i.e. the extent to which domestic supply meets domestic demand). The future food and feed production requirements are based on the outlook on developments for Eastern European Countries of the FAO for the period 2006–2050. The figures for Ukraine are obtained by disaggregating these figures according to national trends in population size, dietary intake, and exports.

### Scenarios

Although several studies project a large bioenergy potential for Ukraine, the political, institutional, and technical changes required to accomplish this are significant. For this reason, two highly divergent scenarios are used to explore the broad range of possible future developments of the agricultural sector of Ukraine.

The Business As Usual (BAU) scenario represents a continuation of historic trends in agricultural productivity (after the dissolution of the Soviet Union). This is in line with the ‘low’ scenario for Central and Eastern European Countries (CEEC) in the study of De Wit and Faaij and with the projections of the FAO. Trends in yield per crop type for the period 1992–2009 are extrapolated toward 2030.

The progressive scenario represents a future with full implementation of agricultural and institutional reforms that enable (foreign) investment in the agricultural sector.

| Table 1. Main characteristics of the two scenarios related to LUC. |
|---------------------------------------------------------------|
| **Characteristic** | **Current (2010)** | **Future (2030)** | **BAU** | **PROG** |
| Population | 45.4 Mpeople | 40.5 Mpeople | | |
| Diet | 3200 kcal cap⁻¹ | 3300 kcal cap⁻¹ | | |
| SSR | 1.14 | 1.29 | | |
| Farming practices | Combination of: | Continuation of trend towards more household and private farms at the expense of large enterprises. | Abandonment of subsistence farming, increase in number and size of private-individual farms and reform of large enterprises. |
| Technology adoption | Low use of irrigation (<2% of arable land), fertilizers (<30 kg nutrients ha⁻¹), pesticides (<0.8 kg ha⁻¹), and machinery. | Little improvement in accessibility of inputs and machinery. | High adoption inputs and machinery; meets West European practices |
| Agricultural productivity | Low crop yield (average 2.7 t ha⁻¹ wheat), low cropping intensity (CI) 0.77. | Little development in yields and modest increase in cropping intensity (0.3% p.a) | High increase in crop yields (3.8% p.a.) and cropping intensity (1.2% p.a.) resulting in a CI of 1 in 2030. |
| Livestock sector | Low livestock numbers compared to historic levels. 66% of cattle, 55% of pigs, 83% goats and 46% of poultry is produced on household farms which are characterized by low number of animals, manual labour and low nutritious fodder which results in a low productivity. Low carrying capacity pastures. | Increase in livestock numbers and modest increase in productivity. Due to modest shift from small to large production farms. | Increase in livestock numbers (same as BAU), shift towards high productive farms, full mechanization. Similar practices and productivity in livestock sector as in Western Europe by 2030 which includes managed pasture (including fertilization) and the use high quality fodder. |
| Bioenergy implementation | No significant commercial bioenergy production. | Abandoned agricultural land is used for bioethanol crops. | |

| Figures are derived from FAOSTAT. |
| Self-sufficiency ratio, the extent to which domestic supply can meet domestic demand. Derived from FAO Agricultural outlook. |
| Based on Kucher, and Lerman et al. Subsistence farmers that produce mainly for own consumption and supply limited proportions of their production to the market (20-40%). |
| Assumptions on future farming practices in progressive scenario are based on studies of De Wit and Faaij et al. |
| The crop productivity is defined by the yield levels in ton ha⁻¹ and the cropping intensity (area harvested/arable land). Low cropping intensities indicate large amounts of fallow/set-aside land. |
| Development in livestock production efficiencies for Eastern European and Western European countries are derived from Bouwman et al. |
| Currently 1 million hectares of land is in used for rapeseed production in Ukraine. Although recent trends show a decrease, in this study it is expected that rapeseed production will double by 2030 (FAO outlook) in line with current trends and announced policies. GHG emissions avoidance by substituting biodiesel is not incorporated in this study. |
and the adoption of more advanced agricultural technologies and management practices resulting in a convergence of yield levels of Ukraine with West European Countries (WEC) by 2050. This is in line with the ‘baseline’ scenario of the CEEC in the study of De Wit and Faaij.\textsuperscript{9} In Table 1, the key characteristics of the scenarios are described. In addition to the progressive scenario, a scenario with more emphasis on sustainable agriculture is developed. This scenario is similar to the progressive scenario, but it is assumed that mitigation measures to reduce agricultural GHG emissions such as reduced tillage, increased carbon input, and fertilizer type improvements are implemented.

**Land-use change model**

Land availability for energy crop production is modeled taking into account the land required for other land-use functions such as nature conservation and food production. In order to spatially assess LUC dynamics, the PLUC model has been developed. The methods and the data requirements for the modeling of land availability for energy crop production are described in Van der Hilst et al.\textsuperscript{16} The technical characteristics of PLUC are described in Verstegen et al.\textsuperscript{15}

The LUCs in the period 2010–2030 are modeled for each year on a grid with a 1 km\(^2\) cell size, by allocating land to a specific land-use class based on the total demand for the products from this class (pasture, crops) and the location-specific suitability of this land-use class. The suitability of land for a specific land use is defined by a weighted summation of a specific set of suitability factors such as the agro-ecological suitability, accessibility (i.e. distance to infrastructure) and population density (the suitability factors included in this study are depicted in Table 2). Areas that

| Suitability factors | Relationship | Land use | Explanation |
|---------------------|--------------|----------|-------------|
| Neighbourhood       | +            | Linear   | Development at each individual location affects the conditions of neighbouring and distant locations. |
| Conversion elasticity| –            | Linear   | Some land use classes are more reluctant to change due to e.g. higher conversion costs. |
| Agro-ecological suitability | +            | Exp.     | The agro-ecological suitability includes climate soil and terrain constraints for agricultural productivity. |
| Land rent prices    | +            | Linear   | Proxy indicator for the demand for land in a specific region. |
| Cattle density\textsuperscript{a} | +            | Linear   | The cattle density represents the demand for grazing. |
| Population density  | +            | Linear   | The population density is an indication of the pressure on land. |
| Population change   | +            | Linear   | Due to decreasing population and urbanization rural areas are abandoned. |
| Unemployment        | +            | Linear   | Unemployed people become more dependent on subsistence farming. |
| Distance to cities  | +            | Inv. prop. | Distance to cities represent the pressure from urban areas on their surroundings, it is a proxy for distance to markets. |
| Distance to villages| +            | Inv. prop. | The small plots in the surrounding of the village are most likely to remain in use compared to the plots further away from the village |
| Distance to railroad| +            | Inv. prop. | Accessibility is an important precondition for the use of agricultural land. The road density quite high and therefore no limiting factor for accessibility |

\textsuperscript{a}Cattle is responsible for 96% of the total grass consumption (remainder is sheep en goat), therefore the cattle density is assumed the best proxy-indicator for the spatial distribution of demand for grazing.\textsuperscript{24}
are not suitable (such as steep slopes) or not allowed (such as conservation areas) to be converted to agricultural land, are excluded from expansion of agricultural land including energy crops. The allocation of land to the land-use classes in one time step (one year) continues until the demand for that specific year is met. The modeling comprises a feedback loop: the map resulting from the allocation in time step \( t \) is an input for the allocation in time step \( t+1 \). As it is a starting point that bioenergy crops should not compete with food and feed production, bioenergy crops are allocated last, when all other land-use requirements for that time step are met.

The PLUC model is tailored for the Ukrainian context by applying country-specific drivers and suitability factors for LUC. In line with other LUC studies focusing on Europe, the agro-ecological suitability, the accessibility, the land conversion elasticity and the neighborhood characteristics are included in the suitability factors for the allocation of cropland and pastures. In addition, Baumann et al. identified socio-economic factors that influence the post socialist LUCs in West Ukraine. The number of villages and the changes in population density and unemployment were correlated with agricultural land abandonment. In this study, it is assumed that these driving forces also apply for the rest of Ukraine. In addition to these suitability factors, the current value of agricultural land expressed in the land rent prices is included as a proxy indicator for the areas where cropland and pastures will not be abandoned easily. The weighting of the suitability factors is difficult and expert consultation in the Ukraine was used to determine the relative importance of each suitability factor. Expert consultation is more often applied in LUC studies to weight the suitability factors, when longitudinal field observations are lacking. Although, there was no consensus among the experts on the relative importance of each individual suitability factor, all experts indicated that agro-ecological suitability is the most important suitability factor. Table 2 depicts the suitability factors and the assigned weights used in the allocation procedure for agricultural land uses. The order of allocation of land use classes in the LUC modeling is:

1. Arable land
2. Mosaic cropland-pasture
3. Pasture land
4. Bioenergy crops or re-growth natural vegetation

In the BAU scenario, agricultural land is allowed to expand in forest areas. In the progressive scenario, however, it is assumed that all forest areas are protected and cannot be converted to agricultural land use. Autonomous deforestation (i.e. deforestation which is not caused by the expansion of another land use) is not included in the LUC modeling as deforestation is mainly related to illegal logging and clearing which is not recorded systematically. Moreover, this study focuses on changes in agricultural land which is the dominant land use in Ukraine (75%), while forest occupies only 15% of the land area. Table 3 depicts the spatial data, the type of data and their source used in the land use allocation.

### Energy crop production

Wheat and switchgrass are selected as bioenergy crops in order to compare the GHG emission abatement potential for a typical first- and second-generation ethanol crop. The conversion technology for production of ethanol from wheat is a well-established technology and Ukraine has a long history of cultivating wheat. However, as Ukraine is perceived to be the breadbasket for Europe and even on a global scale, there could be a psychological barrier for Ukrainians to produce wheat for energy purposes. The production of second-generation ethanol from switchgrass...
is selected because previous studies indicated high production potential of switchgrass in Ukraine.9,14
For the modeling process, it is assumed that the land that becomes available is taken into use for energy crop production in the same year that the land is abandoned. Abandoned agricultural land in the excluded areas (Chernobyl, conservation areas, and slopes >16%) is assumed to be used for re-growth of natural vegetation. It is assumed that the energy crops are cultivated using state-of-the-art cultivation practices. Therefore, high yields can be achieved directly from the beginning, and no learning (in terms of yield improvement over time) is assumed. The maximum attainable yield levels of wheat (9.1 odt ha –1) and switchgrass (21.4 odt/ha) are derived from the studies of De Wit and Faaij and Fischer et al.51–54 The spatial variation in yields due to the suitability is based on the agro-ecological suitability map. The suitability map for rain-fed crops37 is used as a proxy for wheat, and the suitability map for pasture is used as a proxy for the agro-ecological suitability of switchgrass cultivation.38

Re-growth natural vegetation
Without disturbance, natural vegetation can regenerate on abandoned agricultural land. The rate of regeneration and the maximum attainable biomass stock depend on the previous land use,29,39 the suitability of the land for biomass production,29,40 and the dispersal of seeds which is related to proximity of forest.25,41 This study only accounts for the suitability for tree generation, which is considered to be most relevant from a GHG and carbon stock perspective.
Lyssawserts et al.42 argue that old growth forest can continue to accumulate carbon. However, in line with Silver et al., Odum, and Kira and Sihdei,43–45 in this study it is assumed that mean annual increment will level off when the forest reaches maturity: the increment rate of biomass by forest growth will move toward equilibrium with the rate of natural decay.
The average mean annual increment of forest in Ukraine reported in studies varies between 2.2 and 4.4 odt/ha, the observed standing biomass stocks vary between 99 and 220 odt/ha, and the time to reach maturity varies between 30 and 80 years.25,46–50 (comparison based on odt/ha from other units calculated based on tree specific wood density, forest composition in Ukraine, and specie specific carbon content50–52).
The relation between Net Primary Productivity (NPP) and biomass stock is found to be linear in temperate regions and quadratic in regions where higher NPPs are reached.47 In this study, a simplified linear model of forest growth is applied with an average annual increment of 4.4 odt/ha, a growth period of 40 years and an average standing stock of 176 odt/ha. The average increment and standings stock is differentiated for the spatial variation in the suitability of forest growth based on the map of Kindermann et al.47 This results in a range of above ground biomass stock of 0–288 odt/ha.

GHG emissions
The net GHG balance is calculated on a grid cell level, taking into account CO2, N2O, and CH4 emissions, and GHG emission abatement by means of substituting fossil fuels for biofuels. Equation (1) depicts the overall GHG balance. All four types of emissions are spatial and temporal, meaning that they vary over x, y, and t.

\[
GHG\text{balance} = \left( \Delta C \cdot \frac{44}{12} \cdot GWP_{CO2} \right) + \left( N \cdot \frac{28}{44} \cdot GWP_{N2O} \right) + \left( CH4 \cdot GWP_{CH4} \right) - GHG\text{abatement}
\]

GHG \text{abatement} \text{ avoided GHG emissions by replacing fossil fuels}

| GHG | Net greenhouse gas emissions |
|-----|-----------------------------|
| ∆C | Change in carbon stock Kg C ha–1 yr–1 |
| GWP_{CO2} | Global warming potential CO2 factor |
| N_{N2O} | N emitted in the form of N2O Kg N ha–1 yr–1 |
| GWP_{N2O} | Global warming potential N2O factor |
| CH4 | Methane emissions Kg CH4 ha–1 yr–1 |
| GWP_{CH4} | Global warming potential CH4 factor |
| GHG\text{abatement} | Avoided GHG emissions by replacing fossil fuels Kg CO2-eq ha–1 yr–1 |

The global warming potential (GWP) is derived from the IPCC and assume a time horizon of 100 years.53

Changes in carbon stock
When land is converted from one land use to another or when land-use management changes, carbon can accumulate (carbon sequestration) or diminish (carbon emissions). In this study, the IPCC approach is applied to calculate CO2 emissions related to changes in carbon stocks.50 This involves five carbon pools: above ground biomass, below ground biomass, dead wood, litter, and soil organic matter. In line with the Tier 1 approach of the IPCC, equilibrium in the carbon stocks in dead wood and litter is assumed in cropland and pasture. Therefore, these carbon pools are not considered.
The soil organic carbon (SOC) content is related to the soil type, climate, land use, and applied agricultural management and is therefore spatially heterogeneous. Land-use and management changes affect the SOC content: for
example, permanent vegetation cover reduces respiration of the soil and therefore the oxidation of SOC, whereas intensive tillage and drainage increases the loss of SOC. The application of organic inputs such as manure and crop residues could increase SOC.

Figure 1 depicts the relations between the SOC content and other carbon pools.

For every year, the change in SOC is calculated spatially explicitly according to Eqn (2):

\[
\Delta C_{\text{SOC}} = \left( \frac{SOC_t - SOC_{t-1}}{D} \right)_{\text{Mineral}} + \Delta C_{\text{organic}} \tag{2}
\]

- \(\Delta C_{\text{SOC}}\): Annual change in SOC (Ton C ha\(^{-1}\) yr\(^{-1}\))
- \(SOC_t\): SOC at time step \(t\) (Ton C ha\(^{-1}\))
- \(SOC_{t-1}\): SOC at previous time step (Ton C ha\(^{-1}\))
- \(D\): Time required for equilibrium (Years)
- \(\Delta C_{\text{organic}}\): Change in SOC in organic soil (Ton C ha\(^{-1}\) yr\(^{-1}\))

In line with the IPCC the change in carbon in organic soils is assumed to be a fixed annual carbon flux (in ton C ha\(^{-1}\) yr\(^{-1}\)) depending on the land use and climate region.\(^{50}\) The SOC in mineral soils at time step \(t\) is calculated given the soil type, climate, land use, management and previous conversions within the modeling time-frame based on default values of the IPCC.\(^{50}\) The climate region and soil type are spatially explicit and static. The spatial attribution of the climate regions is based on the IPCC climate classification related to average annual precipitation and temperature.\(^{50}\) Maps of annual averages of precipitation and temperature were constructed by interpolating the precipitation data of 45 domestic and 5 neighboring weather stations derived from NOAA weather stations database by applying the tension spline interpolation method.\(^{54,55}\) Spatially explicit data on soil weather stations database by applying the tension spline interpolation method.\(^{54,55}\) Spatially explicit land use map for year \(y\) is the key output of the PLUC model. The management level of the agricultural land use including the tillage regime and the organic carbon application levels are scenario specific. The land use, management, and organic input factors affecting the SOC content are differentiated for the BAU scenario and the progressive scenario and are depicted in Table S1 of the online supporting information. Some studies indicate that it could take up to 50–100 years to reach a new SOC equilibrium.\(^{57}\) However, in this study, a time horizon of 20 years is assumed in line with the IPCC,\(^{50}\) and as proposed by bioenergy sustainability criteria.\(^{58,59}\) This equilibrium time implies a continued SOC change for 20 years after the land-use conversions.

The carbon stocks in above and below ground biomass depend on the land use, the productivity of the land and the management applied. For annual crops, the increase in biomass stocks in a single year is assumed to be equal to biomass losses due to harvest and degeneration in that same year: there is no net accumulation of biomass carbon stocks in annual arable crops.\(^{50}\) For pastures and switchgrass, the biomass carbon stock is equal to the carbon content of the below ground biomass (it is assumed the above ground biomass is removed due grazing or harvested for consumption). For natural vegetation such as forest, shrubland, and natural grassland the carbon in both the above and below ground biomass are included. The amount of below ground biomass is calculated making use of root to shoot ratios of the IPCC.\(^{50}\) Although it is expected that it can take 40 to 100 years before forest reach full maturity,\(^{23,49}\) and even can continue to accumulate carbon after full maturity is reached\(^{62}\) in this study it is assumed that the bulk of carbon sequestration occurs in the first 40 years, and a linear growth rate is applied in the model.

Nitrous oxide emissions

In this study, the nitrous oxide emissions from agricultural soils and from the livestock sector are included in the modeling framework. The \(N_2O\) that is formed during the nitrification and denitrification processes in the soil is emitted to the atmosphere. The amount of nitrous oxide emitted is related to the amount of inorganic nitrogen available. The IPCC guidelines\(^{50}\) propose a default emission factor (EF) of 1% for nitrogen inputs from mineral fertilizers, organic amendment, and crop residues. Many studies regarding GHG emission from energy crop production or GHG in agriculture in general, apply this default emission factor.\(^{21,22,60}\) However, several studies have indicated that \(N_2O\) emissions vary to a great extent depending on local conditions such as mineral nitrogen availability, agricultural land use, soil type and N-origin.\(^{60–63}\) Therefore, this study models the \(N_2O\)
emissions in detail spatially explicitly accounting for these differences.

In line with the MITERRA-EUROPE model, balanced fertilization is assumed. This implies fertilizer and manure application rates in accordance with the nitrogen crop demand after accounting for the crop uptake factor, nitrogen inputs from grazing, atmospheric deposition, mineralization, biological N fixation and accounting for the losses due to direct N2O emissions, volatization (NH3 and NOx), run off and leaching. The losses of nitrogen through direct N2O emissions, volatization and run off are nitrogen source and condition specific. The indirect N2O emissions are related to the amount of nitrogen that is lost due to run off , leaching and volatization. For that reason, the total N application levels for balanced fertilization and therefore the N2O emissions can only be calculated when all nitrogen losses through other pathways are included in the equation. Figure 2 provides an overview of the N pathways addressed in this study. Equation (3) (adapted from Velthof et al.)64 provides the calculation method for balanced fertilization and indicates the relation between the nitrogen sources and nitrogen losses.

\[
(N_{\text{crop}} + N_{\text{res}}) \cdot f_{\text{uptake,crop-res}} = (N_{\text{fert}} - N_{\text{N2O,fert}} - N_{\text{vol,fert}} - N_{\text{runoff,fert}}) + (N_{\text{man}} - N_{\text{N2O,man}} - N_{\text{vol,man}} - N_{\text{runoff,man}})
\]

\[
+ f_{\text{graz}} \cdot (N_{\text{N,graz}} - N_{\text{N2O,graz}} - N_{\text{vol,graz}} - N_{\text{runoff,graz}})
\]

\[
+ N_{\text{fix}} + f_{\text{dep}} \cdot (N_{\text{dep}} - N_{\text{N2O,dep}}) + f_{\text{min}} \cdot ((N_{\text{res}} - N_{\text{N2O,res}})
\]

\[
+ (N_{\text{man}} - N_{\text{N2O,man}}) + (N_{\text{soil}} - N_{\text{N2O,soil}})
\]

\(\text{Figure 2. Schematic overview of nitrogen pathways modeled in this study. Adapted from Velthof et al.}\)
Methane emissions

Methane emissions from enteric fermentation and manure storage depend on the number and type of livestock, their enteric fermentation rate, and the type of storage facility. The number of animals per species is derived from the FAO and the State Statistic Service of Ukraine. In this study the country specific data on methane emissions from enteric fermentation and from housing and storage per head are derived from the Ukraine country report of the UNFCCC. As no point sources of GHG emissions are taken into account, all methane emissions and also N2O from housing and storage are allocated to the manure which is distributed over agricultural land in proportion to the N-gap between N requirements and N supplied by other sources.

Avoided emissions due to replacement of fossil fuels

The total GHG abatement is calculated taking into account the cumulative biomass yield, the conversion efficiency and the abatement figures per liter of ethanol which are derived from JRC and include the emissions related to the cultivation of biomass. It is assumed that wheat straw is not used for energy purposes and the assumed conversion efficiency of lignocellulosic bioethanol is rather conservative, as no future learning and electricity production is assumed. Also, no improvements in the fossil reference are assumed.

The cultivation related N2O emissions have been excluded from the abatement figures as the N2O emissions are already accounted for. The spatial allocation of GHG emission reductions resulting from the replacement of fossil fuel are directly related to the crop yield and the conversion efficiency from the crop to ethanol. Table S3 of the online supporting information depicts the abatement figures for ethanol from wheat and switchgrass.

Mitigation measures of GHG emissions from agriculture

Measures to reduce agricultural GHG emissions include reduced tillage, increased carbon input through less residue removal and fertilizer type improvement. Reduced tillage reduces both carbon and N2O emissions. Increasing the amount of residues left on the field increases SOC and reduces the required nitrogen inputs from manure and fertilizers. However, the direct N2O emissions from residues will increase. Shifting from a mixture of nitrate based and ammonium based fertilizers to ammonium

\[ N_{fix} \] Biological N fixation Kg ha\(^{-1}\)

\[ f_{dep} \] Available fraction of atmospheric deposition

\[ N_{dep} \] N supplied by atmospheric deposition Kg ha\(^{-1}\)

\[ N_{N2O,dep} \] N in N2O emissions from atmospheric deposition Kg ha\(^{-1}\)

\[ f_{min} \] Available fraction of mineralized N

\[ N_{tissue} \] Organic N supplied from residues left on the field (above and below ground) Kg ha\(^{-1}\)

\[ N_{N2O,tissue} \] N in N2O emissions from residues Kg ha\(^{-1}\)

\[ f_{man} \] Organic N supplied by manure Kg ha\(^{-1}\)

\[ N_{N2O,man} \] N in N2O emissions from mineralization of organic N Kg ha\(^{-1}\)

\[ f_{min} \] Mineralized N related to soil organic carbon loss Kg ha\(^{-1}\)

In this study, the method of assessing the nitrogen pathways from agricultural soils described by Velthof et al. is applied. However, some alterations to this method have been made. The direct and indirect N2O emissions factors are differentiated for land use, soil type and nitrogen source and are derived from Lesschen et al. (see Table S2 of the online supporting information). In addition, a link between the SOC losses and nitrogen-mineralization is made. Moreover, in this study, the nitrogen related emissions are modeled both spatially explicitly (on a detailed level, allowing for differentiation in emissions for spatial heterogeneity in biophysical conditions) and dynamically (to allow for modeling of nitrogen emission dynamics over time). Hence, all variables in Eqn (3) vary in space and time.

The total N2O emissions are the sum of direct N2O emissions from the nitrogen supplied by fertilizer, manure, grazing, atmospheric deposition, residues and mineralization; and the indirect N2O emissions from the volatization, runoff and leaching from nitrogen supply (Eqn (4)).

\[ N_{N2O} = (f_{N2O,fert} + f_{N2O,man} + f_{N2O,vol}) + f_{N2O,runoff} \cdot (f_{N2O,fert} + f_{N2O,man}) + f_{N2O,leach} \cdot (f_{N2O,fert} + f_{N2O,man}) + f_{N2O,runoff} \cdot f_{N2O,leach} \] (4)

\[ N_{fert} \] Total N2O emissions Kg ha\(^{-1}\)

\[ f_{N2O,vol} \] Fraction of volatized N that results in N2O emissions

\[ f_{N2O,runoff,leach} \] Fraction of leached and runoff N that results in N2O emissions

\[ N_{leach} \] N that leaches below the rooting zone Kg ha\(^{-1}\)

More detailed information on the method of analysis of the individual N-pathways and the data used in this assessment are described in van der Hil et al.
based fertilizer only decreases the direct N\textsubscript{2}O emission from fertilizer application. The mitigation measures are based on the measures proposed in De Wit et al., Lesschen et al., and Smith et al.\textsuperscript{18–20,22} The input data to calculate the effect of the mitigation measures on the SOCs are included in Table S1 and S2 of the online supporting information.

## Results

### Land-use changes

#### Total agricultural land balance

In Fig. 3, the developments in production of food and feed in million ton dry weight is depicted up to 2030 for the BAU scenario and the progressive scenario. Although it is assumed that the increase in consumption is the same in the two scenarios, the demand for feed is lower in the progressive scenario as the livestock sector is assumed to become more efficient. In the progressive scenario, a shift towards more feed crop consumption at the expense of grass consumption is assumed which results in a higher total crop demand and lower grass demand compared to the BAU scenario. However, differences between the two scenarios in terms of total production are limited.

In Fig. 4, the developments in crop and pasture yields and the efficiency in the livestock sector are presented for the two scenarios compared to the levels of 2010. The productivity increase is close to zero in the BAU scenario, whereas in the progressive scenario the productivity increases rapidly; especially the crop and pasture yields.

Figure 5 presents the total land requirements for crop production and grazing given the demand depicted in Fig. 3 and the productivity presented in Fig. 4 and assuming the average agro-ecological suitability of crop-land and pasture currently in use. Because of the higher yields and the higher cropping intensity in the progressive scenario, only half of the land currently in use for agriculture production is required to meet the demand in 2030. However, the actual land area depends on the location-specific productivity of the land (the agro-ecological suitability). For that reason, developments in actual land requirements and land availability for other land use functions can only be assessed using a spatio-temporal LUC model.

### Spatially explicit results

The land use for the BAU and progressive scenario for 2010, 2020, and 2030 is depicted spatially explicitly in Fig. 6. In both scenarios, there is a tendency towards more dedicated cropland and pasture land at the expense of mosaic cropland-pasture. In the BAU scenario, cropland expands at the expense of mosaic cropland-pasture in...
In the progressive scenario, agricultural land is rapidly abandoned due to the strong increase in agricultural productivity. Agricultural land is primarily abandoned in the areas which are less suitable for agricultural production such as the north and north-western regions, which are relatively marshy; the south-west region, which is characterised by the Carpathian Mountains; the eastern areas, which are more industrialized; and the southern areas, which receive little precipitation. Agricultural production concentrates in the central parts of Ukraine with the highest agro-ecological suitability. In addition, these areas are currently popular for agricultural production and have a
In the progressive scenario, in 2030, up to 5.0 EJ biomass could be produced on the available land compared to the potential wheat production 3.6 EJ (grain). As in the BAU scenario little land becomes available, potential annual production is low compared to the progressive scenario (±2 PJ for wheat and switchgrass in 2030).

**GHG emissions**

Developments in GHG emissions are calculated spatially explicitly on an annual basis on a spatial resolution of 1 km². This results in annual maps for the timeframe 2010–2030 of N₂O, CO₂, and CH₄ emissions, as well as the avoided emissions related to the replacement of fossil fuels for the BAU and the progressive scenario, and for the progressive scenario taking into account the measures to reduce agricultural GHG emissions. In the online supporting information, snapshots of annual N₂O emissions, carbon stock changes, and CO₂ abatement for the years 2010, 2020, and 2030 are presented for the progressive scenario (due to the fewer LUCs, the changes in GHG emissions in the BAU scenario are less significant, and therefore not shown).

**Annual average GHG emissions and sequestration**

In Fig. 9, the average annual GHG emissions (including N₂O, CO₂, and CH₄ and the avoided GHG emissions) for the timeframe 2010–2030 relative to the levels in 2009 are presented spatially explicitly for the progressive scenario. An increase in emissions occurs in all areas that remain in use for agricultural production for food and feed as a result of intensified production (including higher nitrogen supply and full tillage regime). It is assumed that in the progressive scenario the pastures are managed better relatively high population density, many villages and cities, access to railroads and high unemployment rates. In Fig. 7 the developments in land use requirements for the BAU and progressive scenario is depicted for 2010, 2020, and 2030 as they result from the spatially explicit modeling. Figure 7 is constructed based on the spatial modeling using the same food and feed requirements and scenario assumptions on agricultural efficiency as Fig. 5 is based on, but instead of the average agro-ecological suitability of the land currently in use of cropland and pasture (used for Fig. 5), the spatial variability of the agro-ecological suitability is taken into account in Fig. 7. For the BAU scenario, it is clear that the spatially modeled land requirements are higher compared to the level depicted in Fig. 5. This is due of the fact that the agricultural land is forced to expand to areas that are less suitable for agricultural production (as all favorable areas are already in use). For the progressive scenario, the modeled land requirements to meet food and feed productions are significantly lower compared to the levels depicted in Fig. 5. Therefore, more land will become available for energy crop production (32.1 Mha). This is the result of the concentration of agricultural land in the most suitable areas. These results illustrate the importance of assessing land use dynamics and related land availability for energy crops spatially explicitly.

Figure 8 shows the development in potential annual biomass feedstock production of switchgrass (whole plant) and wheat (grain only) for the period up to 2030. Although the assumed conversion efficiency from wheat to ethanol is higher than from switchgrass to ethanol, the potential ethanol yield per hectare is higher for switchgrass due to the higher biomass yields (a maximum yield of 170 GJ ha⁻¹yr⁻¹ for switchgrass and 100 GJ ha⁻¹yr⁻¹ for wheat). In the progressive scenario, in 2030, up to 5.0 EJ biomass could be produced on the available land compared to the potential wheat production 3.6 EJ (grain). As in the BAU scenario little land becomes available, potential annual production is low compared to the progressive scenario (±2 PJ for wheat and switchgrass in 2030).
compared to the levels of 2009, resulting in larger carbon stocks in below ground biomass and higher SOC content but also in increased N₂O emissions. Large GHG emission reductions occur when abandoned cropland is used for switchgrass or regeneration of natural vegetation.

The outliers of high GHG emissions (i.e. >1 ton CO₂-eq per hectare per year, representing ±1% of the area) occur in a few areas in the southern, the north western (when converted to wheat), and central part of Ukraine. The outliers in the south and central area are a result of the conversion of shrubland to pastures and to mosaic cropland-pasture and the conversion of mosaic cropland-pasture to cropland, which results in losses in SOC and above and below ground biomass and an increase in N₂O emissions due to an increased nitrogen supply. The high GHG emissions in the north western area only occur when abandoned pastures are converted to wheat and are caused by the significant increase in annual carbon fluxes of the organic soils that are present in that part of Ukraine. High sequestration potential (i.e. >10 ton CO₂-eq ha⁻¹ yr⁻¹; representing 0.1–3.5% of the area, depending on the usage of abandoned land) are found in high productivity areas on clayey and organic soils where abandoned land is used for re-growth of natural vegetation or switchgrass cultivation.

Re-growth natural vegetation

When the land is used for the re-growth of natural vegetation, a considerable amount of carbon is stored in above and below ground biomass, as well as through an increase in SOC. The highest carbon accumulation levels are reached in the areas with the highest mean annual increment of forest and in moist areas with clayey soils. It should be noted that not all SOC and biomass sequestration is accounted for, as some areas will only become available at the end of the timeframe assessed. Therefore, the carbon sequestration will continue for several years after 2030, but will not go on indefinitely, as it is assumed that equilibrium of SOC will be reached after 20 years, and that mature forests will not continue to sequester biomass carbon after 40 years. In the progressive scenario 90% of the area has an average annual GHG emission or sequestration between −8.8 and +0.7 with an overall average of −2.9 ton CO₂-eq per hectare per year. The national net average annual GHG balance for the period 2010–2030 is −172 Mton CO₂-equivalent.

Wheat

Although a net negative GHG balance is achieved when wheat for bioethanol is cultivated on the abandoned land,
less GHG emissions are avoided in the timeframe 2010–2030 when compared to the use of abandoned land for re-growth of natural vegetation or switchgrass. The N\textsubscript{2}O emissions are significantly higher compared to re-growth of natural vegetation, as in addition to the food and feed crops, wheat for bioethanol requires nitrogen input. In addition, the conversion of pastures to wheat results in a loss of SOC and below ground biomass. However, as it is assumed that currently the pastures are not well managed (e.g. no irrigation, fertilization, weeding, seeding of improved grass species, as well as overstocking) and are therefore semi-degraded,\textsuperscript{70} and that wheat is assumed to be cultivated leaving 50\% of the residues, the losses in organic carbon are limited. In addition, significant parts of the abandoned agricultural land are located in the ‘excluded areas’, which are assumed unsuitable for energy crop cultivation. The re-generation of natural vegetation in these areas results in a considerable carbon stock in above and below ground biomass and SOC, which compensates the losses of biomass and SOC in the areas where pasture is converted to wheat. In the progressive scenario, 90\% of the area has an average annual GHG emission or sequestration ranging between -2.7 and +0.4, with an average of -0.7 ton CO\textsubscript{2}-eq per hectare per year. The national net average annual GHG balance is -45 Mton CO\textsubscript{2}-equivalent.

\textbf{Switchgrass}

The use of abandoned land for the cultivation of switchgrass for bioethanol production results in the most favorable GHG balance. Nevertheless, the N\textsubscript{2}O emissions are the highest for this option compared to the use of abandoned land for wheat or re-growth of natural vegetation. This is the result of the high nitrogen requirements related to the high yields (despite of the relative low nitrogen content of the crop). However, the conversion of cropland to switchgrass results in high increase in SOC (due to the no tillage of switchgrass), and increase in below ground biomass. Also, the conversion from the current poorly managed pastures to well-managed switchgrass results in an increase in SOC and below ground biomass. Moreover, the higher yields and abatement value result in higher avoidance of GHG emission by the replacement of fossil fuel compared to wheat ethanol. In the progressive scenario, 90\% of the average annual GHG balance varies between -9.6 and 0.4 with an average of -3.1 ton CO\textsubscript{2}-eq per hectare per year. The national net average annual GHG balance is -191 Mton CO\textsubscript{2}-equivalent. It should be noted that the gains and losses in organic carbon are assumed to reach equilibrium, but that GHG abatement is assumed to continue (as it is expected that the future harvested biomass will continue to replace fossil fuels).

\textbf{Cumulative GHG emissions and sequestration}

The developments in GHG emissions are assessed spatially explicitly on an annual basis for the timeframe 2010–2030. The results of these assessments are summarized in graphs of the total cumulative emissions for the timeframe 2010–2030 in Fig. 10 for the BAU scenario (1), the progressive scenario (2), and for the progressive scenario + abatement measures (3). The three variants with the use of the abandoned agricultural land for re-growth of natural vegetation (a) and the use for wheat (b) and switchgrass (c) for bioethanol production are considered for all scenarios.

In the BAU scenario there are small differences between the three alternative usages of the abandoned agricultural land, as little land becomes available. The carbon emissions increase due to the expansion of agricultural land at the expense of shrubland and forest, and the conversion of mosaic cropland-pasture to dedicated cropland. The carbon emissions are mainly caused by the losses in above and below ground biomass (85\%); SOC losses play a minor role. The N\textsubscript{2}O emission increase slightly due to higher overall production and related nitrogen requirements. The total cumulative emissions for the timeframe 2010–2030 are ± 1.1 Gt CO\textsubscript{2}-equivalent.

The progressive scenario differs considerably from the BAU scenario, and also the three alternative land usages result in significant differences in cumulative emissions. The most apparent developments are already explained in the description of Fig. 9. The use of abandoned land for re-growth of natural vegetation results total cumulative GHG emissions avoidance of 3.5 Gt CO\textsubscript{2}-equivalent in the timeframe 2010–2030. When the abandoned land is used for wheat for bioethanol production a total of 0.8 Gt CO\textsubscript{2}-equivalent can be avoided. For switchgrass the GHG emission reduction amounts 3.8 Gt CO\textsubscript{2}-equivalent.

When measures are taken to reduce SOC losses and N\textsubscript{2}O emissions, higher net GHG emission reductions can be realized. As it is assumed that reduced tillage is applied on arable land and that pastures are improved, SOC levels increase on all agricultural land resulting in 9 \% (for wheat) to 44\% (for switchgrass) more cumulative carbon sequestration compared to the regular progressive scenario. In addition, it is assumed that only ammonium based fertilizers are used (instead of
In this study, a spatiotemporal model is developed to assess the developments in GHG emissions, taking into account the emissions related to agricultural intensification and LUC. The modeling framework was demonstrated for land use scenarios in Ukraine towards 2030.

Bioenergy potential

The spatiotemporal development in land requirements for food and feed production was analysed making use of the PLUC model. The results of the land-use modeling show that in the BAU scenario almost no land becomes available for energy crop production as the assumed productivity increase keeps pace with the increase in demand. In the progressive scenario, 32.1 million hectares could become available by 2030 as the increase in agricultural

Discussion

For all scenarios the total cumulative methane emissions are equal, since for all scenarios the same number of animals, the same enteric fermentation per animal and the same manure storage facilities are assumed. The spatial results show differences in the spatial distribution of methane emissions as these emissions are allocated to the manure and manure is spread according to the gap between the local nitrogen requirements and the local nitrogen supplied from other sources.

Figure 10. Graphs of development of cumulative GHG emissions for the timeframe 2010–2030 for the BAU scenario (1), the progressive scenario (2) and the progressive scenario with abatement measures (3). The three variants considered are the use of abandoned land for re-growth of natural vegetation (a), the use for wheat for bioethanol (b) and the use for switchgrass for bioethanol (c).
productivity exceeds the increase in demand of agricultural products. The 32.1 million hectares in 2030 is more than the projections of De Wit and Faaij and Fischer et al.1,10 This difference is mainly caused by the level of aggregation of the analyses. In this spatially explicit assessment, agricultural production is abandoned first in the least productive areas. Therefore, large amounts of land could become available while maintaining total agricultural production. In the assessments of De Wit and Faaij and Fischer et al., regional averages for land productivity are used.9,11 Therefore, the amount of land that will go out of production could be underestimated. The difference between a spatiotemporal assessment and a statistical assessment is also clearly demonstrated in Figs 5 and 7. However, when the projected biomass potential of this study (5 EJ in 2030) are compared to the findings of De Wit and Faaij (4.7 EJ in 2030), this is more similar.9 Although in this study more land is projected to become available for energy crops, the productivity of the available land is lower compared to the national average assumed by De Wit and Faaij.9 Even though in this study the cost of biomass are not considered, it is assumed that these will be higher than estimated by De Wit and Faaij as less productive land becomes available resulting in higher biomass production cost.9

GHG emissions

Developments in GHG emissions (N\(_2\)O, CO\(_2\), and CH\(_4\) emissions, as well as the avoided emissions related to the replacement of fossil fuels) were calculated spatially explicitly on an annual basis on a spatial resolution of 1 km\(^2\). There is a high spatial variation in GHG emissions as well as a high variation in GHG emissions between the scenarios and the use of the abandoned agricultural land.

Carbon emissions

The results show that the changes in carbon stocks due to LUC are the main contributor to the overall GHG balance in Ukraine. It was calculated that an average increase in carbon stocks (SOC, and above and below ground biomass) of 0.79 ton C ha\(^{-1}\) yr\(^{-1}\) is achieved when abandoned agricultural area is used for re-growth of natural vegetation. This is higher than found by Vuichard et al.71 who found an average carbon sequestration of 0.47 ton C ha\(^{-1}\) yr\(^{-1}\) on abandoned farmland in the USSR in the timeframe 1991–2000. The difference can be explained by the difference in geographical focus (Ukraine versus former USSR) and therefore different biophysical conditions resulting in other levels of SOC and above and below ground biomass.

In addition, the difference can be explained by the different reference levels applied in the studies. Vuichard et al. considers wheat production including irrigation and fertilization as a reference whereas this study considers only marginal fertilization in line with the agricultural practices in Ukraine in 2010.71 As the reference carbon level is much lower, the potential annual carbon accumulation gain is much higher compared to Vuichard et al.71

N\(_2\)O emissions

The direct and indirect N\(_2\)O emissions have been assessed in detail taking into account the spatial variation in crop requirements, nitrogen losses due to volatization, leaching and run-off , and by using land use, soil type, and nitrogen source specific N\(_2\)O emission factors. The agricultural N\(_2\)O emissions in Ukraine calculated in this study are relatively low compared to the levels in other European countries found other studies, for example De Wit et al. and others.17,22,64 This can be explained by several factors:

- In this study it is assumed that balanced fertilization is and will be applied. It is however likely that currently both under and over fertilization is applied and that in a progressive scenario, over fertilization will be applied like it has been/is done in other parts of Europe. Therefore the N\(_2\)O emissions could be underestimated.

- In this study, the soil, land use and N-source specific emission factors derived from Lesschen et al. are applied which are almost all lower than the 1% default factor that is used in most studies.62

- The N\(_2\)O emissions of grazing and (stored) liquid manure are high. However, the Ukrainian livestock sector is relatively small compared to other European countries and most of the manure is stored in solid systems which results in relative low emissions.

GHG balance

The results of this study show that the changes in carbon stocks related to LUC are the main contributor to the overall GHG balance. The study of De Wit et al. in which an integrated assessment of GHG balance of biofuel production and agricultural intensification in Europe was made,22 showed that N\(_2\)O emissions are mainly dominating the GHG balance. There are several reasons for this difference. First, as explained above, the N\(_2\)O emissions are relatively low in Ukraine compared to the rest of Europe. Second, in this study both SOC and biomass carbon are included.
whereas De Wit et al. only included SOC.\textsuperscript{22} Third, the ratio between the area that is converted to energy crops compared to the area of agricultural land that is intensified is relatively small in Ukraine, due to the relative low productivity of the land that is abandoned. Therefore, the N\textsubscript{2}O emissions related to intensification is relatively small compared to the carbon emissions related to large-scale LUC in Ukraine.

**Time horizon**

The GHG balances are calculated for the timeframe 2010–2030. However, as discussed in Böttcher et al. and Vuichard et al. the considered time horizon highly impacts the overall GHG balance.\textsuperscript{72,73} If a longer time horizon is assumed and it is assumed that no more land use or management changes will occur after 2030, the carbon stock related emissions and sequestration are phased out over time as a result of the assumed equilibrium in SOC (after 20 years) and forest growth (after 40 years). In the progressive scenario, the peak in the carbon sequestration rate in the soil is around 2030 and levels off towards 2050. Thereafter, it is expected that no additional carbon is sequestered in the soil. The sequestration of carbon in biomass when abandoned land is used for re-growth of natural vegetation levels off towards 2070. However, the N\textsubscript{2}O and methane emissions will continue over the years as will the avoidance of carbon emissions due to the replacement of fossil fuels. When the abandoned land is used for re-growth of natural vegetation, the GHG emission reduction potential could increase from −3.5 in 2030 to ± −10.2 Gt CO\textsubscript{2}-eq in 2100 in the progressive scenario. The use of the abandoned land for wheat ethanol production results in GHG emission reductions of −5.7 Gt CO\textsubscript{2}-eq by 2100 compared to the −0.8 Gt CO\textsubscript{2}-eq in 2030. The production of switchgrass ethanol could even result in −19.9 Gt CO\textsubscript{2}-eq by 2100. Therefore it could be concluded that the longer the timeframe considered, the more advantageous it is to use the abandoned land for second generation biofuels. This was also concluded by Vuichard et al.\textsuperscript{73}

**Uncertainties**

Spatiotemporal land use and GHG modeling requires numerous statistical and spatial data inputs. Currently, there is a lack of (spatial) data available for Ukraine. There are many inconsistencies between several sources of spatial and statistical data. Especially data on pastures and abandoned agricultural land is lacking as most land use maps do not distinguish these land use classes. In addition, accurate data is lacking on for example soil organic carbon content, C:N ratios of the soil, above and below ground biomass, succession rates, decomposition rates, effect of mitigation measures, etc. Moreover, in both the LUC and the GHG emission modeling, several simplifications have been made. The main simplification in the LUC model are the selection of the two rudimentary scenarios, the assumptions on land allocation, and the uniform application of the agricultural intensification and LUC allocation to the whole of Ukraine. The main simplifications in the GHG modeling are the use of default emission factors and the linear modeling of SOC and biomass carbon gains and losses given a fixed time horizon. Although, the data quality and model simplifications may lead to uncertainties, it is assumed that the currently available data and modeling efforts has sufficient accuracy to distinguish patterns and hotspots of LUC and GHG emissions. If the presented approach is to be used for the ex-ante assessment, monitoring and certification of biomass production, better data, a finer modeling resolution, more process based modeling and extensive analysis of error propagation and uncertainty could improve the quality of the assessments.

**Conclusion**

In this study, a dynamic modeling framework was developed to assess the developments in CO\textsubscript{2}, N\textsubscript{2}O and CH\textsubscript{4} emissions temporally and spatially explicitly for the period 2010–2030, taking into account the emissions related to agricultural intensification and LUC. The GHG model was developed as an additional module of the PLUC model. The emissions are differentiated for biophysical factors such as land use, climate, and soil. The model was demonstrated for a case study in Ukraine in which agricultural production is intensified and the abandoned agricultural land is used for energy crops or for the regeneration on natural vegetation.

The case study shows that in the BAU scenario little land becomes available for bioenergy crops as all current agricultural land is required to meet future food and feed demand. In the progressive scenario, 32.1 Mha could become available as agricultural land is rapidly abandoned due to the strong increase in agricultural productivity. When the abandoned land is used for energy crops, 3.6 EJ yr\textsuperscript{−1} wheat or 5.0 EJ yr\textsuperscript{−1} switchgrass can be produced by 2030. The modeling of the cumulative GHG emissions related to agricultural intensification, LUC and replacement of fossil fuels shows large spatial variation and large variation between scenarios and uses of the abandoned land. In the BAU scenario, there are no significant
differences between the variations in land use of the abandoned land as there is little intensification and almost no land available. In the progressive scenario, the cumulative GHG emission reduction that can be obtained in 2030 is 0.8 Gt CO₂-eq when the abandoned land is used for wheat ethanol production, 3.8 Gt CO₂-eq when it is used for switchgrass ethanol production, and 3.5 Gt CO₂-eq when it is used for re-growth of natural vegetation. When mitigation measures are taken, 0.8–1.8 Gt CO₂-eq more GHG emission can be avoided compared to the regular progressive scenario.

Although, for the medium term (2030) the use of the abandoned land for switchgrass ethanol and for re-growth of natural vegetation results in almost equal cumulative GHG emission avoidance, in the longer run (i.e. up to 2100) the total cumulative GHG abatement potential is higher when the land is used for second-generation ethanol crops given that fossil fuels will continue to be replaced after an equilibrium is reached in soil and biomass carbon.

The spatiotemporal assessment of LUC and related emissions shows that there are not only large spatial variations in GHG emissions but also that the total national GHG balance is different than when assessed on an aggregated level. The biophysical characteristics of the land that is abandoned for agricultural production and of the land that remains in use for agricultural production determines the overall ratio between agricultural intensification and land availability, the GHG emission factors and therefore the total GHG balance of intensification, LUC and replacement of fossil fuels.

There are several uncertainties in the spatiotemporal modeling of LUC and related GHG emissions. These are mainly related to a lack of detailed and accurate data on e.g. historic and current land use, biomass stocks, SOC levels, etc. In addition, several model simplifications have been made to allow for integrated modeling, consistency and transparency. Improvements can be made by obtaining more detailed and accurate spatial data especially on land use and biophysical factors, applying more process-based modeling and performing extensive analysis of error propagation and uncertainty.

Despite the uncertainties, this analysis shows that it is possible to link a spatiotemporal land use model with a dynamic GHG emission model and to assess spatial differentiations in GHG emission resulting from changes in land use and in land use management related to the implementation of bioenergy crop production. This is a great step forward compared to static and aggregated biomass potential models and to models that have tried to calculate GHG balances on aggregated spatial levels. This model framework allows for the identification of the best areas for intensification of agriculture and the best suitable areas for bioenergy crop production and it could contribute to the assessment of under what conditions the GHG balance could be optimized in conjunction with safeguarding sufficient food and feed production.

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References

1. Dornburg V, van Vuuren D, van de Ven G, Langeveld H, Meeusen M, Banse M et al., Bioenergy revisited: Key factors in global potentials of bioenergy. *Energ Environ Sci* 3(3):258–267 (2010).
2. Wicke B, Vuuren DPv, Verweij PA, Van Meijl H and Faaij APC, Indirect land use change: Review of existing models and strategies for mitigation. *Biofuels* 3(1):87–100 (2012).
3. van Dam J, Faaij APC, Hilbert J, Petruazzi H and Turkenburg WC, Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part A: Potential and economic feasibility for national and international markets. *Renew Sust Energ Rev* 13(8):1710–1733 (2009).
4. van Dam J, Faaij APC, Hilbert J, Petruazzi H and Turkenburg WC, Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part B: Environmental and socioeconomic impacts on a regional level. *Renew Sust Energ Rev* 13(8):1679–1709 (2009).
5. Van der Hilst F, Dornburg V, Sanders JPM, Elbersen B, Graves A, Turkenburg WC et al., Potential, spatial distribution and economic performance of regional biomass chains: The North of the Netherlands as example. *Agr Syst* 103(7):403–417 (2010).
6. Beringer T, Lucht W and Schaphoff S, Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Glob Change Biol Bioenerg* 3(4):299–312 (2011).
7. Van der Hilst F, Van Dam JMC, Verweij PA, Riksen MJPM, Sanders JPM and Faaij APC, Spatial variation in environmental impacts of bioenergy supply chains. *Renew Sust Energ Rev* 16:2053–2069 (2012).
8. Smeets EMW, Faaij APC, Lewandowski IM and Turkenburg WC, A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog Energ Combust* 33(1):56–106 (2007).
9. de Wit M and Faaij A, European biomass resource potential and costs. *Biomass Bioenerg* 34(2):188–202 (2010).
10. de Wit M, Londo M and Faaij A, Productivity developments in European agriculture; Relations to and opportunities for biomass production. *Renew Sust Energ Rev* 15(5):2397–2412 (2011).
11. Fischer G, Prieler S, van Velthuizen H, Berndes G, Faaij A, Londo M et al., Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. *Biomass Bioenerg* 34(2):173–187 (2010).
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12. Morton R, Sharp K, Chomiak B, Stepanets N, Muliar O and Oleshko N. Farm Reference Handbook for Ukraine. USAID, Washington, DC (2005).

13. Hellmann F and Verburg PH. Spatially explicit modelling of biofuel crops in Europe. Biomass and Bioenergy 35(6):2411-2424 (2011).

14. Fischer G, Prieler S, van Velthuizen H, Lensink SM, Londo M and de Wit M. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. Biomass Bioenergy 34(2):159–172 (2010).

15. Verstegen JA, Karssenberg D, van der Hilst F and Faaîj A, Spatio-temporal uncertainty in Spatial Decision Support Systems: A case study of changing land availability for bioenergy crops in Mozambique. Comput Environ Urban Syst 36(1):30–42 (2011).

16. van der Hilst F, Verstegen JA, Karssenberg D and Faaîj APC, Spatiotemporal land use modelling to assess land availability for energy crops – illustrated for Mozambique. GCB Bioenergy 4(6):859–874 (2012).

17. Leip A, Marchi G, Koeble R, Kempen M, Britz W and Li C, Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe. Biogeosciences 5:73–94 (2008).

18. Lesschen JP, Policy initiatives for climate change mitigation agricultural techniques. Deliverable 7: European quantification results. Alterra, Wageningen University and Research Centre, Wageningen (2008).

19. Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P et al., Greenhouse gas mitigation in agriculture. Philos T Roy Soc B 363(1492):789–813 (2008).

20. Smith P, Powidson DS, Smith JU, Falloon P and Coleman K, Meeting Europe’s climate change commitments: Quantitative estimates of the potential for carbon mitigation by agriculture. Glob Change Biol 6(5):525–539 (2000).

21. Popp A, Lotze-Campen H, Leimbach M, Knopf B, Beringer T, Bauer N et al., On sustainability of bioenergy production: Integrating co-emissions from agricultural intensification. Biomass Bioenergy 35:4770–4780 (2011).

22. de Wit MP, Lesschen JP, Londo M and Faaîj APC, Greenhouse Gas Mitigation Effects of Integrating Biomass Production Into European Agriculture. BioFPR DOI: 10.1002/bbb.1470 (2014).

23. Kuemmerle T, Olofsson P, Chaskovsky O, Baumann M, Ostapowicz K, Woodcock CE et al., Post-Soviet farmland abandonment, forest recovery, and carbon sequestration in western Ukraine. Glob Change Biol 17(3):1335–1349 (2011).

24. FAO. World Agriculture Towards 2015/2030 an FAO Perspective. Food and Agriculture Administration, Rome (2003).

25. FAO. Agriculture towards 2050, Outlook for Other Eastern European Countries. United Nations Food and Agriculture Organization, Rome (2011).

26. UNDP. World Population Prospects: The 2008 Revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, United Nations, New York (2009).

27. FAOSTAT, statistical database. [ONLINE]. Food and Agricultural Organization, Rome, (2010). Available at: http://faostat.fao.org/ (April 1, 2010).

28. Britz W, Verburg PH and Leip A, Modelling of land cover and agricultural change in Europe: Combining the CLUE and CAPRI-Spat approaches. Agr Ecosyst Environ 142(1/2):40–50 (2011).

29. Verburg P and Overmars K, Combining top-down and bottom-up dynamics in land use modeling: Exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape Ecol 24(8):1167–1181 (2009).

30. Verburg PH, Eickhout B and van Meijl H, A multi-scale, multi-model approach for analyzing the future dynamics of European land use. Ann Regional Sci 42(1):57–77 (2008).

31. Verburg PH, Schulp CJE, Witte N and Veldkamp A, Downscaling of land use change scenarios to assess the dynamics of European landscapes. Agr Ecosyst Environ 114(1):39–56 (2006).

32. Overmars KP, Verburg PH and Veldkamp T, Comparison of a deductive and an inductive approach to specify land suitability in a spatially explicit land use model. Land Use Policy 24(3):584–599 (2007).

33. Rounsevell MDA, Reginster I, Araújo MB, Carter TR, Dendoncker N, Ewert F et al., A coherent set of future land use change scenarios for Europe. Agr Ecosys Envir 114(1):57–68 (2006).

34. Baumann M, Kuemmerle T, Elbakidze M, Ozdogan M, Radeloff VC, Keuler NS et al., Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. Land Use Policy 28(3):552–562 (2011).

35. USAID, Environmental and Economic Impact Assessment of Land Privatisation in Eastern Europe. National Agrarian University of Ukraine - Institute of Land Resources, MPC Consulting, ARD Inc., Burlington (2006).

36. Kuemmerle T, Chaskovsky O, Knorn J, Radeloff VC, Kruhlov I, Keeton WS et al., Forest cover change and illegal logging in the Ukrainian Carpathians in the transition period from 1988 to 2007. Remote Sens Environ 113(6):1194–1207 (2009).

37. FAO and IIASA, Suitability of global land area for rainfed crops, using maxsimis (FGGD). FAO, Rome (2007).

38. FAO and IIASA, Suitability of global land area for pasture (FGGD). FAO, Rome (2007).

39. Benjamin K, Domon G and Bouchard A, Vegetation composition and succession of abandoned farmland: Effects of ecological, historical and spatial factors. Landscape Ecol 20(6):627–647 (2005).

40. Pueyo Y and Beguería S, Modelling the rate of secondary succession after farmland abandonment in a Mediterranean mountain area. Landscape Urban Plan 83(4):245–254 (2007).

41. Tasser E, Walde J, Tappeiner U, Teutsch A and Noggler W, Land-use changes and natural reforestation in the Eastern Central Alps. Agr Ecosys Envir 118(1/4):115–129 (2007).

42. Luysaert S, Schulze ED, Borner A, Knohl A, Hessenmoller D, Law BE et al., Old-growth forests as global carbon sinks. Nature 455(7210):213–215 (2008).

43. Silver WL, Ostertag R and Lugo AE, The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. Restor Ecol 8(4):394–407 (2000).

44. Odum EP, The strategy of ecosystem development. Science 164:262–270 (1969).

45. Kira T and Sihiode T, Primary production and turnover of organic matter in different forest ecosystems of the western pacific. Jpn J Ecol 17:70–87 (1967).

46. Nordberg M, Ukraine reforms in forestry 1990–2000. Forest Policy Econ 9(6):713–729 (2007).

47. Kindermann G, McCallum I, Fritz S and Obersteiner M, A global forest growing stock, biomass and carbon map based on FAO statistics. FAO, Rome (2008).
48. Nijmik M and van Kooten GC, Forestry in the Ukraine: The road ahead? *Forest Policy Econ* 1(2):139–151 (2000).

49. Houghton RA, The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus* 51B:298–313 (1999).

50. IPCC, IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, ed by Eggleston HS, Buendia L, Miwa K, Ngara T and Tanabe K, Hayaka, Kanagawa, Japan (2006).

51. Franceschini V, Antonini E and Zuccoli Bergomi L, Wood Fuels Handbook. Production, Quality Requirements, Trading. Italian Agroforestry Energy Association, University of Padua, Legnaro, Italy (2008).

52. FAO, Global Forest Resources Assessment 2010 Country Report. State Statistic Service, Ukraine (2010).

53. IPCC, Climate Change 2007: The Physical Science Basis. Contribution of working group I to the Fourth Assessment Report of the IPCC, technical summary. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (2007).

54. NOAA, NOAA weather stations database. [Online], National Oceanic and Atmospheric Administration of the USA, Earth system research laboratory (2008). Available at: http://www.climate-charts.com/world-index.html [April 1, 2011].

55. Renka RJ, Interpolatory tension splines with automatic selection of tension factors. *SIAM J Appl Math* 8(3):393–415 (1987).

56. Batjes NH, SOTER-Based Soil Parameter Estimates for Central and Eastern Europe. ISRIC, World Soil Information, Wageningen, the Netherlands (2005).

57. Kuijman PJ, van den Akker JH and de Vries F, Emissie van N2O en CO2 uit organische landbouwbedemomen. Alterra, Wageningen, the Netherlands (2005).

58. EC, Directive of the European parliament and of the council on the promotion of the use of energy from renewable sources, pp. 40 and appendices. EC, Brussels (2008).

59. NEN, NTA 8080, Sustainability criteria for biomass for energy purposes. NEN, Delft (2009).

60. Smeets EMW, Bouwman LF, Stehfest E, van Vuuren DP and Posthumus A, Contribution of N2O to the greenhouse gas balance of first-generation biofuels. *Glob Change Biol* 15(1):1–23 (2009).

61. Stehfest E and Bouwman L, N2O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. *Natur Cycl Agroecosys* 74(3):207–228 (2006).

62. Lesschen JP, Velthof GL, de Vries W and Kros J, Differentiation of nitrous oxide emission factors for agricultural soils. *Environ Pollut* 159(11):3215–3222 (2011).

63. Britz W and Leip A, Development of marginal emission factors for N losses from agricultural soils with the DNDC-CAPRI meta-model. *Agr Ecosyst Environ* 133(3/4):267–279 (2009).

64. Velthof GL, Oudendag D, Wiltzke HP, Asman W, Klimont Z and Oenema O, Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. *J Environ Qual* 38(2):402–417 (2009).

65. Van der Hilst F, Verstegen JA and Faaij APC, Dynamic and integrated modeling of GHG emission from the implementation of energy crop production and intensification of the agricultural sector. Copernicus Institute, Utrecht University, Utrecht (2012).

66. State Statistics Service of Ukraine. *Agriculture in Ukraine, Statistical Yearbook 2010*, ed by Ostapchuk YM. State Statistics Service of Ukraine, Kiev (2011).

67. UN, National Inventory Submissions 2011: Annex I Party GHG Inventory Submissions. Common Reporting Format: Ukraine [ONLINE]. United Nations Framework Convention on Climate Change (2011), Available at http:// unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/5888.php [December 12, 2011].

68. European Commission, Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, Version 3. European Council for Automotive R&D (EUCAR), European association for environment, health and safety in oil refining and distribution (CONCAWE), the Institute for Environment and Sustainability of the EU Commission’s Joint Research Centre (JRC/IES), Ispra (2008).

69. Hamelinck CN and Faaij APC, Outlook for advanced biofuels. *Energy Policy* 34(17):3268–3283 (2006).

70. Bogovin AV, Country Pasture/Forage Resource Profiles Ukraine, [ONLINE], FAO (2001) Available at: http://www.fao.org/ag/AGP/AGPC/doc/Counprof/Ukraine/ukraine.htm [April 1, 2011].

71. Vuichard N, Ciais P, Belelli L, Smith P and Valentini R, Carbon sequestration due to the abandonment of agriculture in the former USSR since 1990. *Glob Biogeochem Cycl* 22(4):GB4018 (2008).

72. Bottcher H, Freibauer A, Scholz Y, Gitz V, Ciais P, Mund M et al., Setting priorities for land management to mitigate climate change. *Carbon Balance Manage* 7(1):5 (2012).

73. Vuichard N, Ciais P and Wolf A, Soil carbon sequestration or biofuel production: New land-use opportunities for mitigating climate over abandoned Soviet farmlands. *Environ Sci Technol* 43(22):8678–8683 (2009).

74. Kucher O, Ukrainian Agriculture and Agri-Environmental Concern. Universität für Bodenkultur Wien Department for Wirtschafts- and Sozialwissenschaften, Wien (2007).

75. Lerman Z, Brooks K and Csaki C, Restructuring of traditional farms and new land relations in Ukraine. *Agr Econ* 13(1):27–37 (1995).

76. Bouwman AF, Van der Hoek KW, Eckhout B and Soenario I, Exploring changes in world ruminant production systems. *Agr Syst* 84(2):121–153 (2005).

77. Ionia Globcover Project [ONLINE]. MEDIAS-France, ESA (2005). Available at: http://due.esrin.esa.int/globcover/ [April 1, 2011].

78. FAO, Predicted global cattle density (2005), corrected for unsuitability, adjusted to match FAOSTAT totals for the year 2005. FAO, Animal Production and Health Division, Rome (2005).

79. FAO, FGGD 2.3 - Global population density estimates 2015. Food Insecurity, Poverty and Environment Global GIS Database (FGGD), Rome (2005).

80. Demographic statistics by region [ONLINE]. (2011) Available at: http://www.ukrstat.gov.ua/ [September 1, 2011].

81. ILO unemployment rate of population in 2011, by region (information is based on results of sapling survey population of economic activity). [ONLINE]. (2011). Available at: http://www.ukrstat.gov.ua/ [September 1, 2011].

82. Open Street Map, Open street map, Europe, Ukraine, places. [ONLINE]. Open Street Map (2010). Available at: http://www.ukrstat.gov.ua/ [September 1, 2011].
83. Pennsylvania State University Libraries. Railroad Ukraine. [ONLINE]. Pennsylvania, Pennsylvania State University Libraries (1997). Available at: http://www.diva-gis.org. [September 1, 2010].
84. DIVA GIS. Country specific free GIS data: Ukraine. Inland waters: Rivers, canals, and lakes. Separate files for line and area features. [Online]. (2011). Available at: http://www.diva-gis.org [January 5, 2011].
85. World Database on Protected Areas. UNEP World Conservation Monitoring Centre. [Online]. Cambridge (2010). Available at: http://www.protectedplanet.net/ [November 1, 2010].
86. NASA, NGA, Shuttle Radar Topography Mission (SRTM), 30m Digital Elevation Data: CGIAR Consortium for Spatial Information (CGIAR-CSI), Washington, DC (2000).

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