Modelling the carbon and nitrogen balances from energy crops: effect of crop types, soil, climate, residues management, initial carbon level and turnover time

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Abstract

This paper addresses the conversion of Danish agricultural land from food/feed crops to energy crops. To this end, a life cycle inventory, which relates the input and output flows from and to the environment of 528 different crop systems, was built and described. This includes 7 crops (annuals and perennials), 2 soil types (sandy loam and sand), 2 climate types (wet and dry), 3 initial soil carbon level (high, average, low), 2 time horizons for soil carbon changes (20 years and 100 years), 2 residues management practices (removal and incorporation into soil) as well as 3 soil carbon turnover rate reductions in response to the absence of tillage for some perennial crops (0, 25%, 50%). For all crop systems, nutrient balances, balances between above- and below-ground residues, soil carbon changes, biogenic carbon dioxide flows, emissions of nitrogen compounds and losses of macro- and micronutrients are presented.

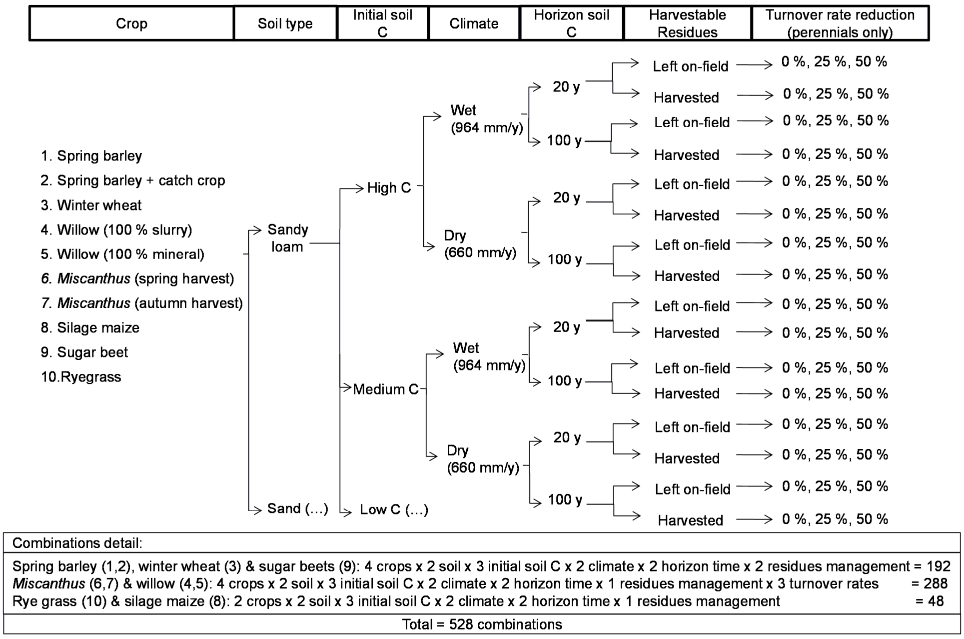
Introduction

The Danish Government has set a long term strategy for Denmark to be independent of fossil fuels in 2050, and several studies have been conducted to design and optimize such a system [e.g. 1]. These studies all point to the need for a biomass potential of around 35 – 50% of the overall energy consumption, being 300 – 450 PJ y^{-1} of biomass out of Denmark's present 850 PJ y^{-1} overall energy consumption. Yet, this supply cannot be provided by the circa 200 PJ of biomass residues from agriculture, forestry, industry and households generated in Denmark every year. To provide the necessary biomass feedstock for a Danish fossil free society, conversion of agricultural land from food/feed crops to energy crops, would, therefore, be necessary, if no significant import dependency of biomass is accepted. This study addresses the environmental consequences of such conversion of agricultural land from food/feed crops to energy crops. These consequences fall into two categories, often named *direct land use changes* (dLUC) and *indirect land use changes* (iLUC). While iLUC refers to the market forces-driven land use changes occurring as a reaction to food/feed displacement on the food/feed market, dLUC represents the change in the land use allocation of a given country or region that caused this displacement to occur in the first place (e.g. allocating more Danish land nowadays used to grow food/feed crops to energy crops). This article addresses the dLUC only. The objective of this study is to develop a consequential life cycle inventory (LCI) for assessing the dLUC consequences of converting Danish agricultural land from food/feed crops to energy crops.

Material and Methods

Inventory structure

As a first step of this LCI, the most influential parameters on the biogeochemical flows of carbon (C) and nitrogen (N) for which a specific inventory was judged necessary were identified. As a result, a considerable level of details has been included in the inventory, resulting in a total of 528 combinations, for which the input and output flows from and to the environment are quantified, including soil C changes. The variables and sub-variables considered are illustrated in Figure 1. The database was established within the life cycle assessment (LCA) software SimaPro 7.3.3. The system boundary includes all activities within the cultivation stage (from soil cultivation to harvest) and the reference flow used for each processes is 1 ha of land in a year. For each agricultural operation involved, background data were obtained from the Ecoinvent v. 2.2 database. All modeling details (e.g. specific background processes used for each crop, pesticides consumption, diesel consumption, partition of the dry matter, C and N among the different crop fractions, fertilization etc.) are presented in Hamelin et al. [2]. Fertilization was modelled assuming that crops' N demand was fulfilled by 50% animal manure (pig and dairy slurry) and 50% mineral fertilizers. A sensitivity analysis considering the application of mineral fertilizers only was also performed. The life cycle considered for perennial crops (ryegrass, willow and *Miscanthus*, respectively) was 2y, 21y (6 cuts; 3 years harvest cycle, but first harvest after 4 years; 1 year establishment; 1 year preparation before planting) and 20y (18 cuts; 1 year establishment: 1 year preparation before planting).



Combinations detail:

Spring barley (1,2), winter wheat (3) & sugar beets (9): 4 crops x 2 soil x 3 initial soil C x 2 climate x 2 horizon time x 2 residues management = 192

Miscanthus (6,7) & willow (4,5): 4 crops x 2 soil x 3 initial soil C x 2 climate x 2 horizon time x 1 residues management x 3 turnover rates = 288

Rye grass (10) & silage maize (8): 2 crops x 2 soil x 3 initial soil C x 2 climate x 2 horizon time x 1 residues management = 48

Total = 528 combinations

Figure 1. Overview of the variables selected for the inventory structure

C flows

Changes in soil C were estimated with the dynamic soil C model C-TOOL [3], developed to calculate the soil carbon dynamics in relation to the Danish commitments to UNFCCC. Changes in soil C were estimated over two time horizons: 20 years and 100 years. Moreover, an initial "high", "medium" and "low" soil C content were considered (Figure 1). These levels are based on an average of 143.9 ± 59.2 t C ha^{-1} for sandy soils and 144.7 ± 76.4 t C ha^{-1} for sandy loam soils, for the depth 0-100 cm. For *Miscanthus* and willow, the C turnover rate in the topsoil may be reduced in response to the absence of tillage over many years. In this study, three different turnover rates have been applied for these two crops; no reduction in turnover rate (as for other crops), 25% reduced turnover rate and 50% reduced turnover rate. The portion of the C input to the soil (i.e. from manure, straw/tops and non-harvestable residues) that does not enter the soil C pool over the time horizon considered was assumed to be lost as a carbon dioxide (CO_2) emission to the atmosphere. Similarly, all losses of native soil C were assumed to be transferred to the atmosphere as CO_2. Carbon flows from lime inputs were estimated as 0.12 kg CO_2-C kg^{-1} lime applied [4].

N flows

In the cropping systems considered in this study, there are three main inputs of N: from fertilizers, from crop residues, and from the atmosphere. The output flows considered are ammonia (NH_3), nitrous oxide (N_2O) (direct and indirect), nitrogen oxides (NO_x), emissions of dinitrogen (N_2) to the atmosphere and nitrate (NO_3^-) leaching to ground- and surface waters. Two NH_3 flows were estimated: the NH_3 from the application of mineral fertilizers and the NH_3 from the application of animal slurry. The emission factors considered for this are presented in Hamelin et al. [2]. Nitrogen oxides consist of the sum of nitric oxide (NO) and nitrogen dioxide (NO_2), but in this study, emissions of NO are assumed to represent total NO_x. An emission factor of 0.010 kg NO-N per kg N applied was considered, based on [5]. For crop residues, based on [6], an emission factor of 0.007 kg NO-N per kg N was used. The IPCC methodology [4] was used to estimate the N_2O emissions from the different crop systems. Leaching of N was, for ryegrass and annual crops, calculated with the N-LES$_4$ model [7], a continuously updated empirical model to predict N leaching from arable land based on more than 1200 leaching studies performed in Denmark during the last 15 years. The estimation of nitrate leaching for *Miscanthus* and willow was performed as described in Hamelin et al. [2].

Other flows

Phosphorus, cooper and zinc losses from agricultural soils as well as biogenic non-methane volatile organic compounds (NMVOC) emitted from photosynthesizing leaves of crops were also taken into account in the inventory, as described in Hamelin et al. [2].

Results and Discussion

Key inventory results include the partition of the DM, C and N flows between the crop, the straw or beet tops, and the above- and below-ground residues. These results, which are shown in detail Hamelin et al. [2], highlighted that yields on sandy loam soils were generally higher than on sandy soils, and this also applied for the above- and below-ground residues. As a result, the C and N input to soil from above- and below-ground residues was generally greater on sandy loam soils for most crops.

As expected, the overall emission of C and N flows varied greatly among the different crop systems. The main results for these are presented in Figure 2.

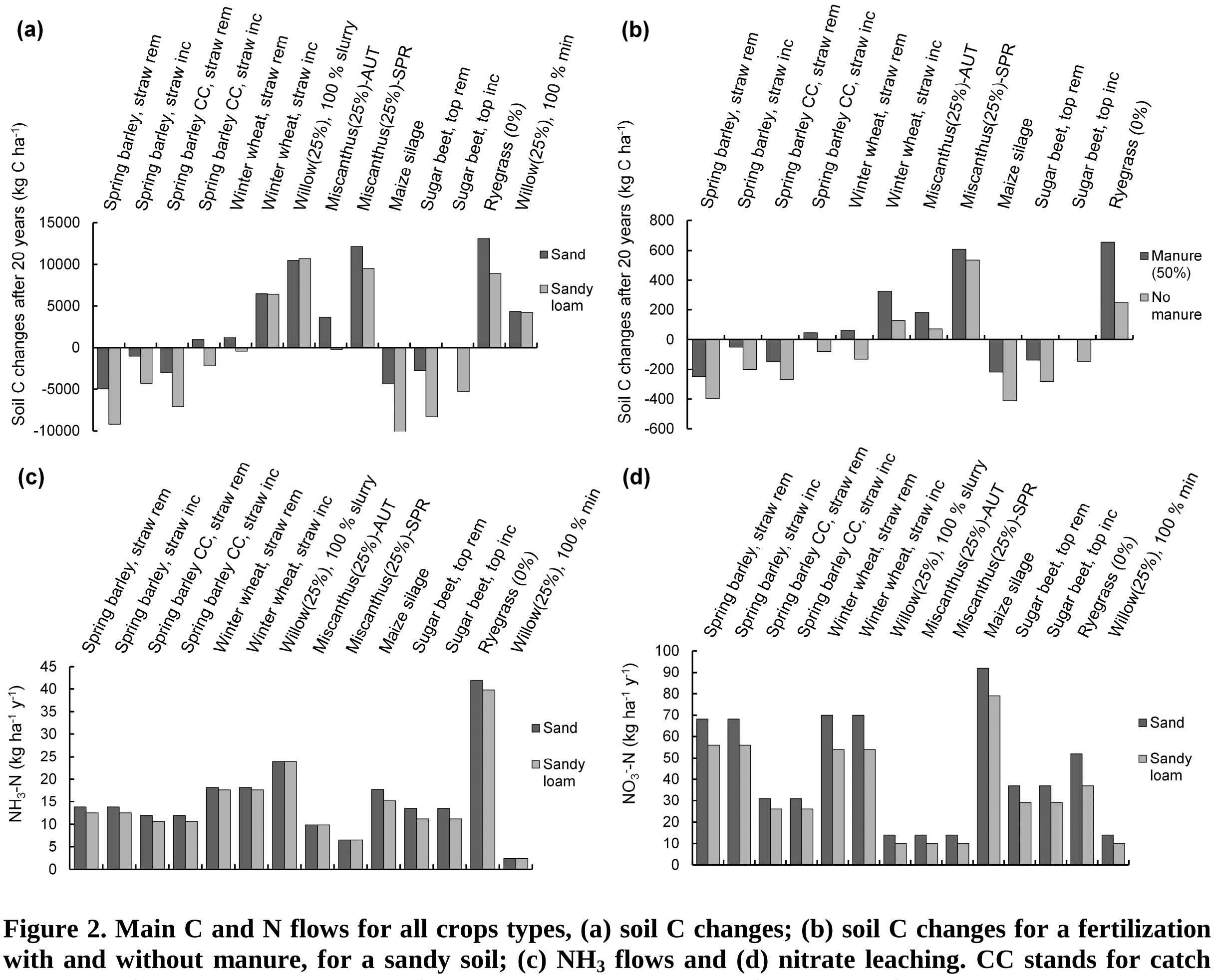


Figure 2. Main C and N flows for all crops types, (a) soil C changes; (b) soil C changes for a fertilization with and without manure, for a sandy soil; (c) NH$_3$ flows and (d) nitrate leaching. CC stands for catch crop, SPR for spring harvest, AUT for autumn harvest and min for mineral fertilizers. Values presented for perennials are for established *Miscanthus* and willow plantations and the value between parentheses indicates the turnover rate reduction considered because of the absence of tillage. Results are for a medium initial soil C and a wet climate.

Figure 2a shows that all perennial as well as a few annual crop systems gave rise to an increase in soil C, although this do not always apply on sandy loam soils. Further, these results are, especially for annual crops, conditional to manure application, as shown in Figure 2b. Incorporating straw and tops instead of harvesting them gave a rise in soil C for all crop systems involving a secondary harvest (Figure 2a). Sequestration potentials of straw and tops ranged between 2.7 (beet tops) and 5.2 (wheat straw) Mg C ha^{-1} on sandy soils, and between 3.0 (beet tops) and 6.9 (wheat straw) Mg C ha^{-1} on sandy loam soils (for 20 years). The effect of a catch crop on soil C was not as significant as for straw and tops incorporation, but yet had a non-negligible impact, the increase in soil C being of approximately 2.1 Mg C ha^{-1}, for 20 years. Overall, higher CO_2-C flows were modelled for the crop systems on sandy loam soils, which reflects the higher yields on this soil type and consequently the higher residue inputs which has the potential to be emitted as CO_2. Although not illustrated here, reducing the turnover rate in response to the absence of tillage had a significant influence on the soil C results, as the soil C content was increased by at least 45% each time the turnover rate was reduced by 25% [2]. Nitrogen-based emission flows were closely related to the amount of N fertilizer that has been applied to the different crop systems: ryegrass, requiring the highest N inputs [2], therefore presented the highest emissions for most N flows, while *Miscanthus* and willow generally presented the smallest (Figure 2cd). Combining spring barley with a catch crop significantly reduced nitrate leaching (approximately 54% reduction), and to some extent also NH_3 volatilization (approximately 14% reduction) (Figure 2d). Phosphorus, Cu and Zn losses tended to be larger on sandy soils, as well as biogenic NMVOC emitted from photosynthesising leaves of crops. This reflects, once again, the higher crop yields on that soil type. Additional results (e.g. effect of climate, effect of the initial soil C level, N_2O and NO_x emissions,) are further detailed and discussed in Hamelin et al. [2].

Conclusion and perspectives

The inventory results highlighted *Miscanthus* as a promising energy crop for Denmark, indicating it presents the lowest emissions of nitrogen compounds, a relatively high yield and allows increases in soil organic carbon. Results also showed that the magnitude of these benefits depended on the harvest season, soil types and climatic conditions. Inventory results further highlighted winter wheat as the only annual crop where straw removal for bioenergy may be suitable, being the only annual crop not involving losses of soil organic carbon as a result of harvesting the straw. This, however, was conditional to manure application, and was only true for sandy soils. The inventory, because of its high disaggregation and transparency, can easily be adapted, with the methodologies presented in this study, so it can as well be used for assessing bioenergy systems of other regions.

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