Assessing availability and greenhouse gas emissions of lignocellulosic biomass feedstock supply – case study for a catchment in England

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ABSTRACT:

Feedstocks from lignocellulosic biomass (LCB) include crop residues and dedicated perennial biomass crops, of which the latter are often considered superior in terms of climate change mitigation potential. Uncertainty remains over their availability as feedstocks for biomass provision and the net greenhouse gas emissions (GHG) during crop production. Our objective was to assess the optimal land allocation to wheat and Miscanthus in a specific case study located in England, in order to increase biomass availability, improve the carbon balance (and reduce the consequent GHG emissions), minimally constrain grain production losses from wheat. Using soil and climate variables for a catchment in East England, biomass yields and direct soil nitrogen emissions were simulated with validated process-based models. A 'Field to up-stream factory gate' Life Cycle Assessment was conducted to estimate indirect management-related GHG emissions. Results show that feedstock supply from wheat straw can be beneficially supplemented with LCB from Miscanthus grown on selected low quality soils. In our study, 8% of the less productive arable land area was dedicated to Miscanthus, increasing total LCB provision by about 150%, with a 52% reduction in GHG emission per ton LCB delivered and only a minor effect on wheat grain production (-3%). In conclusion, even without considering the likely carbon sequestration in impoverished soils, agriculture

should embrace the opportunities of providing the bioeconomy with LCB from dedicated, perennial crops.

Keywords: lignocellulosic biomass, greenhouse gases (GHG), Miscanthus, wheat straw, feedstock supply, STAMINA, DNDC

1 INTRODUCTION

With the potential benefits in climate change mitigation, development of rural economy, energy security and reducing fossil fuel dependency, biomass crops have attracted interest in both bioenergy and biomaterial production. At present 'first generation' biomass (1GB) has been the major feedstock and technology deployed in national bio-economy strategies. However, concerns about competition for food, land use change, loss of biodiversity and raised GHG emissions[1] have led to an increased focus on the utilization of lignocellulosic biomass (LCB), resourced from agricultural and forestry residues and dedicated biomass crops.

The drivers for LCB feedstocks include mainly their higher Energy Return On Investment[2], and better environmental and social performance than 1GB in the sustainability assessment. However, there are concerns regarding the actual provisioning capacity of LCB, especially from agricultural residues such as cereal straw. Although there have been many attempts to calculate this potential[3–6], it remains difficult to quantify[7]. Most estimates of straw production are based on measurements of grain production and assuming a constant relationship between grain and straw yield[5]. Cereal straw production is concentrated in the arable eastern parts of England; around 70% of UK wheat straw is produced in the Yorkshire and Humber region, East Midlands, East Anglia and the Southeast regions[6]. In the UK, straw is mainly used for animal bedding, horticulture and bioenergy[8], with 32% to 39% being incorporated back to the soil to maintain the soil organic carbon (SOC) content[4]. Only approximate 300 to 487kt/year (2-4% of total produced cereal and oilseed rape straw) was used for bioenergy generation[6]. There are no robust official survey data available for straw usage in animal bedding; estimates range between 5.8 Mt and 6.24 Mt annually for all cereal and oilseed rape straw, based on livestock statistics from Defra (Department of Environment, Food and Rural Affairs)[6,8]. Current straw use is shown in Fig. 1 based on a wide range of literature[4,6,8].

Dedicated biomass crops have the advantage that they can be grown on marginal arable land[9,10]. However, the actual land area needed to produce the specified amount of biomass could be higher due to lower and variable local productivity[11]. Currently, one of the main challenges for lignocellulosic bioenergy or biomaterial production is that the high overall production cost is dominated by pretreatment costs of LCB feedstock[12]. The overall production cost could be aggravated when the feedstock prices increase due to emerging competition for biomass across the sub-sectors of bio-economy (bioenergy, biomaterial and traditional uses, such as animal feed and bedding etc.)[12,13,14].

Figure 1.

Most research on biogeochemical impacts of Miscanthus are conducted on silt clay loam soil[15–19]. However, it is less likely that those soils could be converted to Miscanthus production, due to farmers' unwillingness to change, especially on soils where they generally achieve good yields for conventional arable crops. Understanding the performance of Miscanthus on a wider range of soil types, especially on sandy soils which have low cereal yields but high nitrogen (N) losses[20] is important to identify the suitable locations for Miscanthus production. Compared to wheat, higher yields of Miscanthus with lower N inputs and losses per unit of production are likely to reduce Greenhouse Gas (GHG) emissions of biomass production and lower its environmental footprint and costs.

Accurate estimates of GHG emissions and resource use efficiencies are important in understanding and determining the sustainability of bioenergy and bio-based chemicals. Full Life Cycle Assessment (LCA) for biorefinery chains are often constrained by the lack of sufficiently detailed and site-specific information on the pre-harvest GHG balance related to agricultural management, especially N_2O emissions from N fertiliser application, as an important source of GHG[21]. The IPCC Tier 1 method provides a default estimate of N_2O emissions from agriculture for both, direct and indirect emissions, based on N fertiliser inputs, but ignores other important crop management, soil and atmospheric variables. The Tier 3 approach suggests the use of process-based biogeochemical models to achieve more accurate site-specific estimates of the GHG flux from variable agricultural systems[22]. A number of studies have integrated process-based model generated N_2O emission results into LCA[21,23,24]. However, most of this work has been carried out solely for conventional crops (first generation biomass)[21,23]. Very limited work can be found for simulating the pre-harvest N_2O emission for perennial energy crops such as Miscanthus based on process-based models, due to the limited availability of such models developed for dedicated LCB crops integrated into arable cropping systems. To address this gap, process-based models STAMINA (Stability and Mitigation of Arable Systems in Hilly Landscapes)[25] and carbon-nitrogen (C, N) turnover model DNDC (i.e. DeNitrification-DeComposition)[26] were used for Tier 3 approaches to estimate dry matter yields (DMYs) and the N emissions of winter wheat and Miscanthus.

The overall objective of this paper is to estimate the impacts and benefits of moving from an ‘arable only’ to a proposed ‘mixed (arable and perennial)’ feedstock provision scenario.

We assessed the potential of local LCB provisioning capacity, and the resulting GHG emissions under different supply scenarios, whilst exploring the potential impacts arising from integrating Miscanthus into a wheat production system in eastern England.

2 MATERIAL AND METHODS

The crop growth model system STAMINA[25] and C-N turnover model DNDC[26] were calibrated to estimate DMY data only, considering both, winter wheat and Miscanthus. No model evaluation could be done for N_2O emission and NO_3^- leaching arising from their supply due to lack of experimental data. They were up-scaled to the catchment to estimate the LCB supply capacity and GHG balance of production in a rural area nearby the city of Hull in England (max. 50 km as feedstock transport distance from farm to conversion plant; Fig. 2). The catchment consists of parts of the Yorkshire & Humber and East Midlands regions, major wheat production areas in England.

Firstly, crop growth parameters for both, the STAMINA and DNDC models were calibrated based on literature and evaluated against observations on farms across England. Three indicators, including coefficient of determination (R^2), root mean square error (RMSE) and relative mean absolute bias error expressed as a percentage (MBE%) were calculated to assess the goodness-of-fit between model simulated and measured yields of both crops. Secondly, LCB availability, NO_3^- leaching and N_2O emissions were simulated for both, ‘arable only’ and proposed ‘mixed arable-perennial’ feedstock supply scenarios. For the latter, Miscanthus was assumed to replace wheat on selected low-quality soils, which are coarse textured, less productive and have the highest NO_3^- leaching/wheat grain production ratio (kgN/t Grain) based on modelled results. These represent 8% of the total catchment area. Thirdly, the GHG balance results were combined with a ‘field to up-stream factory gate’ LCA to compare the global warming potential (GWP) associated with different lignocellulosic feedstock supply scenarios.

Figure 2

2.1 Process-based models

The STAMINA modelling system simulates micro-meteorology, hydrology, crop development and growth, integrating spatial information on soil and topography for a range of crops, including both arable crops (winter wheat, maize, potato, barley etc.) and perennial crops (Miscanthus, willow, switchgrass etc.). The STAMINA-winter wheat model is described in detail elsewhere[27]. In this work, the catchment region is represented as a matrix of 1km^2 cells, within which all important variables of soil, climate, crop and crop management are assumed to be homogeneous. STAMINA-winter wheat model had been calibrated against winter wheat yields observed in Bedfordshire (England)[27]. Here, three sets of UK weather, soil and on-farm measured yield data from an earlier study[28] (Table 1) were used for model evaluation. DMYs were simulated with an acceptable accuracy (Fig. 3), RMSE of 1.36 t/ha and MBE% of 12%. The STAMINA-BeGRAS Model is a sink-source interaction model based on the principles described in LINGRA for small grasses[29] and was expanded for the allocation of biomass to belowground biomass (rhizomes and roots). BeGRAS model was implemented in the STAMINA modelling system[30] and calibrated for Miscanthus using detailed data collected at Rothamsted Research. In this simulation work for Miscanthus, weather, soil and on-farm measured yield data (Table 1) from the Rothamsted 408 trial[31] are used for model evaluation. The RMSE between measured and simulated yields is 1.58 t/ha and MBE % is 12% (Fig. 3). The BeGraS model simulated Miscanthus DMYs at harvest (1st to 3rd March) after two establishment years, for 13 years of harvest. The RMSE between measured and simulated yields was 1.58 t/ha and MBE% is

12% (Fig. 3). 30-year average scenario yields (two 15-year growing cycles) were generated for each soil type to be used in the overall assessment.

DNDC model was originally designed to simulate C and N biogeochemical cycles occurring in agricultural systems at regional scales in the U.S.[32] and was further extended to cover a wider range of countries and districts and other ecosystems[33,34]. DNDC is capable of predicting the main GHGs fluxes from soil (N_2O, CO_2 and CH_4) and other key environmental and economic indicators, including crop yields, ammonia (NH_3) volatilization and nitrate (NO_3^-) leaching rates and quantities[35,36]. In DNDC, N_2O emissions were determined based on denitrification and nitrification pathways as a function of climate, crop growth and soil environmental factors. DNDC was parameterized for winter wheat by using published values[37] and site specific data. Comparison between modelled and measured yields is shown in Fig. 4. Modelled yields compare quite well with observations, considering the average values (8.64 and 8.65 t/ha respectively) and statistics (RMSE of 1.02 t/ha and MBE% of 12%). Miscanthus parameters in the DNDC model had been parameterized using literature data and tested earlier[18] calibrated and validated using observed yields over four years at a site in Urbana, Illinois, USA. To use the model under UK condition, we recalibrated the parameters using measured Miscanthus DMYs from 1997 to 2004 in the Rothamsted 408 trial[31], soil parameters for a clay loam (Batcombe series) and locally recorded weather data. The simulated and observed DMYs are displayed in Fig. 4, with RMSE of 1.57t/ha, and MBE % of 11%.

Table 1.

Figure 3.

Figure 4.

Figure 5.

Table 2.

2.2 Inputs for feedstock scenario simulations

The catchment used for the scenario simulation covers an area of 5,856 km^2 and comprised 48 soil series according to UK National Soil Map (1 km grid) (NATMAP vector, Cranfield University, 2001), which can be grouped in to nine soil texture classes (Fig. 5). The input data source and the target modelling outputs were listed in Table 2. Key soil information includes soil texture, SOC, bulk density, pH, soil available water capacity (AWC) within rooting depth. STAMINA modelling framework requires information on air temperature, precipitation, wind speed, solar radiation and atmospheric humidity. In this work, three climate scenarios were examined, i.e. baseline, medium and high CO_2 emissions. Hourly data collected from High Mowthorpe weather station from 1961-1990 were used for baseline simulation, assuming an atmospheric CO_2 concentration of 352 mg $litre^{-1}$. Weather data were generated for the medium and high emissions scenarios using UK Climate Projections (UKCP09)[38,39]. In the UKCP 09, CO_2 emissions under the three IPCC SRES scenarios A1FI, A1B1 and B1 are used and labelled High, Medium and Low according to how different emissions pathways affect future climate. We used the projected CO_2 concentrations for 2030 of 447 mg $litre^{-1}$ for the Medium (A1B) and 449mg $litre^{-1}$ for the High (A1F1) Scenario as average CO_2 concentrations for 2020-2050 timeframe[40].

In the DNDC modelling, we applied an approach similar to that of Guo[21] who simulated N and C dynamics using 5 years' of weather data (1986 to 1990) and an atmospheric CO_2 concentration of 360 mg $litre^{-1}$. In addition to the weather data, DNDC also requires N concentration in the rainfall, atmospheric NH_3 concentration and fertiliser application information. Rainfall N concentration were derived from the UK Eutrophying and Acidifying Pollutant Network (UKEAP). The calculated 5 years mean rainfall NH_4^+-N and NO_3^--N concentration at Thorganby station of 1.27mg litre^{-1} was applied in this study. Atmospheric NH_3 5-year average concentration obtained from UKEAP-National Ammonia Monitoring Network (Easingwold station) of 2.54 μgN/m^3 was applied in this study. N fertiliser type is assumed to be ammonium nitrate. For winter wheat, the annual input values range from 160kgN/ha to 220kgN/ha, depending on the soil series. This was calculated using DEFRA's fertiliser manual (RB209) for each soil series, based on the information including soil texture, soil total N level, precipitation, previous crop types and any particular crop quality (feed or backing) requirements[41]. For Miscanthus, 60kgN/ha/year of ammonium nitrate was assumed in the simulation.

For crop production management, the single feedstock production scenario (SP) assumes winter wheat is grown on all the arable land across the whole catchment area (Table 3). The mixed feedstock production scenario (MP) assumes that winter wheat is still the predominating crop, while Miscanthus was cultivated only on selected low quality soils (8% of total area), balancing N_2O emissions, NO_3^- losses, wheat grain production and LCB feedstock provision.

Table 3.

Straw availability was estimated based on the wheat grain production level, wheat planted area, wheat grain harvest index, harvestable straw fraction, incorporation rate and competition in demand of other uses. Due to the limited availability of data on current straw production and use, we adopted a conservative estimation of winter wheat straw provision potential for the case study area. Wheat grain harvest index (HI) is simulated by the

STAMINA-winter wheat model, resulting in a 30-year average value of 0.53 in these study scenarios. We assume that 50% of all the leaves and stems produced over the entire wheat growing season have been lost through decay by the time of harvest. The remaining 50% of the residual biomass is harvested in the first two years, however, in the third year it is left on the ground to maintain SOC content. The total harvestable straw tonnage is calculated with Equation 1, where x is the modelled grain yield (in t/ha, 14.5% moisture) and 265,600 ha was estimated based on the assumption that due to rotation, 2/3 of the total 398,400 ha arable land is used for winter wheat cultivation:

$$Total\ straw\ harvested\ (tonnes) = \left(\frac{x}{0.53} - x\right) * 0.5 * \left(1 - \frac{1}{3}\right) * 265600 \qquad (1)$$

2.3 Life cycle assessment (LCA)

Field to upstream factory gate LCAs were conducted for both single SPBC and MPBC scenarios. The LCA covers the emissions per unit of delivered lignocellulosic feedstock, which includes the cultivation, preparation for transport, transport to storage and transport to processing plant in defined case study locations (Fig. 6.). Within the cultivation phase the emissions are considered from upstream production of materials and raw material extraction, fuel inputs required for on-farm cultivation, as well as direct and indirect N_2O emissions. Indirect N_2O emissions due to NO_3^- leaching were estimated based on modelled NO_3^- leaching values and IPCC default emission factor EF5[42].

Table 4.

Figure 6.

LCA inputs for wheat and Miscanthus cultivation are shown in Table 4. For wheat straw, general agricultural data for operations on the field (including machinery use and associated diesel consumption) is taken from the BEAT database which derives its data from the Farm Management Pocketbook[43]. The cultivation processes include ploughing, harrowing, fertiliser application, top dress, pesticide application, combine harvesting, and straw baling and carting. As defined by the BEAT database, the wheat straw is naturally dried in storage with no additional inputs apart from its offloading and loading from the storage location. Transport is assumed to be bulk freight road transport using >32t gross weight vehicles as defined in the Ecoinvent database[44]. Diesel consumption for loading and offloading of feedstocks is calculated basing on the movement of 15t/hour feedstock with the consumption of 493 MJ/hour diesel[45]. To maintain consistency with the DNDC simulations, same amounts of ammonium nitrate input levels were adopted in LCA and DNDC simulations. The remaining cultivation data for Miscanthus (including subsoiling, ploughing, harrowing, fertiliser application, spraying, weed cultivation and residue removal) has been compiled from the Sustainable Liquid Biofuels from Biomass Biorefining (SUNLIBB) project database[46], which has been developed for Europe primarily from UK data. Transport is assumed to be same as above for wheat straw. Upstream data for the production of the inputs specified in the feedstock cultivation input trees is taken from Ecoinvent v3.1[44]. The combustion of diesel in agricultural equipment for various tasks (e.g. fertiliser application, harvesting, baling etc.) is taken from IPCC [22] and Kubica et al.[47]. The environmental impacts associated with this data is calculated in Simapro 8 using the ReCiPe Midpoint (H) LCA impact assessment methodology.

As cultivation data count for the whole wheat crop, the impacts of cultivation need to be allocated to wheat grain or straw. Three allocation methods were applied in this work, i.e. economic allocation, RED_allocation and CV_allocation. Economic data for wheat straw and grain taken from Statistics Denmark show prices of €0.074 and €0.15/kg, respectively, assuming provision of the public good ‘straw for energy’[48]. According to Renewable Energy

Directive (EU RED)[49], straw shall be considered to have zero life-cycle GHG emissions up to the process of collection of those materials. Additionally, we allocated emissions based on the real calorific values (CV) of wheat grain and straw, which are 16.5 and 17.6 MJ/kg, respectively[50].

3 RESULTS

3.1 Single feedstock production scenarios

Modelled 30-year average grain yields for all the soil series range from 7.20 to 8.33 t/ha (14. 5% moisture), depending on variable soil AWC. Weighted average yield was calculated basing on the proportion of each soil series in total area. The overall weighted average yield in the region is 7.94 t/ha (14. 5% moisture). Yields were also simulated for medium and high emission climate change scenarios (Table 4). Like in the baseline results, soils of high AWC can achieve slightly higher yields. The overall weighted average yields are 8.54 and 8.76 t/ha for medium and high emission scenarios respectively. Total amount of harvestable wheat straw are estimated to be 623, 670 and 688 kt/year for the chosen catchment area under baseline, medium and high emission scenarios, respectively (Table 5). About 97% of the current wheat straw currently has other uses[4,6,8] (Fig. 1), which is 604kt per year. Under the medium and high emission scenario, assuming the annual demands from other uses will remain stable, then a total amount of 66 and 83 kt wheat straw could become available for bioenergy or biomaterial production.

Table 5.

Figure 7.

Simulated NO_3^- leaching and winter wheat grain yields of different soil textures show a high variation in NO_3^- leaching and gas flux from different soil textures (Fig. 7) in the DNDC outputs. NO_3^- leaching is the main sink for N loss; depending on soil texture, the 4-year average NO_3^- leached ranges between 14 and135 kgN/ha/year. The annual leaching fractions (NO_3^- leached per N fertiliser inputs) for different soil textures range from 6 to 60% of total applied N. The weighted average leaching amount is 63.3 kg N/ha which corresponds to a leaching fraction of 30%.

These results are similar to the IPCC Tier 1 estimate for FracLEACH-(H) (N losses by leaching/runoff for regions), according to which the rate of N loss by leaching or run off is 30% of the total N fertiliser input, with an uncertainty range of 10 to 80%[22]. This result is also in accordance with the winter wheat long-term field trial 'Broadbalk Experiment' conducted in England, where 21% and 31% N loss were observed for the 192 and 240kgN/ha N fertiliser application treatments, respectively[51].

3.2 Mixed feedstock production scenarios

In the mixed feedstock production (MP) scenarios, Miscanthus was assumed to be planted on all those soils with loamy fine sand texture. For those soils, simulated winter wheat yields are much lower than on the other soils while the N leaching is substantially higher than finer textured soils (Fig. 7). On these soils, the Miscanthus produces about 12-13t/ha, compared to only 1.5 to 2.0 t/ha of winter wheat straw becoming available. The comparison of modelled NO_3^- leaching and N_2O emissions between wheat straw and Miscanthus on those four loamy fine sand soils are shown in Fig. 8. Similar to winter wheat production, model outputs also show a positive effect of increasing CO_2 concentration on Miscanthus production (Table 6). Compared with the SP scenario, total available LCB increases from 19 kt (SPBC) to 384 kt (MPBC) under the baseline climate. Under the medium and higher climate change scenarios, the differences increase from 365 to 504 kt and 545 kt total available LCB production, respectively (Fig. 9).

Figure 8.

Figure 9.

About 11% of NO_3^- leaching could be prevented when MPBC feedstock scenarios were adopted (Table 7), equating to a saving of approximately 2.81 million kg N/year. A relatively minor reduction (6.06%) in direct N_2O emissions is estimated by DNDC (0.66kgN/ha for SPBC and 0.62kgN/ha for MPBC). In total, 34,925 kg N/year (10,408 t CO_2eq/year) N_2O emission could be saved moving from SPBC to MPBC feedstocks.

Table 7.

3.3 LCA results

The direct and indirect N_2O emission results were included in the field to upstream factory gate LCA for both SPBC and MPBC scenarios (Fig. 10). When economic allocation was applied, the LCA shows an impact of 0.20 kg CO_2eq/kg delivered LCB for SPBC scenario, and this figure decreases for 52% in MPBC system. A similar trend can be found when CV allocation was used. However if RED allocation was considered, the GWP for SPBC is only 0.020 kg CO_2eq/kg and increases to 0.087 kg CO_2eq/kg when MPBC was adopted. This is due to that RED allocation approach requires all the emissions of wheat cultivation to be attributed to grain production. It can also be noted that cultivation phrase contributes to the biggest portion of GWP (from 77% to 94%) in all the scenarios except SP when RED allocation is used. Furthermore, N_2O emission accounts for 14% to 16% of total emissions except for SPBC scenario under RED allocation.

Figure 10.

4 DISCUSSION

In this study, the process based models DNDC and STAMINA, were calibrated and evaluated for winter wheat and Miscanthus under local English conditions. Both models simulated yields quite well when compared to observed yields for both crops. DNDC has been widely used for simulating C and N dynamics for a range of crops. However, as Miscanthus was not included in the original version of the model, only two articles have been published using DNDC to simulate Miscanthus growth before[18,52]. In the work reported here, we tested the DNDC model's performance in simulating Miscanthus yields under local conditions, however, uncertainty remains on the model's ability to accurately simulate N dynamics, for which it was not possible to calibrate the model in this work.

Due to the lack of information on current straw production and use, a conservative estimate of winter wheat straw provision potential was adopted. It has been suggested that straw which was used for animal bedding could be used locally for soil incorporation after (serving as farmyard manure), allowing substantial reduction of the incorporated straw and making more straw available for bio-energy or bio-material production. However, this is less likely to happen considering current records from Copeland and Turley[6] according to which a large volume of straw is moved from the Eastern Counties to the South West of England, Wales and Scotland to meet the market demands for animal bedding in the livestock sector[7], rather than being used locally.

Medium and high CO_2 emission climate change scenarios were used to model production of winter wheat and Miscanthus, however, as both STAMINA and UKCP only examine the impacts of altered atmospheric factors (CO_2 concentration, rainfall, temperature etc.) on crop growth, they do not include issues such as altered occurrence of pest and diseases, which are likely to impact on yields. Based on simulations of projected CO_2 concentration and corresponding weather information from the UKCP, no negative impacts on wheat and

Miscanthus yields have been seen. On the contrary, our simulations predict increases of 7.6% and 10.3% for wheat grain yields under medium and high scenarios respectively, and 33.9% and 43.2% increase of Miscanthus yields compared with the baseline climate. Simulated increases in wheat productivity were in accordance with most of the current research in that C3 crops show yield increases in response to rising CO_2 concentration through increased rates of photosynthesis and decreased water use[53]. Unlike C3 crops, the impacts of elevated CO_2 concentration on C4 crops growth remains uncertain[53]. In theory, the increase of biomass from elevated atmospheric CO_2 concentration on C4 crops should be very limited or even none, however this has been shown only in some of the research conducted[53], whilst others have seen substantial increases in photosynthesis and biomass production at increased CO_2 concentrations[54,55]. Apart from the elevated CO_2 concentration, our simulated increases in Miscanthus yields under climate change scenarios could be explained by the much warmer climate (48.71% and 46.67% higher average hourly temperatures), higher average humidity (13.91% and 14.21% higher humidity) and slightly higher annual precipitation levels (2.51% and 2.56% higher annual rainfall) projected by UKCP compared with the baseline climate. It has been widely discussed that Miscanthus growth in Northern Europe is mainly constrained from reaching its potential by the cold temperature[11,56].

Comparing our estimated total available LCB for single and mixed feedstock production under different climate change scenarios, it is clear that the proposed MP scenarios benefit significantly more than the SP scenarios. Under the SP scenarios, it is impossible to ensure sufficient feedstock for a new development of an exclusively locally supplied lignocellulosic biofuel or biomaterial plant in the case study area, even for the SPHE scenario, when the available LCB is estimated to be 82kt/year. However, if the 8% selected area with low quality soils were to be converted to Miscanthus cultivation, available LCB supply is estimated to be 383kt/year for MPBC and 628kt/year for MPHE, which is sufficient to support one to two commercial scale lignocellulosic biofuel or biomaterial plants, with 3% reduction in regional wheat grain supply.

The simulated and estimated NO_3^- leaching and N_2O emissions of both SPBC and MPBC scenarios indicated that if Miscanthus is integrated into the arable system by replacing conventional cereal crops on low-quality soils (where wheat production levels are lower and N losses higher), weighted average NO_3^- leaching across the whole feedstock supply region would be reduced by 10% and the total of direct and indirect N_2O emissions would be reduced by 8%. The reduction of GWP from SPBC to MPBC scenario becomes larger according to the LCA results, due to the reduced fertiliser application, machinery use and associated energy consumption.

When calculating GWP from agricultural residues, the choice of allocation method is crucial in deciding the LCA results. In this work, when RED allocation is used, the results were completely in contrary to those using economic allocation and CV allocation. It suggests that the current allocation method in RED is too simplified to reflect the real GHG dynamics reliably, especially when comparison with perennial crops is made.

Assessing the C stock impacts arising from the change in land use from wheat to Miscanthus was outside the scope of this work. However, a few studies have shown C stock increases for arable land converted to Miscanthus, in both above ground biomass and below ground C pool[57-60]. Our recent analyses show that soil carbon enrichment under Miscanthus can be marginal on soils rich in carbon[9] but considerable in low quality soils[61]. Thus, we would expect to see a further reduction of GWP by moving from SPBC to MPBC as C stocks would increase from land use change to perennial crops. GWP arising from land use change will be assessed in an additional paper.

5 CONCLUSION

GWP of the non-food bioeconomy can be improved considerably (5-6%) when LCB resourcing is changed from a SPBC to a MPBC system. Integrating Miscanthus on sandy soils into the UK arable system improves the feedstock availability omitting low yield and high N loss locations for wheat production. In such an MP scenario, total available LCB increases by more than an order of magnitude with limited impact on wheat production. Simulated NO_3^- leaching and N_2O emissions from Miscanthus production are 50% to 60% lower than from wheat on these low-quality soils, showing a win-win situation regarding environmental and economic criteria.

This work clearly challenges two preconceptions that have emerged for the non-food bioeconomy:

1. Its increased biomass demand would exacerbate competition for land and environmental impacts of crop production, and
2. Farmers could not produce more with less and not overcome the 'food vs fuel vs biomaterials' conflict through improved cropping and integrated land use.

This work has evaluated the GWP impacts regarding improved N-use to reduce GHG emissions; future work needs to include possible C stock changes likely to arise from arable land converted to perennials. Secondly, this case study is speculative in the sense that the only empirical data available were for wheat and Miscanthus yields, as measurement for N fluxes were not available and solely based on models. Future work should also account for below- and above-ground C stock changes, both, in biomass and soil, which together with N-flux measurements would reduce the uncertainty of the models. Thirdly, this work is limited to the case study area, so the methodology we proposed should also be tested with broader applications.

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Table Caption

Table 1. Three data sets used for model calibration for winter wheat and Miscanthus

Table 2. Specifications of models inputs and outputs

Table 3. Single and mixed crop production (SP, MP) and climate change scenarios Baseline Climate (BC), Medium Emission (ME) and High Emission (HE); atmospheric carbon dioxide concentration [CO_2]

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Table 6. Simulated Miscanthus yield (and standard deviation) on selected loamy fine sand soils

Table 7. NO_3^- Leaching and N_2O emissions (and standard deviation) of SPBC and MPBC scenarios

Figure Legends

Figure 1. Estimated current straw use in UK based on literature, total straw production estimate ranges from 10.70[8] to 11.88 Mt/year[6]

Figure 2. Map showing the case study area-50km radius of Hull

Figure 3. STAMINA model evaluation results for winter wheat and miscanthus

Figure 4. DNDC model evaluation results for winter wheat and miscanthus

Figure 5. Proportion of each soil type in total case study catchment

Figure 6. Process flow diagram showing the LCA system boundary used in this study

Figure 7. Simulated NO_3^- leaching rate and average annual grain yield for winter wheat production for different soil texture groups

Figure 8. (a) NO_3^- leaching and (b) direct N_2O emission from winter wheat straw and Miscanthus cultivation on selected soils under baseline climate scenario

Figure 9. Total LCB provision for SP and MP scenarios

Figure 10. GWP of LCB delivered to feedstock processing plant under SPBC and MPBC scenarios

Table 1. Three data sets used for model calibration for winter wheat and Miscanthus

Crop	Site	Years of Simulation
Winter wheat	Rosemaund (R)	1993-1996
	Gleadthorpe (G)	1991-1994
	Boxworth (B)	1993-1995
Miscanthus	Rothamsted 408 (408)	1997-2004

Table 2. Specifications of models inputs and outputs

	Soil	Weather	Background N	N fertiliser inputs	Output
STAMINA	NATMAP*	Hourly data from High Mowthorpe weather station (1961-1990)	Not needed; assumed to be non-limiting	Not needed	Yield for 30 years winter wheat and Miscanthus cultivations
DNDC	NATMAP*	Daily data from High Mowthorpe weather station (1986-1990)	UK Eutrophying and Acidifying Pollutant Network (UKEAP)	Specific value for each soil series based on RB209 [41]	NO_3^- leaching and N_2O emission from winter wheat and Miscanthus cultivation from 1986-1990

* NATMAP vector, Cranfield University, UK

Table 3. Single and mixed crop production (SP, MP) and climate change scenarios Baseline Climate (BC), Medium Emission (ME) and High Emission (HE); atmospheric carbon dioxide concentration [CO_2]

Scenario	**Description**	**Wheat cultivation allocation**	**Miscanthus cultivation allocation**	**Climate change scenario**
SPBC	Single crop Production under Baseline Climate	On all arable soils	None	Baseline weather [CO_2] 352 mg l^{-1}
SPME	Single crop Production under Medium Emission climate change	On all arable soils	None	Medium Emission [CO_2] 447mg l^{-1}
SPHE	Single crop Production under High Emission climate change	On all arable soils	None	High Emission [CO_2] 449mg l^{-1}
MPBC	Mixed crop Production under Baseline Climate	Excluding selected low quality soils	On Selected low quality soils	Baseline weather [CO_2] 352 mg l^{-1}
MPME	Mixed crop Production under Medium Emission climate change	Excluding selected low quality soils	On Selected low quality soils	Medium Emission [CO_2] 447mg l^{-1}
MPHE	Mixed crop Production under High Emission climate change	Excluding selected low quality soils	On Selected low quality soils	High Emission [CO_2] 449mg l^{-1}

Table 4. Life cycle inventory for wheat and Miscanthus cultivation used in this study. Cultivation data for wheat is taken from the Biomass Environmental Assessment Tool (BEAT) v2.1 database and from the Sustainable Liquid Biofuels from Biomass Biorefining (SUNLIBB) project for Miscanthus.

	Unit	Wheat	Miscanthus
Seeds	kg /ha/year	175	0
Rhizomes	kg /ha/year	0	5921
Ammonium nitrate[a]	kg N /ha/year	205	60
Triple superphosphate	kg P_2O_5 /ha/year	39	7
Potassium chloride	kg K_2O /ha/year	48	0
Potassium sulphate	kg K_2O /ha/year	0	105
Calcium oxide	kg CaO /ha/year	0	175
Manganese sulphate	kg /ha/year	0	5.6
Total pesticides (unspecified)	kg /ha/year	1.03	1.15
Total diesel consumption	kg /ha/year	230	0.74
Direct N_2O emissions from soil[b]	kg N /ha/year	0.66	0.15
NO_3^- leaching[b]	kg N /ha/year	63.30	50.03
Indirect N_2O from NO_3^- leaching	kg N /ha/year	0.48	0.38
Road transport (farm to storage)	km	50	50
Road transport (storage to plant)	km	50	50
Diesel (Loading & Offloading)	kg / kg feedstock	7.68E-04	7.68E-04

a. Ammonium nitrate input levels for winter wheat range from 160 to 220 kgN/ha/year, the weighted average value was applied in this LCA work

b. DNDC simulated results, the weighted average value was applied in this LCA work (0.768 kg diesel per ton feedstock)

Table 5. Weighted average (and standard deviation) grain yield outputs and total annual collectable straw in catchment area based on STAMINA-winter wheat

	Baseline Climate	**Medium Emission scenario**	**High Emission scenario**
Wheat grain yield (t/ha 14.5% moisture)	7.94 (0.39)	8.54 (0.12)	8.76 (0.11)
Total collectable straw (kt/year 14.5% moisture)	623.37	670.48	687.80

Table 6. Simulated Miscanthus yield (and standard deviation) on selected loamy fine sand soils

	Baseline Climate	**Medium Emission scenario**	**High Emission scenario**
Miscanthus yield (t/ha 14.5% moisture)	13.76 (0.35)	18.43 (0.42)	19.71 (0.67)

Table 7. NO_3^- Leaching and N_2O emissions (and standard deviation) of SPBC and MPBC scenarios

	SPBC	MPBC
NO_3^- Leaching (kg N/ha/year)	64.47 (7.25)	57.41 (6.87)
Direct N_2O (kg N/ha/year)	0.66 (0.18)	0.62 (0.17)
Indirect N_2O(kg N/ha/year)	0.48 (0.05)	0.43(0.05)
Total N_2O (kg N/ha/year)	1.14	1.05