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Novel integrated agricultural land management approach provides sustainable biomass feedstocks for bioplastics and supports the UK's "net-zero" target

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Abstract. We investigate the potential in producing biodegradable bio-plastics to support the emergent 'Net-Zero' Greenhouse Gas (GHG) emissions targets in the UK. A 'cradle to grave' Life Cycle Assessment was developed to evaluate GHG mitigation potentials of bio-based polybutylene succinate plastics produced from wheat straw-only (single feedstock) or wheat straw plus *Miscanthus* (mixed feedstocks) agricultural supply systems. For scenarios using mixed feedstocks, significant carbon mitigation potentials were identified at catchment and national levels (emission reduction of 30 kg CO_2eq /kg plastic compared to petroleum-based alternatives), making the system studied a significant net carbon sink at marginal GHG abatement costs of £-0.5 to 14.9 /t CO_2eq. We show that an effective 'Net-Zero' transition of the UK's agricultural sector needs spatially explicit, diversified and integrated cropping strategies. Such integration of perennial bio-materials into food production systems can unlock cost-effective terrestrial carbon sequestration. Research & Development and scale-up will lower costs helping deliver a sustainable bioeconomy and transition to 'Net-Zero'.

1 Introduction

Plastic pollution and climate change are two global sustainability challenges rooted in the exploitation of fossil carbon [1,2]. The UK is the first major economy to implement a legally binding commitment to achieve 'Net-Zero' greenhouse gas emission by 2050. At the same time as world-wide commitments to Net-Zero are made, many countries are introducing regulations on single-use plastics. As a result of research and innovation in biotechnology, the vision of a society far less dependent on petroleum could become reality [3,4]. A recent study estimated the climate mitigation potential of replacing petroleum-based plastics with bio-based polybutylene succinate (bio-PBS) alternatives from lignocellulosic biomass (LCB) [5]. However, this study only accounted for emissions from feedstock pre-treatment to end-of-life without considering site-specific carbon sequestration/emissions resulting from associated land-use change.

Recently, the UK National Farmers Union has developed a roadmap to achieve the Net-Zero target across the agricultural sector by 2040 [6]. In 2017, 41.2 Mt CO_2eq Greenhouse Gases (GHGs) was emitted from agriculture, representing about 10% of the national total of 465.4 Mt CO_2eq [7]. However, whilst overall UK emissions have reduced by 42% since 1990, emissions from agriculture declined by only 16.3% [7]. UK farming's plan to achieve its Net-Zero target are challenging but its GHG reduction potential is substantial. Achieving the co-benefits and avoiding trade-offs will require not only innovative solutions [8], but also careful implementation. Pathways to achieve the required reduction in emissions include boosting productivity, increasing soil carbon storage and feedstock provision for bio-based materials production coupled to carbon sequestration processes [6].

In addition, the conversion of agricultural land to grow feedstocks for new products must become economically attractive. The low petroleum price and high production cost of bio-PBS are currently significant barriers for expanding the application of bio-based chemicals. However, it is likely that the current price of bio-PBS (£3.2 (€4)/kg) will decrease to around £2 (€2.5)/kg as the global production capacity increases and economies of scale are realised [9]. Here we estimate that were the carbon abatement price to increase to £20 (€25)/ t CO_2eq and previous subsidies (e.g from the European Common Agricultural Policy) were transferred to rewards for environmentally beneficial farming practices, opportunities for large scale climate-smart implementation of LCB-based PBS plastics (LCB-PBS) could deliver cost-effective climate mitigation in support of the UK's Net-Zero ambitions.

Previous scenarios for LCB feedstock provision and associated emission impacts compared two land use options in a catchment scale analysis [10]. An annual feedstock requirement for a commercial scale PBS production plant of 350 kilo tonnes (kt) was supplied from two LCB provision options; a single arable crop-derived product (SP), i.e. wheat straw, or a mixed arable with perennial crop-derived product (MP). In this article, we compare these options by combining crop and soil carbon modelling with a Life Cycle Assessment (LCA), to evaluate the climate mitigation potential of LCB-PBS production with improved land stewardship. The proposed introduction of LCB feedstock for the bioeconomy raises questions about sustainable development. The emergent strategies for the (non-food) bioeconomy of the EU [4] and OECD [11] potentially harm the progress towards achieving the Sustainable Development Goals (SDGs) if poorly implemented [12], e.g. exacerbate Hunger (SDG 2) and 'Climate Change' (SDG 13). However, Heimann postulates a 'sustainable bioeconomy' scenario where 'strong sustainability measures' are implemented progressing several SDGs simultaneously is possible [12]. The terrestrial carbon stock change associated with the land use transition from SP to MP was calculated using literature data and the RothC model, implementing the IPCC Agricultural Forestry and Other Land Use (AFOLU) five carbon pool structure [13]. For the first time, we integrate systems level GHG emissions and relevant product outputs (grain, straw and bio-plastics). We also consider emissions from indirect land use change and the potential reductions in food/feed provision when substituting wheat production with *Miscanthus*. Finally, an economic analysis is included to assess the economic feasibility of the MP production pathways and the carbon abatement costs.

2 Methods and Materials

2.1 Case study area, feedstock provision and PBS production scenarios

A catchment-level case study area was selected to understand local feedstock provision capacity and to simulate GHG balances associated with LCB-PBS value chains using spatially explicit soil data. The case study area is around the city of Hull in England with parts of the Yorkshire & Humber and East Midlands region, assuming a maximum transport distance of 50 km for feedstock from farm to the conversion plant. This is the main winter wheat production area in the UK, covering 5 856 km^2 (585.6 kha) with highly variable soil types according to the UK National Soil Map (1 x 1 km^2 grid).

Three scenarios were created in this study to present the different land management and LCA-PBS production pathways. Non-bio (NB) represents the business as usual scenario, where all arable land (396.4 kha) is used for winter wheat production, without local PBS production. SP assumes wheat production and land management identical to NB but considers future development of a bio-economy, assuming a commercial LCB-PBS plant, winter wheat straw being the sole LCB feedstock. MP represents the proposed mixed feedstock provision with *Miscanthus* cultivated on selected low-quality soils and wheat grown on all other soils currently under arable tillage. Thus, in MP, LCB feedstock is supplied from *Miscanthus* and winter wheat straw. Low-quality soils were defined as the soils with highest NO_3^- leaching/wheat grain production ratio (kgN/t Grain) based on DNDC simulation results [10]. *Miscanthus* cultivation was therefore directed to30.2 kha of these loamy fine sandy soils.

2.2 Life cycle assessment

a. General specification

This ‘cradle to grave’ LCA (Supplementary Figure S3) considered feedstock production, feedstock conversion to sugars, polymer production, products manufacture, ‘end-of-life’ treatment and necessary transport. Function unit is defined as CO_2eq per kg plastic product; plastic trays for food packaging are assumed to be the end products [5]. An economic allocation was applied to attribute emissions to wheat grain and straw in LCB provision phase, respectively. For all systems, the adopted economic allocation options are described in the Supplementary Methods. The climate change mitigation potentials of LCB-PBS were compared with two reference systems, maize grain (MG)-based PBS and the petroleum-based alternatives, assuming the same end-of-life treatments. Two types of petroleum-based products, polypropylene (PP) and polyethylene terephthalate (PET) trays were used as reference materials. The ReCiPe Midpoint (H) LCA impact assessment methodology from SimaPro 8 database was used to generate results from the life cycle inventory based on the climate change impact category.

b. Emissions for delivered LCB

LCB provision capacities and N_2O emissions were previously simulated using the STAMINA and DNDC models, respectively [10]. The simulations accounted for the spatial variation of soil type, temporal variations in climate, fertilizer application strategy, residue incorporation and crop rotations. This study further integrated terrestrial carbon stock change estimation into the feedstock supply chain and PBS life cycle. Based on the 2006 AFOLU, carbon stock changes were estimated by integrating above-ground biomass, below-ground biomass and soil organic carbon (SOC) stock changes [13] (Supplementary Methods). Litter carbon pool was not considered in this study, considering that the turnover rate of litter in croplands was generally fast, and its carbon would eventually be lost to either SOC or atmosphere. The deadwood carbon pool was considered irrelevant in cropland system. SOC changes were simulated with the RothC model [14] (see also Supplementary Methods).

c. Emissions from factory gate to 'end-of-life'

Figures for emissions associated with feedstock pre-treatments, polymer production and end-of-life treatments were taken from Patel et al. [5]. Steam explosion (SE) and organic solvent (OS) were considered as pre-treatment options for LCB feedstock conversion to C6 sugars (and co-products). Bio-based PBS are produced from succinic acid (SA) using 1,4-butanediol (BDO), with a SA/BDO mass ratio of 57:43. In other words, PBS can be produced through fully bio-based (FB) or partly bio-based (PB) pathways (with bio-based SA and petroleum-based BDO). Three pathways were considered for BDO production, including petroleum-based pathways (for PB-PBS from either LCB or starch feedstocks), hydrogenation of LCB-based SA (for FB LCB-PBS) and fermentation of C6 sugars (for FB starch-based PBS). For the production of PBS trays, a two-step process 'extrusion and thermoforming' was assumed [5].

For PBS trays, two end-of-life treatments were assumed, energy recovery in a municipal solid waste incineration plant or industrial composting (Supplementary Figure S5). Petro-based reference products were assumed to be disposed by municipal solid waste incineration after use. Biogenic carbon embedded in the products were considered for both, starch- and LCB-based products. For consistency, CO2 (and CH4 when composted) from embedded carbon during end-of-life treatment was also considered in this work. We assumed 99% and 95% release of stored carbon for incineration and industrial composting of PBS trays, respectively. When composting is adopted, 5% of the biogenic carbon embedded in PBS would be converted to soil carbon.

2.3 Accounting for total GHG emissions in the NB, SP and MP scenarios

For each scenario, total GHG emissions were calculated based on respective grain and LCB-PBS production levels, applying emission factors for the grain produced and calculating emissions saved by the use of FB-LCB-PBS trays. GHG emissions avoided by FB trays were determined from differences between FB PBS trays and PET alternatives, and the respective quantities of total LCB-PBS produced in the SP and MP scenarios. The LCB-PBS production is calculated based on the conversion rates of LCB feedstocks to FB LCB-PBS, feedstock mix and processing capacity in SP and MP, respectively. The feedstock processing capacity of commercial scale LCB-PBS plant ranges between 350 and 400 kt/yr [10]. For both LCB-feedstock scenarios processing capacity was set to 363kt, equivalent to the MP LCB feedstock provision. When using SE pre-treatment, the conversion rates of wheat straw and Miscanthus were assumed to be 7.75 and 5.91kg DM/kg PBS respectively [5].

Emissions from reduced grain production in MP and straw deficits/surplus (in SP and NB) were considered as indirect impacts. In SP, local LCB supply was insufficient to support the hypothetical LCB-PBS plant without creating feedstock competitions with the traditional straw market [10]. Indirect emissions from the potential competition for straw were neutral, assuming straw deficits to be compensated by wheat cultivated elsewhere and maintaining emission factors for current management and climate conditions. Improved resource use efficiency or alternative choices for traditional straw uses were not considered. Similarly, the reduced grain production was assumed to be cultivated outside the case study area, with the same grain emission factor.

2.4 Estimating marginal carbon reduction costs

Based on system level emissions and production (Section 2.3) the impacts of three influential factors were considered in a simplified economic analysis: grain production costs, PBS production costs, and carbon prices. We evaluated a 3-factorial combination in a total of 12 scenarios using three carbon price levels (high, current and low), two PBS production cost levels (high and low) and two grain reduction levels (grain production decreases as modelled and “no losses” assuming climatic and management compensation e.g. through enhanced yields).

Marginal carbon reduction cost (MRC) (£/tCO$_2$eq) was calculated with the following equations:

$$\mathrm{MRC} = (\mathrm{V}_{NB} - \mathrm{V}_{MP})/(E_{NB} - E_{MP}) \qquad (1)$$

$$\mathrm{V}_{NB} = \mathrm{Q}_{g-NB} \times \mathrm{P}_g + \mathrm{Q}_t \times \mathrm{P}_t - \mathrm{Q}_{v-PET} \times \mathrm{Ct}_{v-PET} \qquad (2a)$$

$$\mathrm{V}_{MP} = \mathrm{Q}_{g-MP} \times \mathrm{P}_g + \mathrm{Q}_t \times \mathrm{P}_t + (E_{NB} - E_{MP}) \times \mathrm{P}_c - \mathrm{Q}_{v-PBS} \times \mathrm{Ct}_{v-PBS} \qquad (2b)$$

$$\mathrm{Q}_{v-PET} = \mathrm{Q}_t / \mathrm{R}_{v-PET} \qquad (3a)$$

$$\mathrm{Q}_{v-PBS} = \mathrm{Q}_{t} / \mathrm{R}_{v-PBS} \tag{3b}$$

where V = total value generated by grain and tray production; E = total emission generated in grain/straw/plastics trays life cycles; Q = quantity, P = market price, Ct = production cost; R = resource efficiency; $Subscript\ g$ = grain, $Subscript\ t$ = tray product, $Subscript\ v-PET$ = virgin PET, $Subscript\ v-PBS$ = virgin PBS.

In MP, we consider the MRC as, the economic cost of reducing (or avoiding) per unit of carbon emission, by adopting the analysed carbon abatement pathway. Thus, MRC is calculated by the total economic cost and the total carbon reduction achieved in MP, comparing with NB, which represents a business-as-usual scenario. Regardless of the difference in production costs of virgin PBS and virgin PET, we assume the tray products produced by virgin PET and virgin PBS were equal in terms of selling market price and customer preference. Transaction cost was not considered in this study. In MP, we estimate the economic cost by accounting for reduced grain production and the profit loss of the plastic tray production resulted from increases in raw material costs. Feedstock provision cost of lignocellulosic feedstocks were reflected in the raw material costs, i.e. Ct_{v-PBS}. The value of avoided carbon emission is considered as an additional revenue generated in MP.

Assuming $\mathrm{R}_{v-PET} = \mathrm{R}_{v-PBS} = 0.99$, Eq.1, Eq.2a, Eq.2b, Eq.3a and Eq.3b were combined:

$$\mathrm{MRC} = \{ (\mathrm{Q}_{g-NB} - \mathrm{Q}_{g-MP}) \times \mathrm{P}_{g} - (E_{NB} - E_{MP}) \times \mathrm{P}_{c} + \mathrm{Q}_{t}/0.99 \times (\mathrm{Ct}_{v-PBS} - \mathrm{Ct}_{v-PET}) \} / (E_{NB} - E_{MP}) \tag{4}$$

Where Q = quantity, P = market price; E = total emission generated in NB(MP) through grain/straw/plastics trays life cycles; R = resource efficiency; Ct = production cost; $Subscript\ c$ = carbon; $Subscriptg$ = grain, $Subscript\ t$ = tray product, $Subscript\ v-PET$ = virgin PET, $Subscript\ v-PBS$ = virgin PBS. As all the prices were obtained from national and international sources [9, 16]; for simplicity the currency exchange rates were fixed as 1 Sterling (£) = 1.25 US dollar ($) = 1.25 Euro (€). Defined price levels for carbon (P_{c}) and v-PBS production (Ct_{v-PBS}), and assumption on grain production levels of each scenarios were specified in Table 1. Production cost of virgin PET plastics (Ct_{v-PET}) was assumed as £0.696 (€0.87) /kg PET [15].

Table 1. Background data regarding the relevant carbon price (P_c), cost of plastic production ($Ct_{v\text{-}PBS}$) and grain production levels (Q)

	Scenario	Specification and referencing values
$\mathbf{P}_{c}$	Low	€8/t CO_2eq (£6.4/t CO_2eq), based on historical average (2016-2018) on European Union Emissions Trading System (EU ETS)
	Current	€25/t CO_2eq (£20/t CO_2eq), based on 2019 average on EU ETS
	High	£30/t CO_2eq, based on previously targeted 2020 carbon price floor by UK government [16]
$\mathbf{Ct}_{v-PBS}$	High	€4/kg PBS (£3.2/kg PBS) [9]
	Low	€2.5/kg PBS (£2/kg PBS) [9]
Grain production loss ($\mathbf{Q}_{g-NB} - \mathbf{Q}_{g-MP}$)	Grain loss	grain production decreases in MP ($Q_{g-NB} - Q_{g-MP} \neq 0$)
	Non-grain loss	Grain losses are fully compensated through wheat yield improvements in the remaining area/soils with no extra emissions caused ($Q_{g-NB} - Q_{g-MP} = 0$)

3 Results

3.1 Generating carbon sinks by integrating perennial crops (*Miscanthus*) into arable landscapes (wheat) for PBS plastic production

'Cradle to grave' LCA results illustrate the large potential range in GHG emissions between the different production pathways for LCB-PBS trays (-25.1 to 5.72 kg CO2eq per kg bioplastic) (Figure 1a, b) compared to grain-based PBS products (4.29 to 8.16kg CO2eq/kg) (Figure 1c) and conventional petroleum-based plastics (4.22 to 5.01 kg CO2eq/kg) (Figure 1d). For bioplastic, the lowest GHG emissions occurred for FB products using mixed LCB, SE pre-treatment and end-of-life disposal by incineration (MP-FB-Inc; detailed Figures are listed in Supplementary Table S1). Among all LCB-based cases, the highest GHG emissions were a consequence of PB production from wheat straw with the same pre-treatment (SE) and disposal by composting (SP-PB-Com; 5.72 kg CO_2eq/kg). Pre-treatment using OS resulted in life cycle GHG balances from -24.04 to 6.71 kg CO_2eq/kg (Supplementary Figures S1 a and b). The impacts of different end-of-life options on the overall climate change impacts of LCB-PBS were *ceteris paribus* relatively small (incineration was 0.5 kg CO_2eq/kg less than composting). GHG emissions were lower for FB than PB cases, due to avoiding fossil fuel-based requirements for the production of the monomer BDO, gaining extra energy credits from bio-DBO production, and causing no petroleum-based CO_2 emissions during end-of-life treatment. Although biogenic carbon emissions during the end-of-life stage appeared to be higher in FB than in PB products, these biogenic emissions were offset by accounting for the biogenic carbon embedded in the products. In the MP scenarios, extra carbon credits were achieved as a result of increased terrestrial carbon storage under *Miscanthus*. For LCB-PBS produced from MP feedstock provision scenario, GHG emissions ranged from -24.68 to -25.10kg CO_2eq/kg and from -6.12 to -6.54 kg CO_2eq/kg for the FB and PB products, respectively (Figure 1b and Supplementary Table S1). When soil carbon sequestration was excluded from the carbon accounting, the total GHG emission for MP-FB-Inc and MP-FB-Com were 1.36 and 1.78 kg CO_2eq/kg tray product; for MP-PB-Inc and MP-PB-Com were 4.82 and 5.24 kg CO_2eq/kg tray product. In all the cases when feedstock was sourced from the MP scenario, carbon sequestration could be achieved even for PB products.

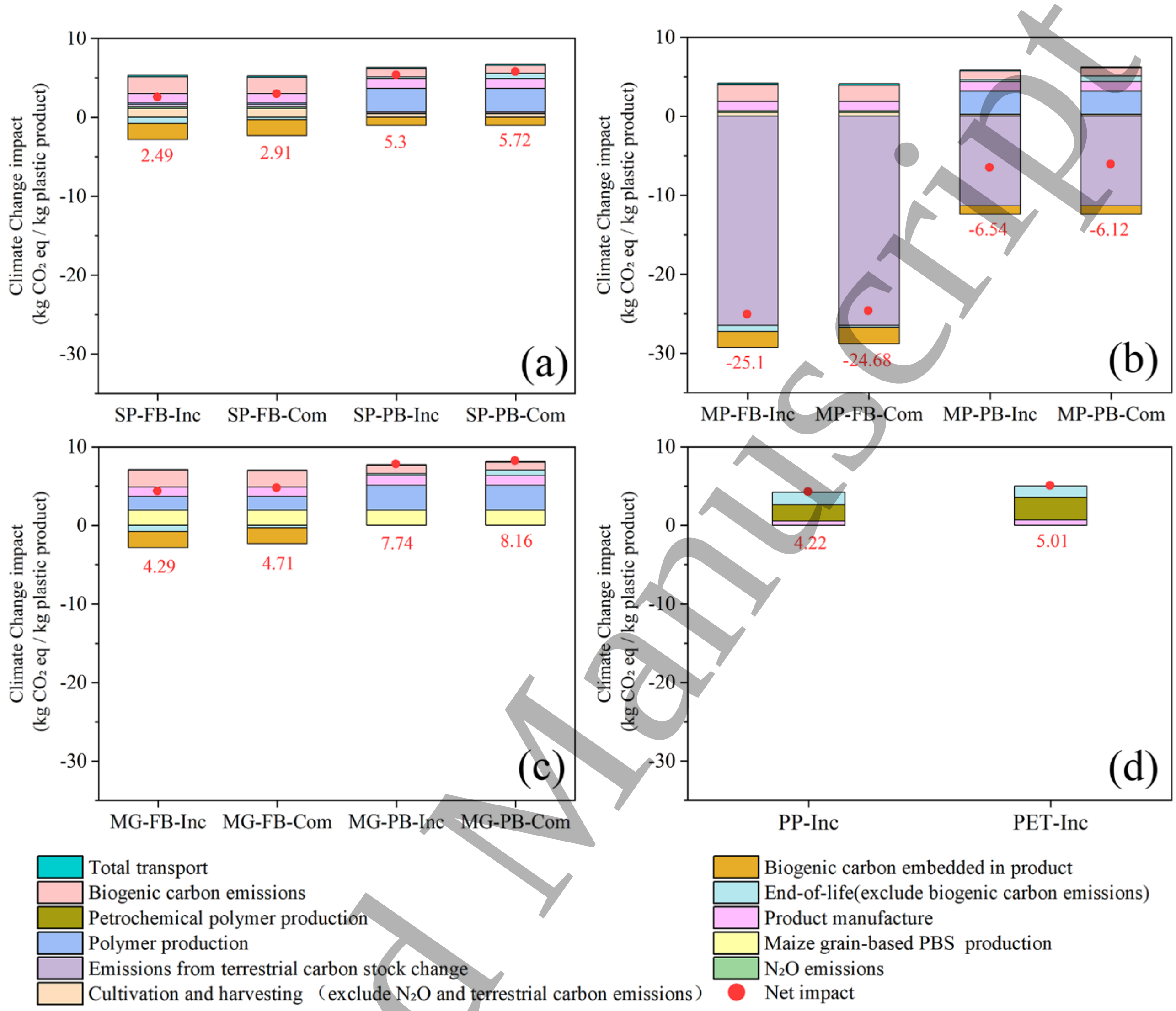

Figure 1. Life Cycle Inventory Analysis profiles: ‘cradle to grave’ climate change impacts for (a) FB and PB PBS plastic trays produced from SP LCB provision scenario with SE pre-treatment and incineration (Inc)/composting(Com) end-of-life treatment; (b) FB and PB PBS plastic trays produced from MP LCB provision scenario with SE pre-treatment and incineration/composting end-of-life treatment; (c) FB and PB PBS plastic trays produced from maize grain (MG) with incineration/composting end-of-life treatment; (d) petroleum-based plastic trays produced from PP and PET with incineration end-of-life treatment. Maize grain, PP and PET-based (bio-) plastic trays are considered as reference products. (MP/SP= mixed/single feedstock; FB/PB=fully bio/partially bio production pathway; Inc/Com=end-of-life choice of incineration/composting in LCA considered.)

With widespread adoption, substantial mitigation potentials are possible for the MP LCB- PBS plastic supply chains. However, without spatially explicit climate-smart land use management, carbon mitigation would be minimal or even potentially exacerbated, as shown for the SP scenarios. Significant GHG reductions were only seen when *Miscanthus* was integrated into the arable landscape, with carbon being sequestered in the SOC pool. In contrast to earlier preconceptions and previous LCA outputs, this work demonstrates that bio-based chemicals, such as starch-based or LCB-PBS, are not inherently carbon neutral. Without climate-smart farm management, especially land use optimisation based on improving soil quality, the GHG emissions of PBS materials could be higher than conventional alternatives.

3.2 Is the emergent bioeconomy a threat to the SDGs?

The proposed strategy to produce bio-PBS from perennial, non-food crops LCB is expected to have only a minor impact on food production (SDG 2, Zero Hunger) and to reduce nitrate leaching from wheat on sandy soils (SDG 6, Clean Water). The results show opportunities for farmers to ‘produce more from less,’ potentially enhancing biodiversity (SDG 15, Life on land) and give practical guidance on sustainable implementation of the bioeconomy at the farm / field levels.

Table 2 provides comparative estimates of the total GHG emissions arising from a counterfactual conventional petroleum-based plastics production (NB) scenario versus two bio-PBS production scenarios, based on single (SP, wheat-straw-only) and mixed feedstock (MP, wheat straw + *Miscanthus*). The spatially explicit replacement of wheat allows us to account for the impact on grain production alongside a consequential assessment of emissions from displaced grain production resulting from the land used for *Miscanthus* LCB production.

In NB, 60.72 kt of conventional plastic products would be produced per year from 61.33 kt petroleum-based PET polymer granulesto meet the same product demand as in SP and MP. With “wheat straw only” (SP) the GHG reduction was minimal (only 3%), compared to NB. The mixed feedstock, using *Miscanthus* (MP), secured more feedstock (and extra income) and significantly improved climate mitigation with 76 to 77% emission reduction compared to NB and SP. Therefore, our scenarios of integrating perennials for bioplastic production had clear climate mitigation effects (SDG 13).

Whilst our analysis does not directly address SDG 2 ‘Zero Hunger’ it accounts for the consequential impacts of displaced food production. In MP, the land area dedicated to *Miscanthus* displaces 8% of the potential wheat area reducing grain production by 115 kt/yr. When indirect GHG emissions associated with additional wheat production outside the case study area are included, total emissions are slightly higher (+185 kt CO_2eq/yr) but still reduced by 72% in MP compared with NB scenario. In MP, GHG mitigation credits would also arise from the improved emission factor per unit wheat grain produced (1.62 instead of 1.99 kg CO_2eq/kg), as replacing wheat production on low-quality soils reduces fertiliser inputs and associated nitrogen leaching and GHG emissions. Over time, perennial *Miscanthus* also increases SOC stocks of these soils.

Further, it is also likely, that the reduced area of wheat production will be compensated by yield increases due to CO_2 fertilization and warmer climate [10,17,18]. Further wheat production improvements can come from improved management, weed control, and improved soil productivity due to increased SOC [19]. Thus, the impacts of the non-food bioeconomy are highly site-specific, calling for spatially adapted implementation and management [20]. Under these circumstances the bioeconomy should be considered as an opportunity for improving the environment and productivity for a better ‘Life on land’ (SDG 15). All scenarios produce 60.72 kt/yr trays, either PBS trays produced locally or PET trays imported.

Table 2 Grain and bio-plastics production, GHG emissions and potential indirect impacts (resources and GHG emissions) from non-bio (NB), single (SP) and mixed (MP) Lignocellulosic Biomass production scenarios; values refer to a UK catchment consuming 60.72kt/yr PBS trays produced locally (or PET trays imported); FB tray produced through SE pre-treatment was assumed; economic allocation applied on wheat straw and grain.

Scenario	**Outputs (kt/yr)**		**Indirect impacts (kt/yr)**		
	Grain DM (Q_g)	FB plastic tray produced and PET tray avoided (Q_t)	Grain deficit	straw deficit	PET polymer consumption
NB	1746	0	0	-18[a]	61.33[b]
SP	1746	46.90[c]	0	345[d]	13.96[e]
MP	1631	60.72[f]	115	0	0
	Emission factors (t CO_2eq/t)		**Emission factors (t CO_2eq/t)**		
	Grain DM	GHG emissions avoided by FB trays	Grain DM	Straw	
NB	1.99	0	-	-	
SP	1.99	-2.52[g]	-	0.22[j]	
MP	1.61	-30.10[h]	1.61[i]		
	Emissions (kt CO_2eq/yr)		**Indirect emissions caused by (kt CO_2eq/yr)**		
	Emission from Grain produced	GHG emissions avoided by FB trays	Grain deficit	Straw deficit	PET polymer consumption
NB	3487.06	0	0	-3.96	Accounted[k]
SP	3487.06	-118.19	0	75.90	Accounted
MP	2625.23	-1827.67	185.15	0	Accounted
	Total emissions (E) (kt CO_2eq/yr)		**Total indirect emissions (kt CO_2eq/yr)**		**Total emissions including indirect impacts (kt CO_2eq/yr)**
NB	3487.1		-3.96		3483.1
SP	3368.9		75.90		3444.8
MP	797.6		185.15		982.7

'FB' = fully bio; 'DM' = dry mass; 'LCB' = Lignocellulosic Biomass; 'PET'= polyethylene terephthalate

a. Negative figure indicates that in NB, there would be 18 kt straw surplus when no PBS is produced;

b. based on the amount of plastic tray products that could be replaced by MP-FB scenario, and assuming a resource efficiency of 0.99 [5];

c. assuming that in SP a total 363 kt/yr straw (LCB provision capacity of MP under a Baseline Climate) would be used to produce PBS; production rates of LCB feedstocks to PBS [5];

d. in SP, due to the commercial scale PBS plant utilized, a total 363 kt straw and this would cause 345 kt straw deficits for current straw uses;

e. in SP, lower conversion rate of straw to fermentable sugar compared to *Miscanthus* 363 kt straw-based LCB produce only 46.9 kt FB-PBS trays and 13.96 kt PET plastic trays are needed to match MP;

f. in MP, a total 363 kt LCB were available to produce 60.72 kt FB trays based on production rate [5];

g. difference of climate change impacts between 'SP- FB -Inc' an 'PET- Inc' cases,

h. difference of climate change impacts between ‘MP- FB - Inc’ an ‘PET- Inc’ cases
i. if the wheat grain production deficit in MP was compensated by production outside the case study area, it is assumed the emission factor of this external grain production is the same as that produced in the case study area; all figures coloured in dark blue were based on assumptions regarding indirect impacts, for which there is a high level of uncertainty;
j. due to the straw deficits for other uses in SP, simplified assumption was made that extra straw needed to be produced outside the case study area but with the same emission level; as with ‘9’, a high level of uncertainty remains;
k. emissions from PET trays have been already accounted for in ‘GHG emissions avoided by FB trays’.

3.3 Estimates of marginal carbon reduction costs (MRC)

Overall, the MRC ranged from £-0.5 to 55.6/t CO_2eq (Figure 2) abated or avoided, which can be considered as cost-effective or a low to medium abatement cost approach [21,22]. Of course, the lowest MRC values all arise for the scenarios applying low PBS production cost and current, ‘high’ carbon prices. It is worth noting that for low PBS production costs, high carbon price (or equivalent) and no grain loss scenario, the LCB-PBS life cycle generates revenue, instead of representing a cost. This indicates further efforts should be made in academia and industry to lower bio-PBS production costs to a target level of £2 (€2.5)/kg PBS [9]. Policy and market regulations should aim to maintain or even increase the value of carbon abatement and extend the scope of climate mitigation and adaptation measures to include non-energy abatement markets.

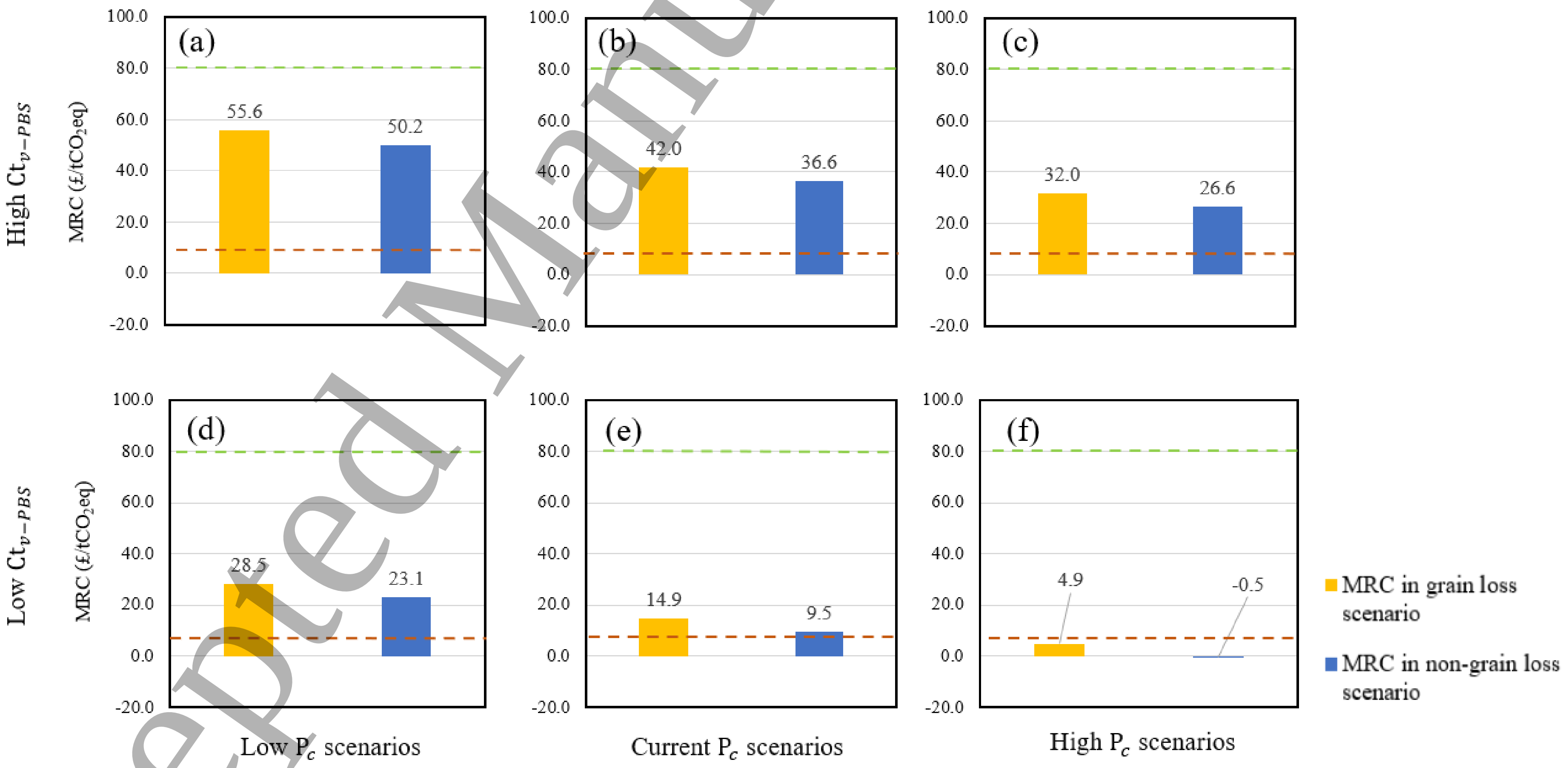

Figure 2. Predicted Marginal Carbon Reduction Cost (MRC, £/t CO_2eq) through MP-PBS production strategy scenarios; Green dashed line represents the identified maximum carbon reduction cost of \$100 /t CO_2eq and the red dashed line represents the identified cost-effective carbon reduction price of \$10 /t CO_2eq [21]

4 Discussion

Evaluating the bioeconomy as a potential tool for climate mitigation, we adopted an approach that optimized land use efficiency and balanced food and LCB production. We combined modelling with an LCA to assess direct and consequential GHG emissions and SOC sequestration metrics. The results show an exciting potential synergy between integrated conventional arable wheat production and the smart deployment of a perennial LCB crop, *Miscanthus*. The cropping integration entailed a minimal disruption of wheat production and simultaneously allowed significant GHG savings by exploiting spatio-temporal dynamics, whilst maintaining food security as the primary indicator of sustainability [23,24]. The analysis shows that bioplastics produced using LCB from straw alone would be insufficient to mitigate climate change. It also demonstrates that the mitigation potential of LCB-PBS plastics mainly originates from smart allocation of perennials into a conventional cropping environment (Figure 1).

The proposed strategy provides a promising approach to achieve significant reductions in GHG emissions, sequester carbon, and simultaneously expand the LCB supply whilst keeping its land footprint small. At the national level, about 3% of the total area of England and Wales is covered with sandy soils (453.4 kha) [25,26]. Most of these sandy soils are under arable production and are located in the eastern parts of England [27,28,29] where wheat is the dominant crop type. Assuming similar GHG reduction rates, deploying MP for LCB-PBS at national scale could achieve a technical climate mitigation potential of ca. 40 Mt CO_2eq/year, which approximates to an offset that equals the current GHG emissions from UK agriculture [7], even without accounting for indirect emission reductions. However, the respective terrestrial carbon balances would depend on previous crop types and initial soil carbon, which lie outside the case-study area and need further investigation [19]. Other important factors include the local topography, machine accessibility [24] and farmers' willingness to adopt alongside the practical effectiveness of implementation [30,31].

As an improvement over previous LCA studies on bio-PBS [5], we considered land-based GHG emissions from all possible sources in the simulations, including stock changes in biomass carbon and SOC, etc. (see 2.3). The timeframe considered in this study is 30 years (2020 to 2050), ignoring GHG balance associated with the PBS life cycles beyond this period. Although RothC simulated SOC change for a 150-year period, the carbon mitigation effects are strongest initially and sequestration rate would slow over time, as SOC contents approach site specific equilibria (Supplementary Figure S2 and Table S2). Our calculations ignored increased carbon inputs due to increased atmospheric CO_2 concentrations and simultaneously increasing soil carbon emissions, which might offset carbon enrichment effects through crop biomass production [32]. Such impacts should be included in future modelling studies for more robust SOC stock estimates considering extended periods and alternative scenarios, e.g. more widely rotating perennial LCB crops.

This work supports the widely suggested yet untested hypothesis that site- and management-specific terrestrial carbon balance analyses are coupled with bio-chemical and biomass techno-economics and LCAs [33]. Research of quantifying GHG emissions from biomass produced in different climate or land use scenarios [14,34,35] stood alongside the LCA for PBS materials [5]. For the first time, we fully integrated the two components, conducting a spatially explicit whole systems evaluation which integrated arable and perennial cropping to achieve robust LCA estimates for sustainable bioplastics, as an example for the bioeconomy. This underpins how spatial and temporal dynamics of land-use change could affect the carbon balance of a full bioplastics' LCA under realistic implementation scenarios. Secondly, only with a persistent end-market for dedicated biomass crops carbon sequestration benefits will be realised through market price for carbon (Figure 2) instead of continued government subsidies [36] but the policy environment remains complex to deliver National Climate Solutions at scale [37]. SOC sequestration potential of smart land use must undergo a full value chain analysis that includes the final product's life cycle so that it is visible and therefore valued in markets. Feedstock supply is a key barrier for the cellulosic refinery industry [38]. As shown earlier [10] and referred to in 3.1, it was impossible to provide sufficient LCB feedstocks to meet the demand of a commercial LCB-PBS production unit without introducing the perennial crop *Miscanthus* into an existing arable landscape. Widely applied, such mixed production systems could significantly increase LCB provision compared with SP scenarios based on conventional crops, in which the competition for existing straw resources would reduce SOC stocks and damage future productivity [39]. Current research suggests that the impacts of climate change on agricultural production are geographically unevenly distributed; globally agricultural productivity is likely to decline under global warming and climate projections [40,41]. Perennials in the MP scenarios are likely more resilient to climate change and extreme events (increased rainfall, higher temperatures) and could better serve diversified markets. Considering the carbon mitigation benefits and financial feasibility, the proposed MP scenario for biomass and food production will result sequestration of SOC, provides an opportunity to mitigate and adapt UK farming in the face of climate change.

The proposed MP strategy aimed to secure feedstock provision for LCB- PBS production whilst optimising terrestrial GHG emission balances during crop production. GHG emission reductions resulted mainly from three major components of feedstock production: i) sequestered carbon into belowground biomass and SOC pools on *Miscanthus*-planted land; ii) reduced direct and indirect N_2O emissions during the *Miscanthus* life cycle due to lower N-fertiliser application levels compared to wheat; iii) lower levels of fertiliser inputs and farming activities for *Miscanthus* compared to wheat. However, nutrients captured by *Miscanthus* from adjacent arable land was not considered here, but would further enhance sustainability by reutilising N surplus and reducing losses [42,43] and removing nitrate from groundwater [42]. Other potential environmental benefits include reducing sediment, phosphate and loss of pesticides from arable fields, stabilising stream banks, and reducing bank erosion [44].

5 Conclusions

Our analysis allows the following conclusions

- The evaluation of mitigation potentials for LCB- PBS plastics was improved by integrating GHG balances of feedstock production with value chain LCA, considering carbon sequestration alongside a comprehensive assessment of direct and consequential impacts
- Allocating perennial crops using spatially specific, climate-smart land use optimisation, significant systems-level GHG emission reductions and SOC storage are likely to be achieved when *Miscanthus* was assigned to low-quality soils displacing under-performing wheat.
- Climate- and resource-smart mixed cropping strategies could play a significant role in offsetting national agricultural GHG emissions, stimulating the bioeconomy and transition of UK farming to its Net-Zero future.
- The economic analysis demonstrates the viability of such strategy and highlights the importance valuing carbon emission reductions as an efficient market mechanism.

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Data availability statement

The data supporting the findings of this study are available through the references provided within the article or the supplemental materials. Additional data related to this paper can be requested from the corresponding author.

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