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Improvements in beef cattle productivity can increase economy-wide activity and simultaneously reduce greenhouse gas emissions in Scotland

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Abstract
Cutting emissions from agriculture will be important in meeting emissions reduction targets. However, there are concerns that such outcomes might require reductions in the scale of agricultural activity, with negative impacts on agriculture reliant economies. A number of policies seek to improve the productivity of the agricultural sector, i.e. permitting increased output from a given set of inputs, but the impact of such policies on emissions or economic activity is unclear. The objective of this study is to demonstrate how a Computable General Equilibrium model can be used to undertake ex ante analysis of the potential economic and environmental impacts of full implementation of a policy targeted at raising productivity in Scotland's beef farming sector. We find positive impacts on economic variables and reductions in emissions, largely generated through reductions in the size of the capital stock in the beef farming sector. Our results contribute to a growing and important literature exploring the future capability of the agricultural sector to provide livelihoods, while minimising its environmental impacts.

Keywords Productivity · Meat production · Agricultural policy · Micro to macro · Computable General Equilibrium

1 Introduction

With countries across the world setting targets to reduce emissions, there is a recognition that all parts of the economic system will be required to contribute. For instance, the IPCC's 2018 report set out that mitigation pathways to restrict temperature increases to 1.5° above pre-industrial levels requires, in addition to overhauls in global energy use, electrification of energy use and decarbonisation of electricity "deep reductions in agricultural emissions" (Masson-Delmotte et al., 2018). The role of land management, including agricultural production, in emissions reduction is critical: "one-quarter of total anthropogenic GHG emissions arise mainly from deforestation, ruminant livestock, and fertiliser

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application" (Arneth et al., 2019, p. 84). With recent rapid reductions in emissions from other sectors (in particular, energy activities) continuing through the next decade, it is likely that from 2030 onwards agricultural emissions will be critical in meeting mid-century targets (Wollenberg et al., 2016).

Reductions in agricultural output would however have catastrophic outcomes for food consumption, food security and the crucial role that agriculture plays in many economies across the world (Alston & Pardey, 2014). However, there are several routes through which a reduction in emissions from agriculture can be achieved without, necessarily, reducing agricultural output. First, a switch in production/consumption towards less emissions-intensive products, such as a shift towards diets containing less meat (Green et al., 2015; Seconda et al., 2018; Tom et al., 2016; Vieux et al., 2012). Secondly, improvements in agricultural productivity, where farms increase their output *per unit of inputs*.[1] The evaluation of the economic impacts of policies aimed at improving farming productivity is a growing area of analysis. Some studies use econometric methods to explore these links (e.g., Warr & Suphannachart, 2020), while there is a small but growing literature using system-wide approaches, including Computable General Equilibrium (CGE) models, These models permit an analysis of the whole economy consequences of policies and have been used to examine the system-wide impacts of agricultural policies (such as Arndt et al., 2016; Jensen et al., 2012; Komarek et al., 2019; Montaud et al., 2017). The use of CGE models to examine the economic impacts of environmental changes, such as those related to climate change, is more developed (Borgomeo et al., 2018; Elshennawy et al., 2016; Robinson et al., 2012). The economic impacts of improvements in farming productivity have been previously analysed, but the consequences for emissions alongside economic impacts remains under researched.

The objective of this study is to demonstrate how a CGE model can be used to undertake *ex ante* analysis of the potential economic and environmental impacts of full implementation of a policy targeted at raising productivity in Scotland's beef farming sector. This paper has two primary objectives, which we now specify.

First, to the best of our knowledge, this is the first system-wide analysis of the economic and emissions impacts of productivity policies targeted at the physical agricultural livestock sector.[2] Linking emissions data to sectoral fuel use and capital stocks facilitates identification of the drivers of the resulting changes in emissions. The CGE framework allows us to track the impact of productivity changes on emissions as well as on the level and composition of output. We focus on territorial emissions from production since these form national emissions targets.

Second, we quantify the possible impacts on the Scottish economy of an increase in productivity in the red meat sector from the implementation of a specific policy programme—the "Beef Efficiency Scheme" (BES). Improving farming methods has been identified in the latest Climate Change Plan (Scottish Government, 2020a) as key in achieving Scotland's GHG emissions targets, which since 2019 have included the target of net zero GHG emissions by 2045 (Scottish Parliament, 2019). Within the formal Climate Change Plan, there are several proposed policies to improve farming techniques (such as marketing schemes and the introduction of feed additives). In particular, for the red meat sector,

[1] This is related to, but not the same as the notion of technical inefficiency, which sets out to identify the extent to which farms are currently operating within their maximum level of production given their inputs (e.g., Bradfield et al., 2020).

[2] Some studies do exist (e.g.Silva et al., 2017; Malahyati & Masui. 2019; Kunimitsu & Nishimori, 2020) which investigate the impacts of agriculture productivity but the focus is on land-use and no specific policy.

which accounted for 12.1% of total GHG emissions in Scotland in 2014 (Scottish Government, 2020b), the Scottish Government has set out a policy to "encourage improved emissions intensity through genotyping, improving fertility, reducing animal mortality, and improving on farm management practices". Starting in 2016, the BES was designed to improve the genetic value of herds, boosting revenue per calf, improving the productivity per unit of inputs, and reducing emissions (as fewer calves are needed to produce the same volume of red meat for sale).[3]

We work from "micro-to-macro," taking evidence from the micro, i.e., farm level, impacts on productivity and use these to generate the simulations in a macroeconomic system-wide framework. Two vital questions for policymakers in the evaluation of the BES scheme then arise: first, do the interventions have the stated impact on productivity at the farm level once system-wide effects are taken into account, and second, what are the consequences for territorial emissions? A general equilibrium perspective is critical here as the productivity improvement will be expected to lower production costs, which could encourage greater consumption (including exports) and could raise the profitability of red meat production.

The paper is organised as follows. Section 2 sets out a brief theoretical framework for understanding the consequences of changes in factor (i.e., capital) productivity before discussing the literature on the economic and emissions analysis of agricultural policies, and focusing on the use of multisectoral models, including CGE. Section 3 outlines the data, the modelling framework, and the simulation we use to capture the initial micro changes in productivity in the red meat sector from the BES. Section 4 presents the aggregate and sectoral results of our simulations, including the sensitivity of our economic and emissions results to key model parameters. Section 5 discusses the findings and highlights the issues raised by our analysis for policymakers, identifies useful research areas for extending this line of inquiry and briefly concludes.

2 Literature review

We begin with a brief overview of the theory relating to the impact of an increase in capital productivity that the BES effectively targets. We then consider empirical analyses of the impact of improved farm productivity more generally.

2.1 The likely impact of an increase in the productivity of capital

The partial equilibrium analysis of the impact of a rise in the productivity of a factor of production like capital is well-established in the theory of derived demand (Hicks, 1963; Holden & Swales, 1993). The improved productivity in the production of beef reduces the effective price of a unit of capital, lowers production costs and puts downward pressure on the product price, which stimulates an increase in demand to a degree that is determined by the price elasticity of the demand for the product. The greater the elasticity of product demand the greater is the stimulus to beef production and therefore to the demand for

[3] As outlined above the BES is only at the trial stage being carried out by a small number of farms. However, in the future there is potential for the BES interventions to be implemented across Scotland. The farms currently on the scheme record high levels of micro data which can be implemented into the macro model to determine the full economic and environmental if the policy is to be extended.

both capital and labour (which are inputs into the production of value-added). However, the reduction in the effective price of capital also induces a substitution in its favour and away from labour. The greater the elasticity of substitution of labour for capital in production, the greater is this substitution effect, which further stimulates the demand for capital, but reduces the demand for labour. Overall, the impact on the demand for labour is ambiguous, depending on the relative strengths of the "value-added" and the "substitution" effects, which depend on the respective elasticities. While the value-added and substitution effects both operate to increase the demand for capital in efficiency units, the impact on the demand for physical units of capital is uncertain. If the overall elasticity of demand for capital is greater than unity then, for example, a 5% increase in capital efficiency will result in a greater than 5% increase in the demand for efficiency units of capital, so that the demand for physical units of capital increases. In contrast, if the elasticity of demand for capital is less than unity a 5% increase in capital efficiency will result in a less than 5% increase in the demand for efficiency units of capital, and the demand for physical units of capital falls. Value added is always stimulated as is the demand for capital in efficiency units, but there is ambiguity around the impacts on the demand for physical units of capital and labour.

In a general equilibrium multisectoral context where firms combine value-added and intermediate purchases from other firms to produce gross output, matters are a little more complicated. In particular, there will be a stimulus to the demand for the output of those sectors that supply intermediates to the red meat sector. Also, the tendency for prices to fall in the red meat sector reduces the costs of those firms that use its output as inputs implying an additional, supply-side stimulus to aggregate output. Furthermore, where wages are determined in real terms (as, for example, is implied by the presence of a wage curve—see below) the stimulus could be further reinforced by downward pressure on nominal wages. Of course, these wider effects will depend on the size of the red meat sector and the strength of its linkages with other sectors.

Greenhouse gas emissions are, in this case, linked to physical units of capital, as well as to fuel use.[4] The unambiguous stimulus to output (and value added) generated by the increase in capital productivity in the beef sector generates an increase in emissions through increased fuel use. However, if the demand for physical capital in the red meat sector falls, there will be a countervailing reduction in emissions. If this effect is sufficiently strong it is possible that there may be a simultaneous rise in output and fall in emissions, as suggested in the title of this paper. The overall impact on emissions is clearly an empirical issue, which depends upon the values of key demand and substitution elasticities.

2.2 Empirical analyses of the agricultural sector

The link between agricultural production and emissions has been well documented in recent years. As noted above, part of this has been a growing focus on dietary changes, i.e. changes to food consumption levels or patterns towards lower emissions diets. A particular focus has been placed on red meat consumption, which declined in the UK by 30% between 2008 and 2017 (Public Health England & Food Standards Agency, 2019), with several studies noting that there could be both positive individual (improved health) and societal (reduced GHG emissions) outcomes. Macdiarmid et al. (2012) develops a diet for adult woman based on food commonly available in the UK which could simultaneously improve health outcomes while reducing GHG emissions from the food system by up to

[4] Emissions are also related to land use but due to data constraints these are not included in our analysis.

32%. Tom et al. (2016) finds, perhaps counter-intuitively, that diets that reduce calorific intake to recommended levels and have a shift towards greater vegetables are associated with higher GHG emissions, as they have higher resource use on a per-calorie basis. Several other papers note the link between improved health outcomes coupled with the environmental benefit of a lower calorie diet. For instance, Yip et al. (2013) and Ivanova et al. (2020) analyse the possible contribution to emissions reduction from changes in food consumption, in particular a switch to a vegan diet.

At the same time, there has been increasing interest in sustainable farming techniques which might improve efficiency. For the red meat sector, Salter (2017) indicates two main approaches in sustainable beef farming such as improved feeding nutrition and selective breeding. Hayes et al. (2013) notes that the continued increase in population and wealth will increase demand for livestock products such as red meat. The authors review a range of selective breeding techniques (such as genomic selection) noting that these have the potential to improve (i.e., reduce) the emissions intensity of farms while increasing production efficiency. Mayberry et al. (2019) identifies and analyses a wide range of possible methods which the Australian red meat sector could implement to reduce carbon emissions, including improving livestock feeding. They note that there is the potential for the Australian red meat sector to be carbon neutral, but that this would require significant policy support as well as substantial private and public investment.

In much of the literature to date, the objectives of a reduction in consumption or shifts to more productive farming methods have exclusively been environmental or health-related, with little attention paid to the economy-wide impacts of such changes or the policies that could bring about such an outcome. This is beginning to change, however, and there is a growing use of modelling approaches. Their multi-sectoral structure means that they are particularly useful for energy-economy-environment analysis since they can capture the significant variation in energy use and carbon emissions among industries. This also facilitates a focus on the impact of any particular sector, including agriculture, in a system-wide context. Allan et al. (2019) use Input–Output (IO) analysis to find that reduced consumption of red meat and a move to a diet reflecting healthy eating guidelines has the potential to not only reduce emissions but also stimulate the economy. However, this result depends crucially on how previous spending on meat is switched to other products.

Computable General Equilibrium (CGE) models provide a detailed description of the economy which captures the key interlinkages between the private sector, households, government, trade and the labour market. Duarte et al. (2016) use a CGE model of Spain to consider the global emissions impacts of changes in consumption patterns from policies aimed at reducing environmental impacts, including a shift to a healthier diet. They find that the results of their scenario for improved dietary choices depend on how households use their additional incomes, a result echoed in Allan et al. (2019). There are a small number of studies which have sought to address these wider economic impacts of agricultural productivity policies using CGE models. Komarek et al. (2019) link micro-level estimates of the increases in maize and wheat yields to "climate smart agriculture" policies being implemented at the farm level, with a CGE analysis to capture the economy-wide impacts. They found that these have the potential to deliver positive economic gains and to reduce poverty, to an extent that exceeds those impacts from more "active" (and costly) policies like using fertiliser or extending irrigation. More closely related to our own study, Jensen et al. (2012) looks at the farm level and the macroeconomic impacts of implementing precision farming technologies and controlled traffic farming on four types of crops in Denmark. They find increased economic activity, a rise in Gross Domestic Product (GDP) of

€34.4 million, at the same time as positive environmental impacts from reductions in the use of pesticides and fertilisers.

As noted above, emissions in the agriculture sector can be related to land use and several studies focus on the system-wide impacts of changes in land-use in the agriculture sector. Malahyati and Masui (2019) use a CGE framework to investigate the impacts of land-use mitigation efforts to reduce emission in Indonesia, finding that that costly mitigation efforts can reduce emissions. Kunimitsu and Nishimori (2020) focuses on the impact of land-use mitigation measures to reduce emissions from rice fields in Japan using a multi-region CGE framework, with the results indicating that such measures can reduce emissions but will increase rice costs throughout Japan. Silva et al. (2017) analyses the economic impacts of a policy of productivity gains in Brazilian livestock, particularly related to land-use, through the use of a multi-region CGE. They find that an increase in agriculture land-use productivity may be counterproductive as the reduction in price increases consumption and thus emissions. Our paper differs as we focus on the physical capital of livestock instead of land use.

3 CGE model, the inclusion of emissions and simulation strategy

In this paper, we use "micro" evidence on the changes in farm-level production following the introduction of the Beef Efficiency Scheme and introduce a shock consistent with the full implementation of this across Scotland's red meat sector into our CGE model. We set out the simulation strategy and calculation of the shock in Sect. 3.1. The sectoral and aggregate economic and environmental impacts are captured by the use of a CGE model for Scotland with a disaggregated red meat production sector for 2014[5] extended to incorporate sectoral GHG emissions. In Sect. 3.2, we describe the CGE model, while the linking of economic and GHG emissions data is discussed in Sect. 3.3.

3.1 Simulation strategy—micro to macro

We scale micro (i.e., farm level) information on the productivity gains associated with the implementation of the Beef Efficiency Scheme (BES) to measure the potential macroeconomic and emissions impacts of implementing the BES across all eligible farms in Scotland. As previously outlined, the red meat sector was responsible for 12.1% of Scotland's total territorial GHG emissions in 2014, the majority of which are from the production of beef. The current level of demand for beef necessitates large suckler cow herds[6] which not only require significant land use, but the livestock produces large quantities of methane gas, which has an climate change impact 25 times greater than CO_2 over a 100-year period (US Environmental Protection Agency, 2020).

The BES approach uses whole-life data for individual animals to significantly improve management practices. The concept of the BES is to feed and breed cows in such a manner that they are able to "first calve" in a shorter period of time, meaning fewer cows are needed for the herd to maintain the same level of output. While BES is currently within the initial 5-year trial period, if successful, it could be rolled out across Scotland. Through

[5] Full details on the disaggregation method and the Input Output database used can be found in Sect. 3.1 of Allan et al. (2019).

[6] In Scotland 430,000 beef herd calves were born in 2017.

correspondence with the Scottish Government, we were provided with micro-level data on the effectiveness of the BES which we scale as a shock into the CGE model. In the base year there were 566,000[7] calves registered in Scotland, 136,500 of which were dairy calves leaving 429,500 live beef calves. In total, accounting for the natural barren rate, there are 477,000 beef herd females in Scotland. With annual herd replacement rate of 15% in the base year there is 71,500 beef heifers to calve for the first time, 35% (25,000) under the age of 27 months. Farm-level microdata from the Scottish Government suggested that with a BES feasible adoption date of 70% an additional 22,500 extra calves from heifers under 27 months can be added to the beef stock, amounting to a 5% increase in total stock. With the modelling the assumption is that the same level of output will be produced with a smaller herd. There is, of course, the potential for "rebound" effects which we discuss in the results section.

Calves however are only one component of capital in the red meat sector, which also includes machinery, building and other farm animals (such as pigs and sheep). As such a 5% increase in the productivity of the beef herd does not correspond to a 5% increase in capital productivity in the red meat sector. The BES improvement in productivity is thus "scaled" to account for the relative value of the beef herd compared with total capital stock in the red meat sector. Using the Farm Business Survey (Scottish Government, 2019) and information made available by the Scottish Government, we calculated that—if rolled out across all eligible beef farms in Scotland[8]—the BES would increase capital productivity in the red meat sector by 3.41%,[9] which is the "disturbance" introduced to our CGE model.

3.2 CGE model

Computable general equilibrium (CGE) models provide a detailed description of the economy which capture the key interlinkages between the private sector, households, government, international trade and the labour market. They combine current economic data with a complex system of equations to give a comprehensive picture of the structure and operation of the economy. These models are extremely useful for simulating the impact of policy on the economy and are used extensively by governments and think-tanks internationally to assess the merits of alternative policy choices.

In this paper we use a version of the CGE modelling framework AMOS, calibrated on a 30 sector Social Accounting Matrix (SAM) for Scotland for 2014 with a disaggregated red meat sector to explore the impact of the BES improvement in productivity.[10] In addition to the 30 sectors/commodities within the model there are three internal institutions—households, firms and governments—and two external institutions —the rest of the UK (RUK) and the rest of the world (ROW). Scotland is treated as a small open economy so that RUK

[7] Rounded to the nearest 100.

[8] We assume a costless policy, with Scottish Government expenditure coming from the reallocation of spending in other parts of the agriculture sector.

[9] From the Total Income From Farming (TIFF) survey (Scottish Government, 2018), the total capital value of cattle in Scotland was £119.6 million with £73.3 million related to red meat (with the remaining cattle attributed to dairy production). Total red meat capital, which includes sheep and pigs, amounts to £111.4 million thus beef cattle represents 65.9% of all red meat capital. An increase of 5% in cattle efficiency corresponds to an overall increase in capital productivity in the red meat sector of 3.41% (i.e., 5%*65.9%).

[10] The list of these 30 sectors can be found in Appendix 1. The SAM is based on the Scottish Government's input–output tables, augmented by supplementary data on incomes and expenditures.

and ROW variables are treated as exogenous.[11] Commodity markets are assumed to be competitive. Financial flows are not explicitly modelled, and the interest rate is assumed to be exogenous.[12]

This AMOS framework has been used in a number of applications (e.g., Allan et al., 2014; Figus et al., 2018) and allows for a degree of flexibility in choice of model closures and parameters. The version of the model for this paper is a myopic specification in which agents have adaptive expectations.[13] Fundamentally, the model assumes that producers minimise cost using a nested multilevel production function. The combination of intermediate inputs with RUK and ROW inputs is based on the Armington function (Armington, 1969). Gross output is produced from a combination of intermediates and value added, where labour and capital combine in a constant elasticity of substitution (CES) function to produce value added, allowing for substitution between these factors in response to relative price changes, i.e.:

$$Y_{j,t} = \left(\alpha [EK]_{j,t} K_{j,t}^{\frac{\sigma-1}{\sigma}} + \beta [EL]_{j,t} L_{j,t}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (1)$$

where $Y_{j,t}$ is the value added of a sector j at time t and K and L are the stocks of labour and capital respectively. σ is the elasticity of substitution between labour and capital, with α the capital share parameter and β the labour share parameter ($\beta = 1 - \alpha$). EK and EL are the efficiency parameters for capital and labour, which are both equal to unity in the initial equilibrium. When we improve productivity in the simulations later, we do so by increasing the value of EK in the relevant sectoral production function (to 1.0341). This also directly reduces effective capital costs in the corresponding cost function and so the price of sector j's value-added and output is directly impacted.

There are four components of final demand in the model, namely household consumption, investment, government expenditure, and exports. Household consumption is assumed to be a linear function of real disposable income. Government expenditure in the model is held constant, while exports are determined by an Armington function (Armington, 1969) thus are dependent on relative prices.

While the model can be run in a dynamic mode, with periods interpreted as years as both the SAM and behavioural relationships are benchmarked using annual data, here we focus primarily on long-run equilibria in which both capital stocks and population are optimally adjusted. The model is initially assumed to be in steady-state equilibrium, implying that with no exogenous disturbances, the model simply replicates the initial value over all subsequent time periods. Capital stocks are fixed in the short run, but subsequently each sector's capital stock is updated through investment, set as a fraction of the gap between the desired and actual (adjusted for depreciation) level of capital stock—in line with the Jorgenson (1963) neoclassical investment formulation. In the long-run, equilibrium investment is equal to depreciation.

A single labour market with perfect sector mobility is imposed on the model, and it is assumed that wages are subject to a bargaining function in which the bargained real wave varies inversely with the unemployment rate, given by:

[11] Scotland contributes less than 10% of the UK economy of any metric.

[12] At run time the model solves a large set of non-linear simultaneous equations that ensure all commodity markets clear simultaneously.

[13] As we are only concerned later with the long-run results, we note that the role of expectations does not change the long-run equilibrium (e.g., Lecca et al., 2013).

$$ln\frac{w^s}{cpi^s} = c - \varepsilon ln(u^s) \tag{2}$$

where w^S is the net of tax nominal wage in Scotland, cpi^S the Consumer Price Index, u^S is the Scottish unemployment rate, c is a calibration parameter and ε is wage rate elasticity set to 0.113.

Labour force changes in the model are completely attributed to migration as there is no assumed change in natural population. Migration in the model is determined by the real wage and unemployment rate differential between Scotland and the rest of the UK. We assume zero net migration in the base year (2014) and net migration flows re-establish this equilibrium.

The migration function is given by:

$$m = v - \varepsilon^u \left[ln(u^s) - ln(u^r)\right] + \varepsilon^w \left[ln\left(\frac{w^s}{cpi^s}\right) - ln\left(\frac{w^r}{cpi^r}\right)\right] \tag{3}$$

where v is a calibration parameter to generate net zero migration in the base year and u the unemployment rate with the S and R superscripts standing for Scotland and the Rest of the UK, respectively. ε^u and ε^w are elasticities which measure the differences in logs between regional and national unemployment and real wage rates and set to 0.06 and 0.08 respectively.

3.3 Economic and emissions data

As outlined previously, the single agriculture sector in the Scottish IO table was disaggregated to include a separate red meat production sector, which is the focus of this study. The disaggregation follows the method outlined in Moxey (2016), while the disaggregation used to split the agriculture sector into red meat production (MET) and other agriculture (AGR) is given in full in the Appendix of Allan et al. (2019).

In this paper, the AMOS framework described above has been extended to incorporate sectoral GHG emissions in such a way that the emissions consequences of economic changes can be tracked.[14] A common method used in determining changes in emissions uses sectoral GHG-intensity coefficients (Pascual-González et al., 2016), which are typically the GHG emissions per monetary unit of sectoral output. Where the results of an economic modelling framework give the change in sectoral output, the analyst would link the new size of each sector with the original "emissions coefficients" to report absolute and proportionate changes in sectoral GHG emissions. While this method is a widely used, its critical—and unrealistic—assumption is that these emissions coefficients remain fixed irrespective of the scale of the sector or its fuel use.

Economic changes are likely to alter these GHG coefficients due to the adoption of different production technologies (i.e., changes in the input mix to each sector in line with changes in relative prices), different processes and fuel uses. We therefore incorporate

[14] GHG emissions refer to emissions from the seven Kyoto Agreement gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen triflouride (NF_3).

emissions via a "fuel use" and capital stock methodology.[15] Sectoral GHG emissions from fuel are calculated from physical fossil fuel use (coal, oil, gas), with changes in fuel consumption tracked in the AMOS model and used to determine sectoral emission changes.[16]

Emissions in the MET sector are linked to two elements. First, as in other sectors, we link GHG emissions to fuel use. Red meat is not separately identified in the fuel use database, instead we estimate the red meat sector's fuel use based on the proportion of output of the non-disaggregated agriculture sector. Second, non-fuel related GHG emissions are based on the Scottish Greenhouse Gas Inventory with changes tracked through sectoral capital stock.

Base year (2014) capital stock emissions in the MET sector (red meat production) are taken directly from the Scottish greenhouse gas inventory (Scottish Government, 2020b). This process of assigning capital stock emissions, in addition to fuel use, could be adapted to other sectors of the economy (such as forestry), but this is outwith the scope of this paper. Therefore, in all sectors, with the exception of the MET sector, the emissions from production vary only with changes in the relative use of fossil fuels, while emissions in the MET sector will include both those from fossil fuel use and changes in the levels of capital stock.

4 Results

We begin by looking at the impacts of the improvement in capital productivity in the Red meat production sector on the sector itself (Sect. 4.1) before looking at the aggregate impacts on economic and emissions variables (Sect. 4.2) and then the sectoral impacts (Sect. 4.3). At each stage, we show the model results as well as adding further details on the mechanisms through which these arise with reference to the underlying specification and adjustment within our simulation framework. We also test the sensitivity of our results to specific parameter values in Sect. 4.4 by repeating the analysis with alternative values.

4.1 Impacts in the red meat sector

In Table 1 we isolate the impacts of the BES on the red meat sector in Scotland.

The table reports the changes in the long-run relative to the baseline economy. With the introduction of the improvement in capital productivity in the MET sector, sectoral output price in the long-run reduces by 0.83%, which increases the competitiveness of the red meat sector in both domestic and international markets. With the reduction in the red meat sector's output price, there is an increase in household consumption of 0.25% coupled with a reduction in imports of 1.42%. The price reduction also leads to an increase in exports of 1.68% as Scottish red meat becomes more competitive. This increase in domestic household consumption and exports leads to a significant increase in value added amounting to

[15] Note that since we do not allocate emissions from land use change, international aviation and shipping and from private transport, our base year emissions correspond to 89.58% of inventory emissions in the base year CO2e emissions for Scotland in 2014.

[16] For more details see Allan et al. (2018).

Table 1 Long-run impacts of improved capital productivity associated with BES on the Red meat production sector (percentage changes from base). *Source*: Authors' calculations based on model simulations

Variable	% change (unless otherwise stated)
Value added	1.798
Value added (£m)	14.12
Employment	1.018
Employment (FTE*)	216
Output price	− 0.831
Investment	− 1.321
Capital stock	− 1.321
Households consumption	0.255
Total import	− 1.424
Total export	1.683
Emissions	1.321
Emissions (M KG)	− 57.24

*Full time employment

£14.12 million and a stimulus to employment of 216 on a full-time equivalent (FTE) basis. Notice that the fall in the relative price of capital makes production more capital intensive, as we expected from our earlier discussion. (Employment does increase in this case, but by less (1.02%) than capital in efficiency units (i.e., 2.09% = 3.41% minus 1.32%)).

Although we have improved the productivity of capital in the MET sector, the consequences for the level of capital employed in this sector in the long-run are ambiguous (as discussed in Sect. 2 above). On one hand, the now more productive capital implies that the same output could be produced for a lower level of capital input. However, cost minimising producers are induced to substitute towards the now effectively cheaper capital input (and away from labour in the production of value-added), and the expansion of value-added also stimulates the demand for capital in efficiency units. Any tendency for capital demand to decline is at least partially offset by these changes induced by the fall in the effective price of capital. This recalls the "rebound" debate where improvements in energy efficiency can lead to less than proportional reductions in energy use. The use of the CGE model is perfectly suited to capturing the quantitative outcome for the whole system of such targeted improvements in productivity. In the simulation we model a 3.41% increase in capital productivity in the MET sector, while in the long-run the level of capital in the MET sector falls by only 1.32%; the demand for capital (in efficiency units) is relatively price inelastic in the long-run; the demand for capital in efficiency units rises less than in proportion to the reduction in its price.

4.2 Aggregate results

Table 2 shows the aggregate economic and environmental impacts of the fully implemented BES scheme under our central assumptions for parameter values and the adoption rate. A number of points can be highlighted. First, we find that the overall economic impacts—changes in the long run relative to the base year—are modest. We see that, for the base case of a 70% adoption rate (estimated by the Scottish Government), the total (annual) impact on GDP is 0.028% above the base year, equivalent to an absolute increase of £33.70 million, and a 0.024% or a 538 increase in employment on a full-time equivalent (FTE) basis. This small aggregate impact is somewhat expected given that the output of the red meat sector (MET) is only 0.16% of total Scottish economic output. Second, the increase in capital productivity in the MET sector does slightly reduce consumer prices and the nominal wage, and so has the properties of a supply-side stimulus to the economy, which reinforces the demand stimulus to those sectors that supply inputs to the beef sector, as expected from our discussion of the relevant theory. The reduction in prices (measured by the Consumer Price Index) also increases the competitiveness of Scotland's exports (compared with RUK and ROW), thus the total amount of exports increases (by 0.027%). This increase in aggregate consumption, investment and exports increases economic activity, in terms of both the level of GDP and employment. If we sum the discounted annual impacts of the first 50 periods following the intervention, we see a total cumulative impact on GDP in Present Value (PV) terms of £880.21 million.

On impact, the stimulus to competitiveness increases the demand for labour putting slight upward pressure on real wages and downward pressure on the unemployment rate. However, in-migration moderates this response. We also find decreases in emissions of −0.135%, or 50.79 Mkg. There is a fall in emissions in the MET sector itself, however we find an increase in emissions in both the AGR sector and (summed) across the rest of the economy. These increases in emissions outside the MET sector, reflecting the general

Table 2 Long-run economic and emission changes; percentage differences from base, unless otherwise stated. *Source*: Authors calculations based on model simulations

Variable	%percentage change (unless otherwise stated)
GDP	0.028
GDP (£million)	33.70
Consumer price index	−0.011
Unemployment rate	0.000
Employment (FTE)	538
Employment	0.024
Nominal gross wage	−0.011
Real gross wage	0.000
Labour supply	0.016
Investment	0.004
Capital stock	0.004
Household consumption	0.008
Total exports	0.027
Percentage% change in emissions	−0.135
Absolute change in emissions in millions of KG, CO2 equivalent (M KG, CO2e)	−50.79
Absolute change in MET emissions (total, (M KG, CO2e)	−57.24
Of which change in MET emissions from capital (M KG, CO2e)	−63.28
Of which change in MET emissions from fuel (M KG, CO2e)	6.03
Absolute change in AGR emissions (M KG, CO2e)	1.76
Absolute change in all other sector emissions (M KG, CO2e)	4.69
Absolute PV of GDP change (£million)	880.21

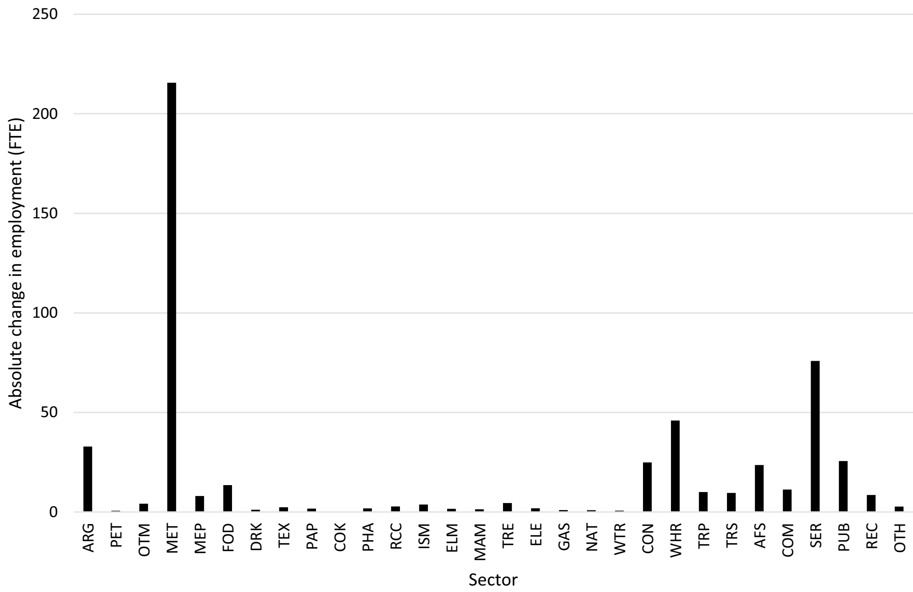

Fig. 1 Long-run employment impacts of BES by sector, absolute changes

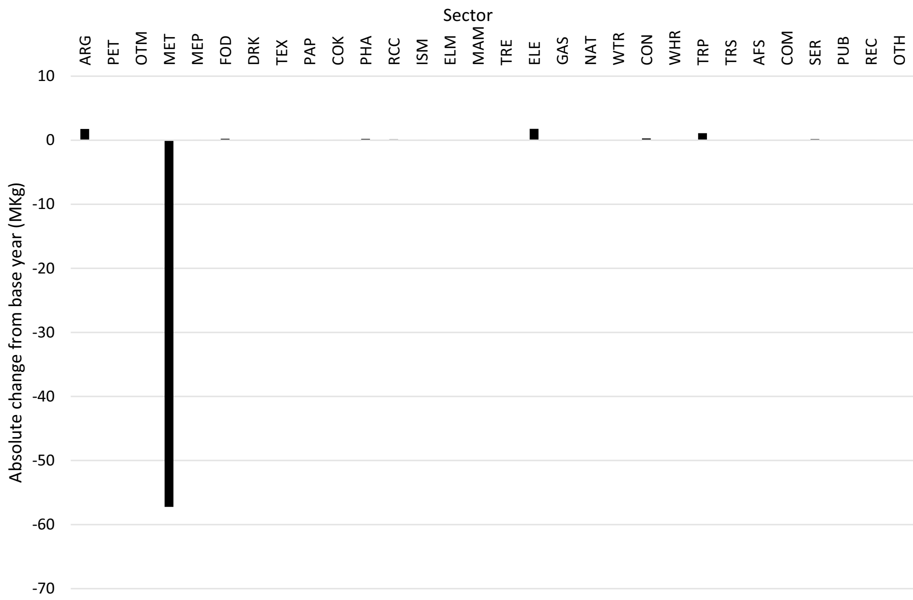

Fig. 2 Long-run emissions impacts of BES by sector, absolute changes

expansion in output there, are not sufficient to offset the reduction in emissions in that sector due to the fall in the capital stock. As we noted in our earlier discussion the change in emissions reflects the net effect of two counteracting processes. First, with the reduction in

Table 3 Long-run economic and emission changes: sensitivity to scale of adoption, % differences from base unless stated. *Source*: Authors calculations based on model simulations

	Adoption rate						
	40%	50%	60%	70%	80%	90%	100%
GDP	0.004	0.012	0.020	0.028	0.036	0.043	0.051
GDP (£Million)	4.88	14.58	24.18	33.70	43.13	52.47	61.73
Employment (FTE)	78	233	387	538	689	837	985
Employment	0.004	0.011	0.018	0.024	0.031	0.038	0.045
Capital stock	0.001	0.002	0.003	0.004	0.005	0.006	0.008
Change in MET emissions (MKG)	−8.31	−24.80	−41.11	−57.24	−73.20	−88.99	−104.61
Change in AGR emissions (MKG)	0.26	0.76	1.27	1.76	2.26	2.75	3.23
Change in all other sector emissions (MKG)	0.68	2.03	3.37	4.69	5.99	7.29	8.57
Net change in emissions (MKG)	−7.38	−22.01	−36.48	−50.79	−64.95	−78.95	−92.81
Net change in emissions	−0.020	−0.058	−0.097	−0.135	−0.172	−0.210	−0.246
NPV GVA (£million)	127	381	632	880	1127	1371	1613

cattle needed to produce the same level of output, there is a reduction in capital stock and so lower emissions from this source, while, as with other sectors, there is a tendency for emissions to increase due to the stimulus to economic activity and so to the demands for capital (in other sectors) and fuel.

In summary, we find that the economic and environmental impacts of the improvement in productivity of the BES would be wholly positive—with an increase in GDP and employment coupled with a simultaneous reduction in GHG emissions—indicating the 'double-dividend' of increased economic activity while simultaneously reducing emissions. While the reduction in emissions seems small, despite red meat accounting for a large proportion of overall Scottish emissions, this reflects the fact that the BES only increases overall red meat efficiency by 3.41%.

4.3 Impacts across all sectors

Figures 1 and 2 show the long-run employment and emissions impacts by sector. In absolute terms, although the increase in employment in the MET sector dominates other individual sectors, it only accounts for an increase of 216 FTE jobs, out of the aggregate total of 538; making clear that the majority of the employment effects happen outside of the directly affected MET sector. For employment, in absolute terms, the five sectors with the largest changes outside of the MET sector are: SER (76), WHR (46), AGR (33) and PUB (26). In terms of emissions, the overall decline is wholly attributable to the MET sector; emissions in all other sectors tend to increase, reflecting the higher level of economic activity.

4.4 Sensitivity analysis

Here, we explore the sensitivity of our results to three key elements. The first is the extent of uptake amongst relevant Scottish farms. Second, we explore the sensitivity to the extent to which capital and labour are substitutable in production within the MET sector and the third element in our sensitivity analysis is the response of exports to changes in relative prices.

4.4.1 Sensitivity to the degree of adoption

In our central simulation, we have assumed a 70% adoption of the BES intervention across all appropriate farms, in line with Scottish Government estimates. We would expect that a larger (smaller) uptake would lead to larger (smaller) impacts (i.e., more (less) positive or negative effects on the variables set out in Table 2). What is unclear is the extent to which the size of effects would be related to the degree of adoption.

First, note that the central scenario adopted above is shown in the column that refers to a 70% adoption rate in Table 3. We can see that there is a broadly linear impact on headline aggregate results from increasing the level of uptake across potential adopters. Each 10% increase in the share of Scottish beef farms which adopt the intervention leads to a roughly £9.5 million increase in GDP in the long run (this reduces slightly to an increase of £9.26 million between 90 and 100% adoption). The impacts on employment and net emissions also show a slightly diminishing—but positive—increase with higher adoption rates.

4.4.2 Sensitivity to capital-labour substitution parameter

Recall from our earlier discussion that the greater the elasticity of substitution, the greater will be the stimulus to the demand for capital and the smaller the stimulus to the demand for labour. As noted above, we have assumed a base elasticity of substitution of 0.3, which allows a degree of substitution towards the now more productive factor input (whose relative price has effectively fallen). We have seen some substitution of capital for labour, with the lower than proportional decrease in capital stock in the MET sector. We can vary the elasticity of substitution between capital and labour in the MET sector. In the limit, it can be lowered to zero, mirroring the Leontief case where substitution between inputs is not possible. As the elasticity approaches unity, the production function becomes Cobb–Douglas. As the substitution elasticity increases, this increases the overall elasticity of the demand for capital to the reduction in its effective price, and so we would expect a bigger stimulus to capital, a smaller fall in emissions and a smaller increase (or even decrease) in employment.

Changing the assumed elasticity of substitution between capital and labour in the production function for output in the MET sector has interesting impacts. From Table 4, we can see that there is only a very modest impact on GDP: the difference in the expansion of GDP between the highest and lowest value for this elasticity is only £0.2 million.

The impacts on capital, and especially employment and emissions, are more marked, however. As expected, greater substitutability between capital and labour (a higher substitution elasticity) results in more movement away from labour and a bigger increase in the demand for capital in efficiency units in the MET sector. The greater use of capital in efficiency units in the MET sector reduces the scale of the fall in capital stock and emissions in that sector; the demand for capital in efficiency units in MET still falls throughout, but by less as the elasticity of substitution rises. However, the aggregate capital stock increases slightly in response to the small increases in activity and production becomes more capital-intensive reflecting substitution against labour. There are only small impacts on emissions outside of the sector or the total change in Scottish emissions, in part due to the small

Table 4 Long-run economic and emission changes: sensitivity to elasticity of substitution between capital and labour, % differences unless stated. *Source*: Authors' calculations based on model simulations

	Capital-labour substitution parameter								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
GDP	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
GDP (£Million)	33.75	33.73	33.70	33.68	33.65	33.63	33.60	33.58	33.55
Employment (FTE)	649	594	538	483	428	373	318	263	209
Employment	0.029	0.027	0.024	0.022	0.019	0.017	0.014	0.012	0.009
Capital Stock	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.009
Change in MET emissions (MKG)	−64.81	−61.02	−57.24	−53.47	−49.70	−45.94	−42.19	−38.45	−34.71
Change in AGR emissions (MKG)	1.76	1.76	1.76	1.77	1.77	1.77	1.78	1.78	1.79
Change in all other sector emissions (MKG)	4.71	4.70	4.69	4.67	4.66	4.65	4.64	4.63	4.62
Net change in emissions (MKG)	−58.34	−54.56	−50.79	−47.03	−43.27	−39.52	−35.78	−32.04	−28.31
Net change in emissions	−0.155	−0.145	−0.135	−0.125	−0.115	−0.105	−0.095	−0.085	−0.075
NPV GVA (£million)	888	884	880	878	877	876	876	876	876

Table 5 Long-run economic and emission changes: sensitivity to Armington trade elasticity, % differences unless stated. *Source*: Authors' calculations

	Export elasticity							
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
GDP	0.021	0.028	0.035	0.042	0.050	0.057	0.064	0.072
GDP (£Million)	25.03	33.70	42.43	51.22	60.07	68.97	77.94	86.96
Employment (FTE)	359	538	719	901	1085	1269	1455	1642
Employment	0.011	0.024	0.022	0.027	0.033	0.038	0.044	0.049
Capital stock	−0.005	0.004	0.014	0.023	0.033	0.043	0.053	0.062
Change in MET emissions (MKG)	−75.30	−57.24	−39.05	−20.74	−2.30	16.28	34.98	53.81
Change in AGR emissions (MKG)	1.23	1.76	2.30	2.83	3.38	3.92	4.47	5.02
Change in all other sector emissions (MKG)	3.12	4.69	6.26	7.85	9.45	11.05	12.67	14.30
Net change in emissions (MKG)	−70.95	−50.79	−30.49	−10.06	10.53	31.25	52.12	73.13
Net change in emissions	−0.188	−0.135	−0.081	−0.027	0.028	0.083	0.138	0.194
NPV GVA (£million)	687	880	1054	1211	1353	14807	1596	1700

contribution of the targeted sector to total emissions, but also because there is very little impact on economic activity. Overall, the elasticity of substitution between capital and labour provides an important determinant of the scale of emissions savings but has little impact on the economic benefits associated with the improvement in efficiency in the MET sector.

4.4.3 Sensitivity to Armington trade elasticities

Relative price changes depend on the values of the Armington parameters that effectively govern the elasticity of the demand for the product within the model, which our earlier discussion emphasised, and this has a significant effect on the impact of the productivity stimulus. Increasing (reducing) the elasticity makes exports more (less) responsive to changes in relative prices, and so generates a larger (smaller) increase in exports for any given change in relative prices. In the main scenario described in Sect. 4.1, the Armington parameter is set at 2.0 for all sectors. We would expect that when this parameter is increased, the initial reduction in consumer prices in the MET sector would serve to increase sectoral exports and boost the economic impact. This, in turn, is expected to increase emissions due to fuel use in all sectors. Furthermore, the demand for capital in efficiency units within MET will be further stimulated (so that the fall in physical capital in the sector will be reduced and possibly offset). This, together with the stimulus to other sectors, tends to increase net overall emissions.

We show the impact of alternative values for the trade elasticities in Table 5. Each column reflects the different values of the Armington elasticities. In each sensitivity simulation, all sectors have this parameter set to the value at the head of each column. We can see that this strongly impacts the economic and emissions findings. Changing this parameter to a value of 5.0 produces an impact on GDP which is almost three times greater than the central scenario, while we see a similar increase in the boost to employment. As expected, these larger economic outcomes come from a larger increase in exports (which increases in aggregate by 0.070% in the case when the export elasticity is set to 5). The demand for capital in efficiency units increases with the elasticity and when it is raised beyond 3.5, the demand for capital in physical units also increases within MET; the percentage increase in the demand for capital in efficiency units now exceeds the percentage increase in capital efficiency.

Along with the more positive economic impacts, we also see that higher emissions are associated with higher elasticities, reflecting generally higher fuel use and increases in the physical capital stock. Indeed, we find raised emissions relative to the base values in all non-agricultural sectors, as well as the AGR sector when the elasticity of export demand is raised. As noted above, emissions in the MET sector—from both fuel use and capital stock—increase relative to their base values when the parameter value is 4.0 or above. This serves to emphasise that the combination of increased economic activity alongside emissions reduction depends on the economic response induced by the improvement in farming productivity.

4.5 Discussion

Our results show that the sector-specific productivity improvements can generate economy-wide economic as well as environmental impacts. Several further points should be noted as relevant for extending this analysis and exploring the emission consequences of productivity changes in agriculture. First, we have assumed a linear relationship between the size of uptake and the disturbance introduced. In practice, it is possible that the benefits of the scheme could vary by farm size, for example. Second, we have modelled productivity benefits which persist into the long-term. It is possible that a smaller productivity improvement may be justified if the outcome of the scheme was a lower genetic diversity in the animal herd. De Roest et al. (2018) writes convincingly of the role that economic specialism within Agriculture could play in reducing the resilience of farms to economic disturbances.

Third, the importance of the role of agriculture in providing livelihoods in rural areas, in particular, is critical for the spatial distribution of economic activity across many countries. Extensions to show the spatial distribution of impacts across the regions of Scotland would therefore be useful. It may be that governments support agriculture precisely because of this important aspect of its activities, which will be different across countries.

Fourth, we have shown that in the case of a full roll-out of the BES to all potential adopters in Scotland, emissions fall by 0.246%, based on our default parameter values. With emissions from the red meat sector responsible for 12.1% of total Scottish GHG emissions, this productivity policy alone would not deliver significant reductions in emissions. Our analysis shows, however, that policies aimed at boosting agricultural productivity can bring about positive economic gains alongside reductions in emissions both at the sectoral and national level and could be a valuable element of the overall portfolio of policies to reduce emissions. A wide range of possible on-farm interventions to reduce emissions from the supply chain for beef and dairy farming in the US, are set out in Vargas et al. (2024). However these do omit the potential emissions and economic impacts within the sector as well as across the wider economy, but which could be explored further through the approach we adopt here.

5 Conclusions

The emissions impact of agriculture is significant and needs to be reduced significantly in order to support nations' progress towards emissions reduction targets. Meeting these will necessitate profound changes in the types of diets which are consumed across the world, as well as changes in the way in which food is produced. Policies to bring about these outcomes will need to support not only the move towards lowering emissions, but also consider the economic impacts of such policies, given agriculture's role in supporting livelihoods across the world. From our review of the literature, we identify that policies targeting improvements in agricultural productivity are increasingly being developed. However, as far as we know, there is only limited analysis of the system-wide impacts of such policies on emissions outcomes (in addition to the more studied economic impacts).

In this paper, we apply a "micro to macro" modelling approach to explore the consequences of the Scottish Government's Beef Efficiency Scheme (BES), an intervention targeted at delivering greater productivity in beef farming practices in Scotland. Using an appropriately sectorally disaggregated Computable General Equilibrium model, which we extend to incorporate emissions from fuel use and (critically) capital stock in the red meat production sector, we have demonstrated the potential system-wide consequences of this intervention on aggregate as well as sectoral indicators of GDP, employment, and emissions.

We find that there is an unambiguous economic boost to the BES intervention. Under our central assumptions about the uptake of the scheme, long run GDP is boosted by £33.7 million, and employment rises by 538 FTEs. There are simultaneously beneficial impacts on emissions, which fall by 0.135%, or 50.79 M KG in absolute terms.[17] We have shown that the effect on employment differs across sectors and while the red meat (MET) sector sees the largest single increase in output and employment, the majority of the employment increase is outside of the directly targeted MET sector. Importantly, our analysis implies that any evaluation of agricultural policies, such as the BES, should adopt a wider perspective that considers impacts beyond the immediate agricultural activities on which they are targeted.

Appendix 1: Sectoral aggregation

Sector number	Name	Abbreviation	SIC codes (2007)
1	Agriculture	AGR	(Part of) 1+2–4
2	Oil	PET	6–8
3	Mining	OTM	5,9
4	Red meat production	MET	(Part of) 1
5	Meat processing	MEP	10.1
6	Food and drink	FOD	10.2–10.9, 11.07, 12
7	Alcohol	DRK	11.01–11.06

[17] These results relate to our central scenario. In general, this result depends on the price elasticity of demand for exports; high elasticities could stimulate demand for efficiency units of capital in the MET sector to the point where emissions actually increase (Table 5).

Sector number	Name	Abbreviation	SIC codes (2007)
8	Textile, leather and wood	TEX	14–16
9	Paper and printing	PAP	17–18
10	Coal	COK	19-20B
11	Chemicals and pharmaceuticals	PHA	20.3–21
12	Rubber, cement and glass	RCC	22–23.6
13	Iron, steel and metal	ISM	24.1–25
14	Electrical manufacturing	ELM	25–26
15	Manufacturing of motor vehicles	MAM	28–30
16	Other manufacturing	TRE	31–33
17	Electricity	ELE	35.1
18	Gas	GAS	35.2
19	Water	NAT	36–37
20	Water and waste management	WTR	38–39
21	Construction	CON	41–43
22	Wholesale and retail	WHR	45–47
23	Transport	TRS	49.1–51
24	Transport support	TRSP	52–53
25	Accommodation and food services	AFS	55–56
26	Communications	COM	58–61
27	Services	SER	62–84
28	Education, health and defence	PUB	85–88
29	Recreational	REC	90–94
30	Other services	OTH	95–97

Source: Authors' calculations

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Data availability The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article. The authors have no relevant financial or non-financial interests to disclose. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

References

Allan, G., Connolly, K., Ross, A., & McGregor, P. (2018). *Incorporating CO_2 emissions into macroeconomic models through primary energy use.* Accessed December 3, 2024, https://www.strath.ac.uk/media/1newwebsite/departmentsubject/economics/research/researchdiscussionpapers/18-18.pdf.

Allan, G., Comerford, D., & McGregor, P. (2019). The system-wide impact of healthy eating: Assessing emissions and economic impacts at the regional level. *Food Policy, 86*, 101725. https://doi.org/10.1016/j.foodpol.2019.05.008

Allan, G., Lecca, P., McGregor, P., & Swales, K. (2014). The economic and environmental impact of a carbon tax for Scotland: A computable general equilibrium analysis. *Ecological Economics, 100*, 40–50. https://doi.org/10.1016/j.ecolecon.2014.01.012

Alston, J., & Pardey, P. G. (2014). Agriculture in the global economy. *Journal of Economic Perspectives, 28*(1), 121–146. https://doi.org/10.1257/jep.28.1.121

Armington, P. S. (1969). A theory of demand for products distinguished by place of production. *Staff Papers, 16*(1), 159–178. https://doi.org/10.2307/3866403

Arndt, C., Pauw, K., & Thurlow, J. (2016). The economy-wide impacts and risks of Malawi's farm input subsidy program. *American Journal of Agricultural Economics, 98*(3), 962–980. https://doi.org/10.1093/ajae/aav048

Arneth, A., Denton, F., Agus, F., Elbehri, A., Erb, K., Osman, B., Rahimi, M., Rounsevell, M., Spence, A., Debonne, N., Valentini, R. (2019). Climate change and land: an ipcc special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems: Chapter 1: Framing and context. In *Intergovernmental Panel on Climate Change*. Accessed December 3, 2024. https://www.ipcc.ch/srccl/chapter/chapter-1/.

Borgomeo, E., Vadheim, B., Woldeyes, F. B., Alamirew, T., Tamru, S., Charles, K. J., Kebede, S., & Walker, O. (2018). The distributional and multi-sectoral impacts of rainfall shocks: Evidence from computable general equilibrium modelling for the Awash basin, Ethiopia. *Ecological Economics, 146*, 621–632. https://doi.org/10.1016/j.ecolecon.2017.11.038

Bradfield, T., Butler, R., Dillon, E., Hennessy, T., & Kilgarriff, P. (2020). The effect of land fragmentation on the technical inefficiency of dairy farms. *Journal of Agricultural Economics, 72*(2), 486–499. https://doi.org/10.1111/1477-9552.12413

De Roest, K., Ferrari, P., & Knickel, K. (2018). Specialisation and economies of scale or diversification and economies of scope? Assessing different agricultural development pathways. *Journal of Rural Studies, 59*, 222–231. https://doi.org/10.1016/j.jrurstud.2017.04.013

Duarte, R., Feng, K., Hubacek, K., Sánchez-Chóliz, J., Sarasa, C., & Sun, L. (2016). Modeling the carbon consequences of pro-environmental consumer behavior. *Applied Energy, 184*, 1207–1216. https://doi.org/10.1016/j.apenergy.2015.09.101

Elshennawy, A., Robinson, S., & Willenbockel, D. (2016). Climate change and economic growth: An intertemporal general equilibrium analysis for Egypt. *Economic Modelling, 52*, 681–689. https://doi.org/10.1016/j.econmod.2015.10.008

Figus, G., Lisenkova, K., McGregor, P., Roy, G., & Swales, K. (2018). The long-term economic implications of Brexit for Scotland: An interregional analysis. *Papers in Regional Science, 97*(1), 91–115. https://doi.org/10.1111/pirs.12349

Gonçalves da Silva, J., Ruviaro, C. F., de Souza, B., & Ferreira Filho, J. (2017). Livestock intensification as a climate policy: Lessons from the Brazilian case. *Land Use Policy, 62*, 232–245. https://doi.org/10.1016/j.landusepol.2016.12.02

Green, R., Milner, J., Dangour, A. D., Haines, A., Chalabi, Z., Markandya, A., Spadaro, J., & Wilkinson, P. (2015). The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. *Climatic Change, 129*(1–2), 253–265. https://doi.org/10.1007/s10584-015-1329-y

Hayes, B. J., Lewin, H. A., & Goddard, M. E. (2013). The future of livestock breeding: Genomic selection for efficiency, reduced emissions intensity, and adaptation. *Trends in Genetics, 29*(4), 206–214. https://doi.org/10.1016/j.tig.2012.11.009

Hicks, J. R. (1963). *The theory of wages* (2nd ed.). MacMillan.

Holden, D., & Swales, J. K. (1993). Factor subsidies, employment generation and cost per job: A partial equilibrium approach. *Environment and Planning A, 25*(3), 317–338. https://doi.org/10.1068/a250317

Ivanova, D., Barrett, J., Wiedenhofer, D., Macura, B., Callaghan, M., & Creutzig, F. (2020). Quantifying the potential for climate change mitigation of consumption options. *Environmental Research Letters, 15*(9), 093001. https://doi.org/10.1088/1748-9326/ab8589

Jensen, H. G., Jacobsen, L.-B., Pedersen, S. M., & Tavella, E. (2012). Socioeconomic impact of widespread adoption of precision farming and controlled traffic systems in Denmark. *Precision Agriculture, 13*(6), 661–677. https://doi.org/10.1007/s11119-012-9276-3

Jorgenson, D. W. (1963). Capital theory and investment behavior. *The American Economic Review, 53*(2), 247–259.
Komarek, A. M., Thurlow, J., Koo, J., & De Pinto, A. (2019). Economy wide effects of climate-smart agriculture in Ethiopia. *Agricultural Economics, 50*(6), 765–778. https://doi.org/10.1111/agec.12523
Kunimitsu, Y., & Nishimori, M. (2020). Policy measures to promote mid-summer drainage in paddy fields for a reduction in methane gas emissions: the application of a dynamic, spatial computable general equilibrium model. *Paddy and Water Environment, 18*, 211–222. https://doi.org/10.1007/s10333-019-00775-6
Lecca, P., McGregor, P. G., & Swales, J. K. (2013). Forward-looking and myopic regional computable general equilibrium models: How significant is the distinction? *Economic Modelling, 31*, 160–176. https://doi.org/10.1016/j.econmod.2012.11.010
Macdiarmid, J. I., Kyle, J., Horgan, G. W., Loe, J., Fyfe, C., Johnstone, A., & McNeill, G. (2012). Sustainable diets for the future: Can we contribute to reducing greenhouse gas emissions by eating a healthy diet? *The American Journal of Clinical Nutrition, 96*(3), 632–639. https://doi.org/10.3945/ajcn.112.038729
Malahayati, M., & Masui, T. (2019). The impact of green house gas mitigation policy for land use and the forestry sector in Indonesia: Applying the computable general equilibrium model. *Forest Policy and Economics, 109*, 102003. https://doi.org/10.1016/j.forpol.2019.102003
Masson-Delmotte, V., Zhai, P., Pörtner, H. -O., Roberts, D., Skea, J., Shukla, J., Waterfield, T. (2018). Special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In: *Intergovernmental Panel on Climate Change,* Accessed December 3, 2024. https://www.ipcc.ch/sr15/.
Mayberry, D., Bartlett, H., Moss, J., Davison, T., & Herrero, M. (2019). Pathways to carbon-neutrality for the Australian red meat sector. *Agricultural Systems, 175*, 13–21. https://doi.org/10.1016/j.agsy.2019.05.009
Montaud, J.-M., Pecastaing, N., & Tankari, M. (2017). Potential socio-economic implications of future climate change and variability for Nigerian agriculture: A countrywide dynamic CGE-microsimulation analysis. *Economic Modelling, 63*, 128–142. https://doi.org/10.1016/j.econmod.2017.02.005
Moxey, A. (2016). *An assessment of the economic contribution of Scotland's red meat supply chain*. Accessed December 3, 2024. https://www.qmscotland.co.uk/sites/default/files/economic-contribution-of-scotlands-red-meat-supply-chain.pdf.
Pascual-González, J., Jiménez-Esteller, L., Guillén-Gosálbez, G., Siirola, J. J., & Grossmann, I. E. (2016). Macro-economic multi-objective input–output model for minimizing CO_2 emissions: Application to the U.S. economy. *AIChE Journal, 62*(10), 3639–3656. https://doi.org/10.1002/aic.15376
Public Health England and Food Standards Agency. (2019). *National diet and nutrition survey: Years 1 to 9 of the rolling programme (2008/2009 – 2016/2017): Time trend and income analyses*. Accessed December 3, 2024. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/772434/NDNS_UK_Y1-9_report.pdf.
Robinson, S., Willenbockel, D., & Strzepek, K. (2012). A dynamic general equilibrium analysis of adaptation to climate change in Ethiopia. *Review of Development Economics, 16*(3), 489–502. https://doi.org/10.1111/j.1467-9361.2012.00676.x
Salter, A. M. (2017). Improving the sustainability of global meat and milk production. *Proceedings of the Nutrition Society, 76*(1), 22–27. https://doi.org/10.1017/S0029665116000276
Scottish Government. (2018). *Total income from farming: estimates for Scotland 2015–2017.* Accessed December 3, 2024. https://www.gov.scot/publications/total-income-farming-estimates-fo-scotland-2015-2017/.
Scottish Government. (2019). *Farm Business Survey*, Accessed December 3, 2024. https://www.gov.scot/publications/farm-business-survey-2018-19-profitability-scottish-farming/.
Scottish Parliament. (2019). Climate change (emissions reduction targets) (Scotland) Act 2019, Accessed December 3, 2024. https://www.legislation.gov.uk/asp/2019/15/contents/enacted.
Scottish Government. (2020a). *Climate change plan: third report on proposals and policies 2018–2032 (RPP3)*, Accessed December 3, 2024. https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/pages/13//.
Scottish Government. (2020b). *Greenhouse gas emissions 2018: estimates,* Accessed December 3, 2024. https://www.gov.scot/publications/scottish-greenhouse-gas-emissions-2018/.
Seconda, L., Baudry, J., Allès, B., Boizot-Szantai, C., Soler, L. G., Galan, P., Hercberg, S., Langevin, B., Lairon, D., Pointereau, P., & Kesse-Guyot, E. (2018). Comparing nutritional, economic, and environmental performances of diets according to their levels of greenhouse gas emissions. *Climatic Change, 148*(1–2), 155–172. https://doi.org/10.1007/s10584-018-2195-1

Tom, M. S., Fischbeck, P. S., & Hendrickson, C. T. (2016). Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary recommendations in the US. *Environment Systems and Decisions, 36*(1), 92–103. https://doi.org/10.1007/s10669-015-9577-y

US Environmental Protection Agency. (2020). *Overview of greenhouse gases,* Accessed December 3, 2024. https://www.epa.gov/ghgemissions/overview-greenhouse-gases#methane.

Vargas, J. J., Menezes, T. C., Auvermann, B., Derner, J. D., Thoma, G., Hales, K., Johnson, K., Leytem, A. B., Place, S. E., Plaut, J., & Ritten, J. (2024). Net zero initiative in US beef and dairy systems: integrative on-farm recommendations for greenhouse gas reduction. *Environmental Research Communications, 6*(10), 101010.

Vieux, F., Darmon, N., Touazi, D., & Soler, L. G. (2012). Greenhouse gas emissions of self-selected individual diets in France: Changing the diet structure or consuming less? *Ecological Economics, 75*, 91–101. https://doi.org/10.1016/j.ecolecon.2012.01.003

Warr, P., & Suphannachart, W. (2020). Agricultural productivity growth and poverty reduction: Evidence from Thailand. *Journal of Agricultural Economics*. https://doi.org/10.1111/1477-9552.12412

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F. N., Herold, M., Gerber, P., Carter, S., Reisinger, A., & Van Vuuren, D. P. (2016). Reducing emissions from agriculture to meet the 2 °C target. *Global Change Biology, 22*(12), 3859–3864. https://doi.org/10.1111/gcb.13340

Yip, C. S. C., Crane, G., & Karnon, J. (2013). Systematic review of reducing population meat consumption to reduce greenhouse gas emissions and obtain health benefits: Effectiveness and models assessments. *International Journal of Public Health, 58*(5), 683–693. https://doi.org/10.1007/s00038-013-0484-z