Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences
Department of Economics

WORKING PAPER 03/2020

Cost effective reduction in emissions of greenhouse gases - fuel and food consumption and negative emissions in Sweden

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Swedish University of Agricultural Sciences,
Department of Economics, Uppsala
ISSN 1401-4068
ISRN SLU-EKON-WPS-1305-SE

Working Paper Series 2020:03

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Abstract: Reduction in emissions of green house gases (GHG) from consumption of fuel and food and implementation of negative emissions, such as forest carbon sequestration and carbon capture and storage, have been suggested in practice and literature. One challenge is the uncertainty in reductions of GHG depending on e.g stochastic weather conditions. This paper calculates cost effective combinations of the emission reductions in fuel and food and creation of negative emissions in Sweden under uncertainty by using probabilistic constraint modelling. The results show that the cost of emission reductions in fuel and food consumption are relatively expensive and carbon sequestration by forest management and conversion of arable land are low cost measures. It is also shown that the regional welfare effects at the county level are regressive, i.e. that relatively poor counties carry a large cost burden in cost effective solutions.

Key words: GHG emissions, cost-effectiveness, meat consumption, carbon sequestration, transports, uncertainty, Sweden
JEL codes: Q28, Q25, H23

Introduction

Mitigation of climate change impacts by reducing emissions from the transport sector has been suggested in the literature and implemented in practice in many countries (e.g. Sterner and Coria 2012). Voices have also been raised to reduce GHG emissions by reducing the consumption of meat and dairy products (e.g. UNEP, 2009; Säll and Gren 2015). However, several studies have shown that the price elasticity of food demand is low which implies that large price increases are needed in order to obtain a certain emission reduction. The cost of GHG reductions in terms of reductions in consumer surplus can then be high. However, this is also the case for reductions in GHG from transports, for which policies are implemented in several countries. Emission reductions from decreases in consumption of food would contribute to cost effective achievement of targets including fuel and food. Another option is the possibility of negative emissions, i.e. the reduction of the concentration of carbon dioxide in the atmosphere. In principle, this can be made by ecological engineering measures by increasing the carbon sequestration on forest and arable land and by man-made technologies which include carbon capture methods (e.g. van Vuuren et al., 2013).

However, most of these measures are associated with uncertain impact on GHG emission from a unit change in e.g. consumption or land use. In a risk averse society, such uncertainty is costly and a unit GHG emission reduction from these measures should then not be equalized with a unit emission reduction from fossil fuel combustion. The purpose of this study is to calculate the cost effective combination of reductions in fuel and food consumption and the creation of negative GHG emissions when the impact on emission is uncertain. To this end, we use chance-constrained programming, which has a long tradition in economics (e.g. Tesler 1955). Emission reduction targets are then formulated in terms of probabilistic target where a certain emission reduction is to be achieved at a minimum probability level. The study is applied to Sweden.

There is a large body of literature on the calculation of costs for reductions in fuel consumption and negative emissions (e.g. van Kooten et al. 2009; Gren et al. 2012), but there are few studies on costs of reducing GHG emissions under uncertainty (e.g. Gren et al. 2012) and from food consumption. Similarly, despite the large and old literature on price elasticity of fuel (see reviews in Dahl 2012 and Aklilu 2020), there are very few studies on the estimation of costs of emission reduction from this sector. To the best of our knowledge, there is no study estimating and comparing costs for these three classes of measures; reductions in consumption of fuel, food and creation of negative emissions.

A simplification in this study is the use of marginal abatement cost (MAC) approach where costs are calculated only for the direct impact of the emission reduction, such as the cost of reducing beef consumption and increasing carbon sequestration from land use change. Unlike the large body of literature on costs of climate mitigation, we do not consider the dispersal of impacts in the rest of the economy and associated responses (see Babatunde et al. 2017 for a review). This relatively simple approach has been used in several studies calculating costs of GHG emission reduction (e.g. Gren et al. 2012; Sotiriou et al. 2019). In this study, the advantages of the simplicity is that is allow for the consideration of uncertainty in a chance-constrained framework.

The study is organised as follows. The theoretical model is presented in Section 2, data retrieval is described in Section 3, and the results are presented in Section 4. The study ends with a discussion and conclusions.

2. The model

In each county, c, there are three classes of abatement measures; reductions in consumption of fuel for transports, food, and the creation of negative emissions. There are $f=1,..,n$ different options in food consumption, $t=1,...,m$ in the transport sector, and $k=1,..,o$ measures with negative emissions. For example, consumption of fuel is reduced by decreasing diesel and gasoline, food consumption by reductions in e.g. beef and cream, and negative emissions include measures in forests, agriculture, and carbon capture and storage (CCS). Without any abatement measures, or under business-as-usual (BAU) conditions, the total emission amounts to G^{BAU}. Total emission, G, including uncertain abatement from each of the classes of measures is then written as:

$$G = \sum_c (G^{cBAU} - \sum_t A^{ct} - \sum_f A^{cf} - \sum_k A^{ck}) \qquad (1)$$

where A^{ct}, A^{cf}, and A^{ck} are the abatements which are uncertain with mean μ^{ct}, μ^{cf} μ^{ck} and the variances σ^{ct}, σ^{cf}, and σ^{ck} .

Emission targets are imposed on total emissions *G* and uncertainty in reading the target because of uncertain abatement is accounted for by applying the safety-first decision framework, which has a long tradition in economics (e.g. Tesler 1955). This means that a decision-maker has to decide on the minimum probability, α, at which the target should be achieved. The probabilistic reduction target is written as:

$$prob(G \le \overline{G}) \ge \alpha \tag{2}$$

Chance-constrained programming is used to solve the cost-minimization problem with a probabilistic constraint (Taha, 1976). Equation (2) is then transformed into a deterministic equivalent by normalizing the expression within parentheses at the left hand side of (2) according to:

$$prob\left[\frac{G-\mu}{(\sigma)^{1/2}} \le \frac{\overline{G}-\mu}{(\sigma)^{1/2}}\right] \ge \alpha \tag{3}$$

where μ is the average total emission, $\sigma = Var(G)$ and the term $\frac{G-\mu}{(\sigma)^{1/2}}$ shows the number of standard deviations at the chosen probability, ϕ^{α}, that *G* deviates from the mean. By the choice of α, there is a level of acceptable deviation, ϕ^{α}, and the expression within brackets in equation (3) then holds only if:

$$\mu + \phi^{\alpha}(\sigma)^{1/2} \le \overline{G} \tag{4}$$

Equation (4) shows that the emission target restriction becomes tighter because of the risk discount shown by the second term on the left-hand side of the inequality sign in the equation. This means that more abatement is needed in order to ensure achievement of the target, which raises the total abatement costs. This cost of uncertainty is determined by the level of ϕ^{α} and σ.

The parameter ϕ^{α} reflects the decision-maker's risk aversion against non-attainments of the abatement targets, when ϕ^{α} >0 the decision maker is concerned about reaching the targets and

$\phi^{\alpha U}$ =0 otherwise. The level of ϕ^{α} is determined by the choice of probability of reaching the targets, α, and the probability distribution. A common approach is to assume a normal probability distribution, and ϕ^{α} is then determined where $\int_{-\infty}^{\phi^{\alpha}} f(\phi^{\alpha})d\phi^{\alpha} = \alpha$, the calculations of which can be found in students' t-tables where, for example, ϕ^{α} =1.26 when $\alpha=0.9$ (see e.g. Taha 1976).

In the numerical application in this study, simplifications are made by assuming no dependency in the variances between the abatement measures. Since data is not available on uncertainty in each of the measures at different levels of abatement, the variances are calculated based on information on coefficient of variation (CV) which is defined as the standard deviation divided by the mean in abatement for each measure. The total variance is then written as:

$$Var(G) = \sigma = \sum_c \left(\sum_t (CV^{ct} A^{ct})^2 + \sum_f (CV^{cf} A^{cfj})^2 + \sum_k (CV^{ck} A^{ck})^2 \right) \quad (5)$$

where CV^{ct}, CV^{cf}, and CV^{ck} are the coefficients of variation in the emission coefficients of different fuels, foods, and negative emission.

A cost function is associated with each measure and region, $C^{ct}(A^{ct})$, $C^{cf}(A^{cf})$, and $C^{ck}(A^{ck})$, and the planner minimizes total cost for achieving the target in eq. (4). However, each abatement measures is subject to constraints such as minimum requirements of fuel and food use, and maximum land areas suitable for forest carbon sequestration, which is written as:

$$A^{ct} \le \overline{A}^{ct}, A^{cf} \le \overline{A}^{cf} \; A^{ck} \le \overline{A}^{ck} \quad (6)$$

The decision problem is then formulated as the choice of abatement measures minimizing total cost, C, according to:

$$\underset{A^{ct}, A^{cf}, A^{ck}}{Min} \quad C = \sum_c \left(\sum_t C^{ct}(A^{ct}) + \sum_f C^{cf}(A^{cf}) + \sum_k C^{ck}(A^{ck}) \right) \quad (7)$$

The first-order conditions for a cost effective solution are;

$$\frac{\partial C}{\partial A^{ct}} = \frac{\partial C^{ct}}{\partial A^{ct}} - \lambda(\frac{\partial \mu}{\partial A^{ct}} + \frac{\theta^{\alpha}}{\sigma^{1/2}}(CV^{ct})^2 A^{ct}) + \lambda^{ct} = 0 \quad (8)$$

$$\frac{\partial C}{\partial A^{cf}} = \frac{\partial C^{cf}}{\partial A^{cf}} - \lambda(\frac{\partial \mu}{\partial A^{cf}} + \frac{\theta^{\alpha}}{\sigma^{1/2}}(CV^{cf})^2 A^{cf}) + \lambda^{cf} = 0 \quad (9)$$

$$\frac{\partial C}{\partial A^{ck}} = \frac{\partial C^{kf}}{\partial A^{ck}} - \lambda(\frac{\partial \mu}{\partial A^{ck}} + \frac{\theta^{\alpha}}{\sigma^{1/2}}(CV^{ck})^2 A^{ck}) + \lambda^{ck} = 0 \quad (10)$$

where $\lambda<0$ is the Lagrange multiplier which shows that change in total cost for a marginal change in the target, and λ^{ct}, λ^{cf}, and λ^{ck} are the Lagrange multipliers on the capacity constraint of the abatement measures. The expressions in parenthesis at the right hand side of eqs. (8)-(10) show the impact of the measure on the target. For all measures, this consists of two parts: the effect on average emissions and on the variability. The impact on expected emission is negative, which is counteracted by the positive effect on the variance.

It can be seen from eqs. (8)-(10) that the marginal costs of impacts on the target is the same and equal to - λ for all measures in the cost effective solution:

$$\frac{\frac{\partial C^{ct}}{\partial A^{ct}} + \lambda^{ct}}{(\frac{\partial \mu}{\partial A^{ct}} + \frac{\theta^{\alpha}}{\sigma^{1/2}}(CV^{ct})^2 A^{ct}} = \frac{\frac{\partial C^{cf}}{\partial A^{cf}} + \lambda^{cf}}{(\frac{\partial \mu}{\partial A^{cf}} + \frac{\theta^{\alpha}}{\sigma^{1/2}}(CV^{cf})^2 A^{cf}} = \frac{\frac{\partial C^{ck}}{\partial A^{ck}} + \lambda^{ck}}{(\frac{\partial \mu}{\partial A^{ck}} + \frac{\theta^{\alpha}}{\sigma^{1/2}}(CV^{ck})^2 A^{ck}} = \lambda \quad (11)$$

The numerator of each expression shows the marginal cost at source and the denominators show the impact on the target. A high marginal impact of a measure, i.e. high impact on the mean emissions and low on the variance, implies a cost advantage. Measures with a relatively high impact on the variance then have cost disadvantages.

3. Description of data

Costs for all abatement measures except CCS are calculated based on changes in consumer and producer surplus of the good in question. For example, changes in consumption of gasoline, beef, or supply of land for afforestation. These changes are calculated by assigning linear demand and supply functions to each of the food, fuel and negative emission items. The functions are obtained by information on price elasticities, ε^{ci}, and point estimates of the price of the good, $p^{i,2018}$, and quantity, $Q^{ci,\,2018}$,in the year 2018 where $i=f,t,k$ is fuel, food and negative emission. For all goods, the cost function is quadratic and calculated as:

$$C^{ci}(A^{ci}) = e^{ci}a^{ci}(Q^{ci,2018} - Q^{ci})^2, \text{ for } i=t,f,k \tag{12}$$

where e^{ci} are the emission coefficient per unit Q^{ci}, which are assumed to be constant, and $a^{ci} = \frac{p^{ci,2018}}{2\varepsilon^{ci}Q^{ci,2018}}$. Because of lack of data, the cost function for CCS is assigned a linear form. The cost functions for reductions in consumption of fuel and food and creation of negative emissions are presented in the following subsections together with information on data on CV^{ci}.

3.1 Costs and impacts of reductions in consumption of food and fuel

Fuel and food prices at the national level are used for all goods, since there are no county level markets with equilibrating prices. Prices on fuels and all data at the county level on quantity of and price elasticity for fuels, diesel and gasoline, are obtained from Tirkaso and Gren (2020). Regarding food items, it is shown in Gren et al. (2020) that almost 90 % of GHG emissions from food originate from consumption of beef, pork, cheese, milk products, and cream and these products are therefore included in this study. Regional data on quantities and elasticities for these food items are not available. Regional quantities of the food items are calculated by assuming that the consumption per capita is the same in all counties and corresponds to the average of Sweden calculated from Swedish Statistics (2020) . However, the data on quantities in Swedish Statistics (2020) do not report the total use of beef and pork. The data is therefore adjusted with the quantities reported in Säll and Gren (2015), who report total quantities of beef and pork in 2012, by assuming that the beef and pork sold relation between total meat and the report in Swedish Statistics are the same in 2018 as in 2012. It is assumed that the elasticities in all regions are the same and correspond to the national level elasticities, which are obtained from Säll et al. (2020). Prices are found in Gren et al. (2020). All calculated regional coefficients in the cost functions for food and fuel goods are presented in Table A2.

Uncertainty in emission reduction of each food and fuel item is measured by the coefficient of variation. Uncertainty associated with food items usually includes a life cycle perspective, but in this study, we introduce only the emissions from the production of the food which mainly includes methane and nitrous oxides. The emission of methane is relatively certain since it is related to livestock enteric fermentation, whereas the emissions from land in terms of nitrous oxides and carbon dioxides depend on weather condition which are stochastic. Sykes et al (2019) calculate mean and standard deviations in emissions of CO_2, CH_4, and N_2O from beef. The coefficient of variation in emission factors varies between these three GHGs, between 0.1 and 0.6, being lowest for enteric fermentation and highest for N_2O from fertilizers from the soil. In this paper, we use a weighted average where the emission coefficients are used as weights which gives CV= 0.07. Because of lack of data, this CV is assigned to all included food items. The corresponding CV for fuel is found in Gren et al. (2012).

With respect to emission reduction capacities, they are guided by requirements of minimum consumption of each food and fuel consumption. Since we use a static model, the adjustments are limited and we simply impose a minimum consumption level corresponding to 40 % of the consumption of each good in 2018. The total emission from fuel amounts to 19.1 million tonnes, and from food to 8.2 million tonnes, which gives a total of 27.3 million tonnes. All data are presented in Table 1.

Table 1: Consumption of food and fuel, emission coefficients, CV in emission reduction, and maximum capacity in 2018

	Thousand tonne for food and thousand m^3 for fuel, in 2018[a]	**CO_2e/tonne food and tonne CO_2/m^3 for fuel**[b]	**CV in emission coefficient**[c]	**Maximum emission reduction, mill tonne CO_2**[d]
Food:				
Beef	256	16.96	0.07	2.605
Pork	368	2.54	0.07	0.561
Cheese	190	5.85	0.07	0.663
Milk products	1005	1.25	0.07	0.753
Cream	113	4.75	0.07	0.322
Fuel:				
Gasoline	2942	2.24	0.030	3.936
Diesel	5149	2.42	0.030	10.123

[a]Table A1; [b]Gren et al. 2020 and SPBI 2020b; [c] Standard deviations in emission coefficient for beef in Sykes et al (2019) used for the food items and CV from Gren et al. (2012) for crude oil which is assumed to be the same for both fuels; [d]Minimum consumption 40 % of each fuel and food item in 2018.

3.2 Costs and effects of negative emissions

In principle, there are two main technologies for negative emissions; by nature from growing biomass and man made in terms of carbon capture and storage (CCS). In Sweden, the negative emissions from forests have increased by 20 % since 1990 from 35 to 42 million tonnes CO_2eq in 2018 (SEPA 2020). On the other hand, agriculture contributes by emissions from animal and land by approximately 7 million tonnes in tonnes, which has been quite stable since 1990. Negative emissions provided by nature can thus be created by changing land use in forestry and agriculture by converting high leaching land, such as drained peat land, to low leaching land such as grass land.

Starting with Sedjo and Solomon (1989) there is now a large body of literature on the estimation of costs for carbon sink enhancement. The rapid development of this literature has resulted in several reviews on calculations of carbon sequestration costs (e.g. Sedjo et al. 1995; van Kooten et al. 2004; Manley et al., 2005; van Kooten et al. 2009; Phan et al. 2014). Except for Manley et al. (2005) all surveys are relatively broad with respect to coverage of forest activities and regions. In principle, the literature points out three main carbon sink enhancing technologies with low costs; increase in forest rotation time, afforestation, conversion of arable land to grassland, and restoration of drained peatlands on arable land.

Despite the large literature on cost estimates, there are few studies applied on Sweden. Therefore, we include only three options for which cost estimates can be made; forest management, afforestation and restoration of drained peat land. Guo and Gong (2017) calculated supply curves for carbon sequestration by forests, Norway spruce, in Sweden in a partial equilibrium model. The curves present the supply of carbon sequestration at different prices paid for sequestration and thus show the marginal cost. Calculations are made for several time periods, 5, 15, 25 and 35 years and the supply of carbon sequestration at a given price increase for longer time periods. In this study, we use the supply curve for the 5 year period to calculate a supply elasticity which is assumed to be the same in all counties. An increase in price at the price from 51 to 142.8 euro per tonne CO_2e increases supply by approximately 60 %, which gives a supply elasticity of 0.33. The total supply at the low carbon price amounts to 4 million tonne CO_2e per year. It is assumed that this is allocated between the counties in proportion to their area of productive forest (Table A3). The coefficients in the quadratic cost function derived from the linear supply functions for each county are then evaluated at the price of 51 euro per tonne and supply of CO_2e at the county level (Table A3).

The cost of afforestation and restoration of drained peat land is calculated as the foregone profits based on the supply of arable land, which are calculated as shown in eq. (12) with point estimates of rental value of land and area of arable land and drained peatland in 2018 (Table A3) and a supply the elasticity of 0.2 (Gren et al. 2012). The estimated coefficients in the quadratic supply functions for land for afforestation and restoration of peat land are presented in Table A3.

With respect to maximum capacity, Goe and Gong (2017) report an annual maximum carbon sink enhancement of 6 mill tonne CO_2e from forest management. Given the static model, it is assumed that 33 % of this sequestration can be implemented. It is also assumed that forest are planted only on impediment land, which is defined as the agricultural land not managed during the last five years (Table A3). Restorations of drained peatland can be made only at sites where peatlands have been drained (Table A3). It is assumed that half of the impediment and drained peatlands can be used for afforestation and restoration. .

Regarding man made negative emissions, CCS, it is widely recognized as an effective mechanism in achieving climate change targets. Particularly, CCS is known for supplying low carbon heat and power, reducing carbon emission from the industry and, its capability to ease the net removal of capturing carbon dioxide (CO_2) from the atmosphere and store in the bedrock. The process of CCS involves capturing CO_2 emission before entering the atmosphere and transporting to a geological (or other) storage site where it is sequestered (McCoy and Rubin 2008; Naucler et al. 2008; Hammond et al. 2011). According to Teir et al (2010), there are 88 facilities in Sweden with emissions exceeding 0.1 million tonne CO_2/year, which provide the potential for CCS. The total emissions from these facilities corresponded to 30 % of the emissions in 2007, or 19 million tonnes.

There are costs (fixed and variable costs) at each stage of CCS processes, i.e., capture, transport, and storage process that is essential to evaluate CCS effectiveness (e.g. Bergström and Ty 2017). Carbon capture constitutes the main part of the total unit cost. Various studies estimate the cost of CCS projects in multiple sectors, including natural gas or coal-fired plants, cement factories, and other electricity generation plants. The reported unit cost of CCS shows substantial variation across studies. The variation could be associated with either considered cost component, technologies, estimation method, project location, or year of implementation. For instance, Irlam (2017) reported total cost ranging between 22 and 167 euro/tonne CO_2 (in 2018 prices). A review study by Lilliestam *et al*. (2012) indicated a range of total unit costs between 36 -77 euro/tonne CO_2 (in 2018 prices).

In this study, we will use estimates for facilities in Sweden by IVL (2011) which reported that total unit cost varied between 47 and 112 euro/tonne CO_2 (in 2018 prices). The average cost then amounts to 80 euro/tonne CO_2. By assumption of a normal probability distribution and that the range covers 95 % of possible unit costs, the standard deviation is 16, which gives a CV of 0.2. With respect to removal capacity, our static model envisages a short run perspective during which the implementation of CCS at most facilities is not possible. It is therefore simply assumed that a fraction, 15 %, of the reported emissions from the plants can be captured and stored. However, the reported emissions in 2007 amounted to 19 million tonnes, and it is likely that the emissions have been reduced. Assuming that the share of total emissions in 2018 is the same as that in 2007, gives emissions from the facilities corresponding to 15 million tonne. The assumed capacity is then 2.3 million tonnes.

All data on the effects of negative emissions and maximum capacities are displayed in Table 2.

Table 2: Effects, CV and capacities of measures increasing negative emissions

Measure	**Carbon sequestration per ha**	**CV**	**Assumed capacity, mill tonne CO_2e**
Carbon sink;			
Forest management		0.42[a]	2.05[c]
Afforestation	3.5 tonne CO_2e/ha[a]	0.42[a]	0.5
Restoration of peatland	20 tonne CO_2e/ha[b]	0.28[b]	2.2
CCS		0.27	2.3[d]

[a]Gren and Carlsson (2013); [b]SBA (2014); [c] 33% of maximum capacity from Guo and Gong (2017); [d]15% of emissions from facilities which is assumed to have the same share in 2007 (Tier et al. 2011) and 2018

4. Results

As discussed in the foregoing section, there is no specific emission target for emissions from the consumption of food, but only for the transport sector. Minimum costs are therefore calculated for different levels of reductions in total emissions which ranges between 0 and 70

% of calculated total emissions in 2018. Calculated total emissions from the consumption of fuels amounted to 19052 ktonnes in 2018 based on the consumption of fuels and emission coefficients (SPBI, 2020). This estimate includes all sales of the fuels in Sweden, which can be used for both domestic and foreign transport and is thus higher than the reported emission of approximately 16500 ktonnes from domestic transports in 2018, which correspond to almost half of the total territorial emissions in Sweden (SEPA 2020). Calculated emissions from consumption of the included food products based on the quantities and emission coefficients presented in Table 1 amount to 8186 ktonnes CO_2e. This is lower than the emissions from consumption of the same food items calculated by Säll and Gren (2015) since secondary emissions from transports etc. of the inputs in production of the food are not included. Total calculated emissions thus amounts to 27.2 mill tonnes CO_2e, and it can be noticed from Table 2 that approximately 25 % or 7.1 mill tonnes of this emissions can be reduced by increases in carbon sink.

4.1 Marginal costs

As a first test of the cost effective allocation of emission reductions and negative emission, we calculated the marginal costs at different levels for each class of measure (Figure 1).

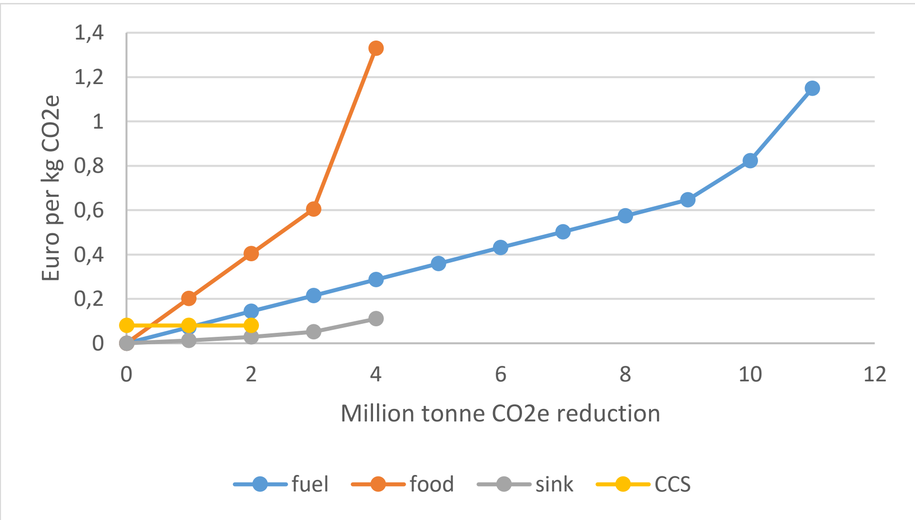

Figure 1: Marginal costs of emission reductions in fuel and food consumption and negative emissions

The marginal cost curves in Figure 1 demonstrate considerable differences in marginal costs and reduction capacities. Carbon sequestration has the lowest and reduction in emissions from food consumption the highest marginal cost at all reduction levels. As expected, emission reductions in fuel consumption show the highest reduction capacity because of the relatively large BAU emissions.

It can be interesting to examine the necessary tax for achieving the Swedish target of a 70 % reduction in 2010 emissions to be obtained in 2030. Emissions decreased by almost 20 % between 2010 and 2018, and expected impacts of implemented policies will generate further reductions so the necessary reduction from the calculated emissions in 2018 are then 58 % (Tirkaso and Gren 2020). The marginal cost at this reduction level, and hence the necessary CO_2 tax, is approximately 9 euro/kg CO_2. The introduction of such a tax would increase the price of diesel and gasoline in 2018 by approximately 140 %. However, the increases in CO_2e taxes on food would generate larger increases in prices. For example, the marginal cost at a reduction in food consumption by 4 million tonnes, or 50 %, amounts to 1.33 euro/kg CO_2e . If such a tax is introduced on beef, the price in 2018 would increase from 12 to 34.6 euro/kg beef. The price increase on pork would be lower because of the smaller emission coefficients and, from 9.5 to 12.9 euro/kg pork.

It can also be of interest to examine the effects of introducing the current Swedish tax of 0.115 euro/kg CO_2 emission on food consumption and carbon sequestration. It is already levied on fuel consumption. The introduction of the tax on food consumption would reduce the emissions by approximately 0.7 million tonnes, or 9 % of the emissions from food consumption. The effect on negative emissions would be considerably higher if the tax was introduced and, hence, becomes a subsidy. It would then be profitable for society to implement all carbon sink and CCS measures corresponding to 6 million tonne negative emissions.

However, the consideration of uncertainty affects marginal costs in particular for carbon sequestration because of the relatively large uncertainty (Figure A1). The marginal costs of carbon sequestration is then slightly higher than the marginal cost of reductions in fuel emissions at 3 million reduction in CO_2e. The introduction of the Swedish carbon tax would still generate approximately 6 million tonne negative emissions.

4.2 Cost effective solutions

The total costs for different emission reduction levels under different assumptions of inclusion of carbon sink measures and uncertainty are displayed in Figure 2. In the uncertainty case, it is assumed that the probability of reaching the target is 0.9.

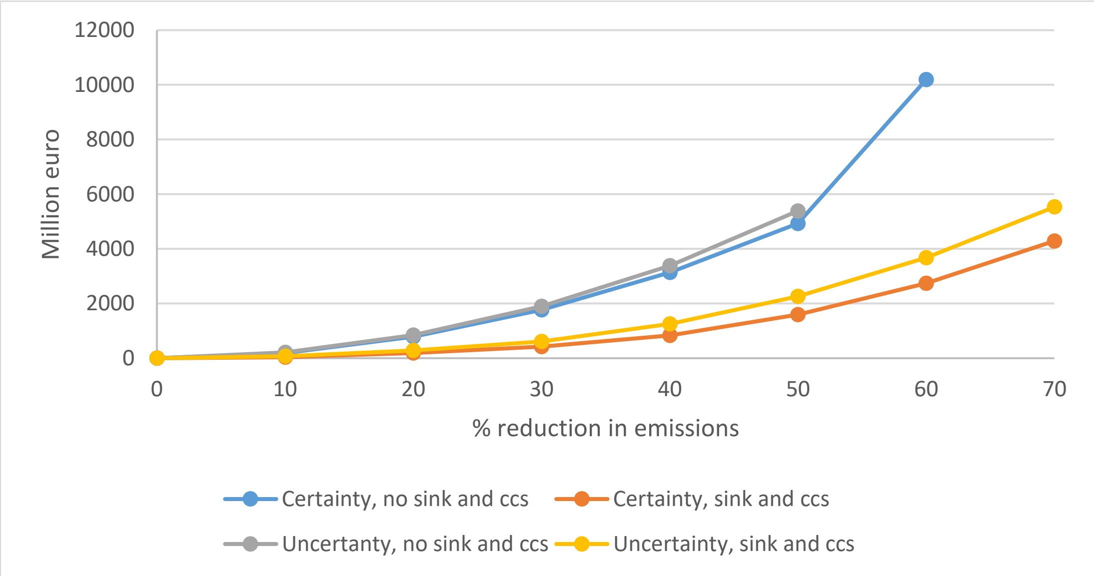

Figure 2: Minimum costs for reaching different reductions in total emissions from food and fuel with and without uncertainty and negative emissions, prob=0.9

As expected, the costs are increasing at an increasing rate for all combinations of carbon sink and uncertainty cases. Without a carbon sink measure, the maximum reduction capacity is 60 % because of the constraints on minimum food and fuel consumption in all counties. The costs are lower at all reduction levels when carbon sink is introduced, and can correspond to less than half of the cost for the same reduction level when only emissions from fuel and food are reduced. The cost increases when uncertainty is included, relatively more when carbon sink is introduced then when it is not included. The reason is the relatively larger uncertainty in carbon sink enhancement than in emission reductions.

The marginal cost at different reduction levels under alternative combinations of negative emissions and uncertainty shows a similar pattern as total cost (Figure 3). Marginal cost for the 60 % reduction without negative emissions and uncertainty is not displayed since it exceeds 8 euro/kg CO_2e and would make it difficult to discern the marginal cost in all other cases.

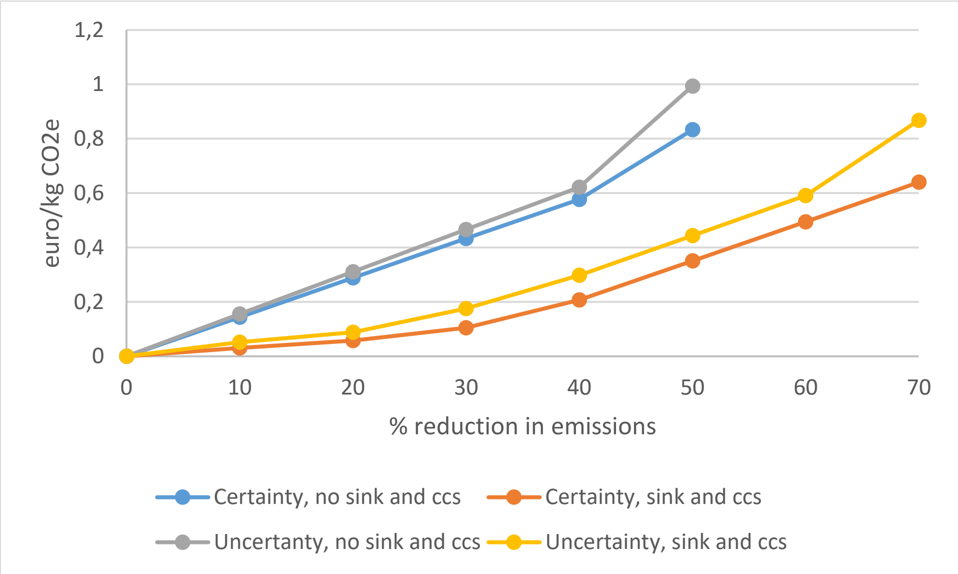

Figure 3: Marginal costs for reaching different reductions in total CO_2 emissions from food and fuel with and without uncertainty and negative emissions, prob=0.9 under uncertainty

The introduction of the Swedish CO_2 tax would result in a maximum of 30 % reduction, which occurs without uncertainty and inclusion of negative emissions. When uncertainty is considered the reduction is 25 %. There are small differences in effects without negative emissions with and without uncertainty, a reduction by approximately 5 % would be obtained in both cases. The marginal cost curves also show the necessary taxes on CO_2 under the different schemes for reaching a certain reduction level. For example, a reduction by 30 % requires a tax of 0.175 euro/kg CO_2 with negative emissions and no uncertainty, which increases at the most to 0.466 euro/kg CO_2 emission when uncertainty is considered but negative emissions excluded.

Despite the higher uncertainty in carbon sink measures, the cost effective allocation of emissions reductions implies relatively much use of this measure compared with emission reduction until the maximum carbon sink enhancement is reached (Figure 4).

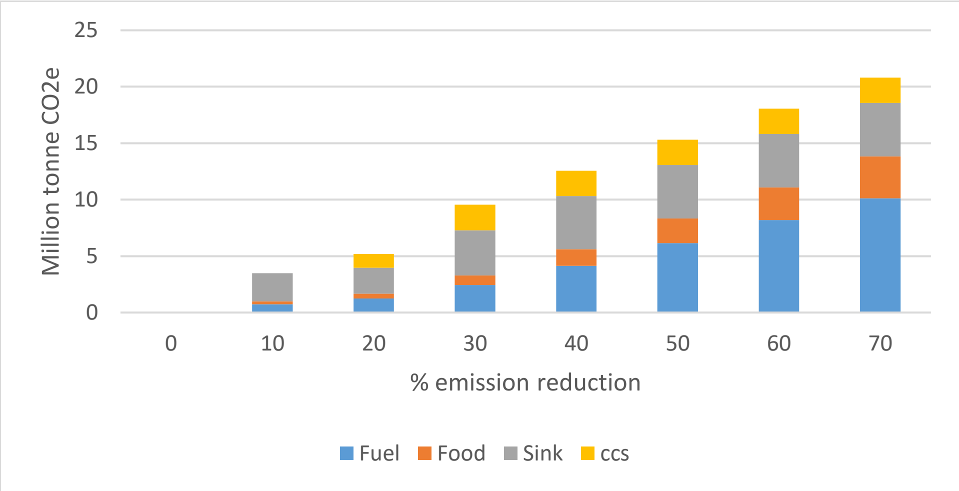

Figure 4: Cost-effective allocation of emission reduction between fuel and food and negative emissions under uncertainty with prob=0.9.

The share of negative emissions is decreasing at high total emission reductions because of the assumed maximum sequestration capacity. The share of total reduction of carbon sequestration and reductions in emissions from food consumption are almost the same at the 70 % reduction level and amount to 0.22. Reductions in emissions from fuels as a share of total reduction varies between 0.21 and 0.55.

However, the total cost varies, not only between different reduction levels, but also between different reliability levels for a given reduction level. This is show for an overall reduction of 50 % with and without carbon sequestration in Figure 5. The 50 % reduction level is chosen since higher levels would hit the maximum reduction capacity in the uncertainty case when negative emissions are not included.

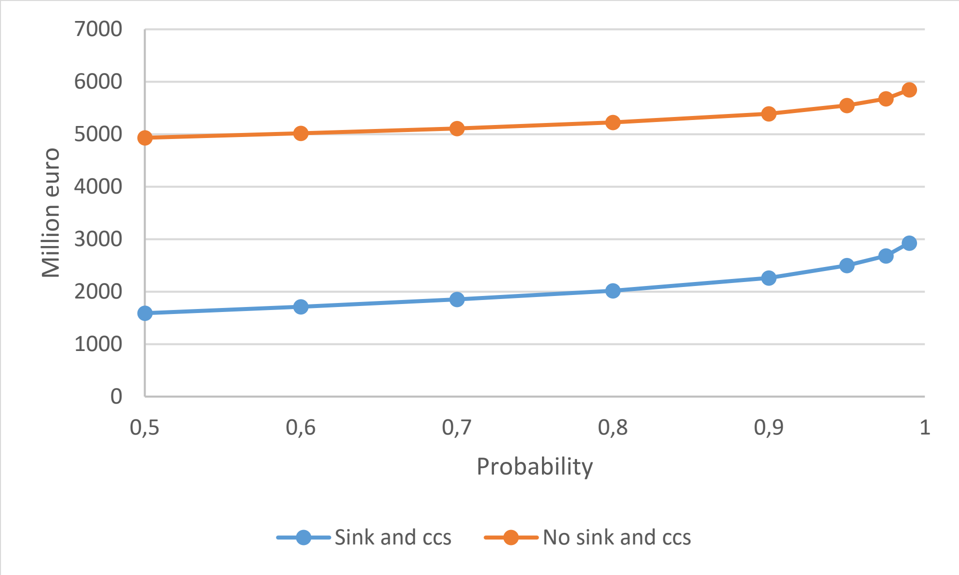

Figure 5: Minimum cost of reduction in total emissions by 50 % at different reliability levels with and without negative emissions.

The increase in costs at different reliability levels is largest when carbon sequestration and CCS are included, where the cost almost doubles when moving from prob=0.5 to prob=0.99. The corresponding increase in costs without negative emissions is lower, 20 %, because of the lower uncertainty in fuel and food emission reductions. The difference in costs with and without negative emissions then decreases at high reliability levels. At the low reliability level, costs decrease by 67 % when including negative emissions whereas the cost decrease is 49% at the highest reliability level.

4.3 Regional effects

There are 21 counties in Sweden (Figure A2), which differ with respect to emissions from fuel and food, and the availability of negative emissions. While the prosperous counties with relatively high population density show large emissions from fuel and food consumption, counties with less population density provide the largest capacities for negative emissions. Forests and facilities for negative emissions are located in northern Sweden, and carbon sink enhancement on agricultural land can be made mainly in the south and mid regions. In order to examine the allocation of costs among counties, we relate the costs for a 50 % overall emission reduction to the gross regional product (GRP).

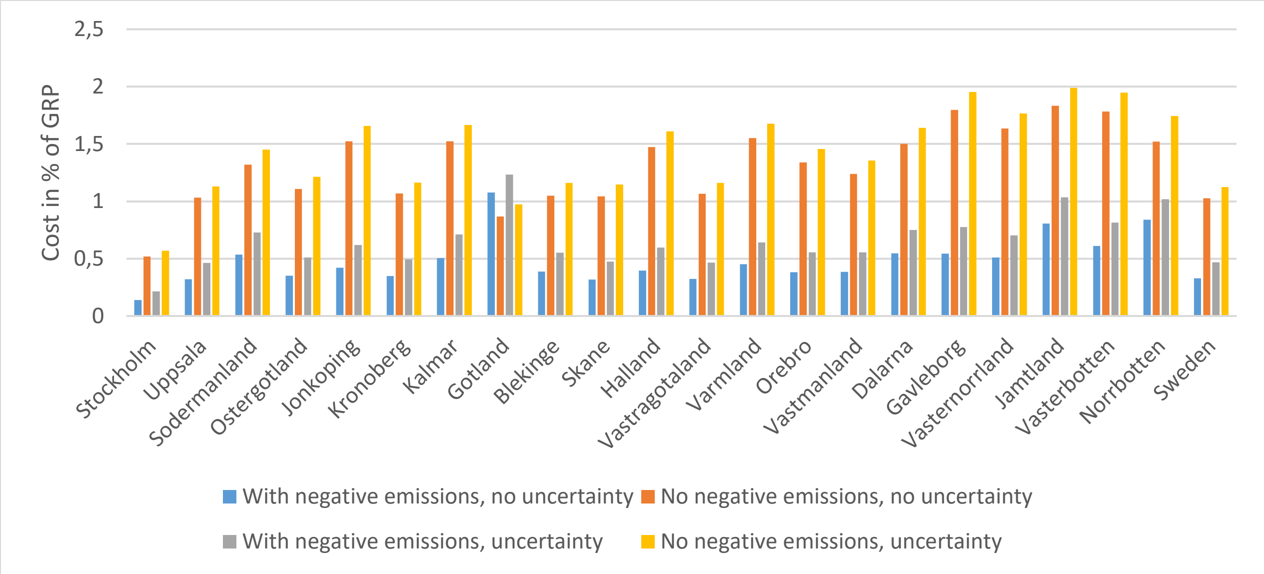

Figure 6: Allocation of emission reduction cost as % of GRP under different combinations of negative emissions and uncertainty for 50 % overall emission reduction.

Except for one county, Gotland, all counties show the same pattern of emission reduction costs under the different combinations of negative emissions and uncertainty at the 50 % emission reduction level. The cost is lower when negative emissions are included and when uncertainty is not considered. The latter is valid also for Gotland, but the inclusion of negative emissions raises cost because of the location of a large factory for cement production, which emitted approximately 1.6 million tonne CO_2 in 2018. This implies a relatively large cost for CCS at the facility.

The unequal allocation of costs among the counties raises the question whether the cost burdens are regressive or progressive, that is if relatively poor regions as measured by GRP faces a relatively high or low share of the total cost. This can be measured by the so-called Suits index, which is negative when the cost allocation is regressive and positive otherwise (Suits 1977). This measure has been used extensively when evaluating impacts on equity of different programs (e.g. Eliasson et al. 2018; Tirkaso and Gren 2020). The results show that the cost allocation is regressive for all for combinations of uncertainty and negative emissions, and that the degree of regressivity is the same for both cases without negative emissions, -0.20, and amounts to -0.23 and -0.25 with negative emission without and with uncertainty, respectively.

4.4 Sensitivity analysis

The results presented so far rest on a number of different assumptions on costs and effects of the measures as presented in Section 3. In principle, calculated costs for a given emission reduction are decreased (increased) when the cost for a measure decrease (increase), when reduction capacity of low cost measures increases (decreases), and uncertainty in effect decreases (increases). In order to examine how much costs are affected by such changes, we examine the impact of changes in consumption patterns and technologies for negative emissions The emissions from both fuel and food may decrease because of the ongoing electrification of the car fleet and changes in consumption patterns of food. Given the linear demand functions, this will not affect the cost for a given reduction as measured in tonnes, but it will reduce total emissions and thereby the assumed maximum capacity of 60 % reduction from the BAU level. Calculations are therefore made with an increase in reduction capacities by 10 % of the BAU emissions. Calculations are also made for similar changes in costs of emission reductions in fuel and food consumption.

Other assumptions include the cost and negative emission, which are new technologies and difficult to predict. Calculations are therefore made by assuming increases and decreases in costs and maximum capacities by 10 %.

The impact of the changes on total minimum costs are calculated as elasticities, which measures the change in percent in the cost from 1 % change in the parameters (Table 4)

Table 4: Calculated elasticities with respect to impacts on total minimum cost from changes in emission reduction capacities and costs under different combinations of uncertainty and negative emission inclusion at 50 % mission reduction and prob.=0.9 under uncertainty

	No uncertainty	**Uncertainty**	**No negative emission, no uncertainty**	**No negative emission, uncertainty**
Increase in fuel and food reduction cost	0.73	0.81	1.07	1.09
Decrese in fuel and food reduction cost	-0.73	-0.82	-0.94	-0.93
Increase in fuel and food capacity	0.00	0.00	-0.03	-0.12
Decreasse in fuel and food capacity	0.00	0.00	0.41	0.59
Increase in negative emission max capacity	-1.02	-0.69		
Decrease in negative emission max capacity	1.22	0.78		
Increase in cost of negative emission	0.27	0.18		
Decrease in cost of negative emission	-0.27	-0.19		

Source: Table A4 in appendix

According to the results in Table 4, an increase by 1 % in the capacity of reductions in emissions from fuel and food reduces total cost by 0.12 % with uncertainty but without the option of negative emissions. The same change has no impact when negative emissions are included because of the relatively low emission reductions in fuel and food in cost effective solutions. The results are most sensitive to changes in the maximum capacity of negative emissions, the cost increases by 1.22 % when the capacity decreases with 1 % when uncertainty is considered.

5. Discussion and conclusions

The main purpose of this study has been to calculate and compare costs of emission reductions from consumption of fuel and food and negative emissions in Sweden when accounting for uncertainty in effects. The main result in this paper is that reduction in consumption of food and fuel are expensive compared with negative emissions. Reductions in food consumption is the most expensive measure for a given emission reduction, and can be more than times higher than the marginal cost of carbon sequestration which is the least costly measures. The marginal cost of reductions in fuel consumption is lower than for food consumption and can be 4 times higher than for carbon sequestration. Consideration of uncertainty raises the marginal cost of negative emissions relative to the other measures, but are still considerable lower at all emission reduction levels. This means that the total minimum cost for reaching different reduction levels shows a large decrease when negative emissions are allowed also under conditions of uncertainty, which support results from other studies (see Raihan et al 2019 for a review). However, the results also show a slight increase in the regressivity of the cost between regions when negative emissions are included since they are located in counties with relatively high capacities of these measures but also relatively low gross regional product. Similar findings were obtained by Munnich et al. (2013) for emission reductions at the EU level.

In our view, the results point our important policy implication. One is that the achievement of climate targets by reducing food and fuel consumption can be quite costly, but the inclusion of negative emissions, which is currently not allowed in Sweden, reduces the cost burden considerably. Another is on the design of policy instruments. The necessary CO_2 tax for implementing e.g. 50 % emission reduction without negative emissions is almost three times higher than when this option is included. The high cost in consumption of food and fuel consumption is explained by the low price elasticities. This raises the question of an environmental tax-refund system which has been suggested in the literature and implemented in practice in several countries (e.g. Millock and Nauges 2006).

In this study, a tax-refund system would imply that CO_2 taxes on food and fuel are used for subsidizing negative emissions, not only to reduce total cost but also mitigate regressivity in the allocation of costs between counties. The low price elasticity not only imply high costs for reductions in consumption for reaching certain emission reduction targets, but would also generate considerable tax revenues. For example, at the 50 % overall reduction without uncertainty, the cost effective carbon tax amounts to 0.351 euro/kg, which gives tax revenues amounting to 7.2 billion euro, which highly exceeds the cost by paying the same price to negative emissions of 2.4 billion euro.

Appendix: Tables A1-A4 and Figures A1-A2

Table A1: Population, food and fuel consumption in different counties in 2018

County	Population, 1000[a]	Food 1000 tonne;					Fuel, 1000 m3;	
		Beef	Pork	Cheese	Milk	Cream	Gasoline	Diesel
Stockholm	2344	28.1	35.2	43.6	230.2	22.0	478	683
Uppsala	376	4.5	5.6	7.0	36.9	3.5	109	176
Södermanland	295	3.5	4.4	5.5	29.0	2.8	102	140
Östergötland	462	5.5	6.9	8.6	45.4	4.3	147	220
Jönköping	361	4.3	5.4	6.7	35.5	3.4	132	258
Kronoberg	200	2.4	3.0	3.7	19.6	1.9	59	101
Kalmar	245	2.9	3.7	4.6	24.1	2.3	87	147
Gotland	59	0.7	0.9	1.1	5.8	0.6	25	19
Blekinge	160	1.9	2.4	3.0	15.7	1.5	54	58
Skåne	1362	16.3	20.4	25.3	133.7	12.8	434	579
Halland	329	3.9	4.9	6.1	32.3	3.1	113	190
Västra Götaland	1710	20.5	25.7	31.8	167.9	16.1	503	917
Värmland	282	3.4	4.2	5.2	27.7	2.7	80	177
Örebro	302	3.6	4.5	5.6	29.7	2.8	92	176
Västmanland	272	3.3	4.1	5.1	26.7	2.6	84	139
Dalarna	287	3.4	4.3	5.3	28.2	2.7	110	185
Gävleborg	287	3.4	4.3	5.3	28.2	2.7	110	212
Västernorrland	245	2.9	3.7	4.6	24.1	2.3	73	182
Jämtland	130	1.6	2.0	2.4	12.8	1.2	49	103
Västerbotten	270	3.2	4.1	5.0	26.5	2.5	55	242
Norrbotten	251	3.0	3.8	4.7	24.6	2.4	47	245
Total	10230	122.8	153.5	190.3	1004.6	96.2	2942	5149

[a]Statistics Sweden 2020a; [b]Calculated by assuming that consumption per capita (Table XX) is the same in all counties; [c]Tirkaso and Gren (2020)

Table A2: Coefficients in regional quadratic cost functions for emission reductions

County	Food[a];					Fuel[b];	
	Beef	Pork	Cheese	Milk	Cream	Gasoline	Diesel
Stockholm	0.343	0.416	0.2	0.016	1.581	0.001	0.004
Uppsala	2.141	2.595	1.249	0.102	9.871	0.046	0.015
Södermanland	2.725	3.303	1.59	0.13	12.566	0.055	0.018
Östergötland	1.739	2.107	1.014	0.083	8.018	0.036	0.012
Jönköping	2.19	2.655	1.278	0.105	10.1	0.034	0.011
Kronoberg	4.026	4.88	2.349	0.192	18.566	0.083	0.027
Kalmar	3.279	3.974	1.913	0.157	15.117	0.057	0.019
Gotland	13.676	16.575	7.978	0.654	63.057	0.301	0.099
Blekinge	5.01	6.072	2.923	0.239	23.1	0.118	0.039
Skåne	0.59	0.716	0.344	0.028	2.722	0.013	0.004
Halland	2.452	2.972	1.431	0.117	11.308	0.044	0.014
Västra Götaland	0.47	0.57	0.274	0.002	2.168	0.009	0.003
Värmland	2.848	3.452	1.661	0.136	13.132	0.052	0.017
Örebro	2.658	3.222	1.551	0.127	12.258	0.049	0.016
Västmanland	2.953	3.579	1.723	0.141	13.617	0.059	0.02
Dalarna	2.801	3.394	1.634	0.134	12.914	0.045	0.015
Gävleborg	2.811	3.407	1.64	0.134	12.962	0.041	0.014
Västernorrland	3.279	3.974	1.913	0.157	15.117	0.052	0.017
Jämtland	6.171	7.479	3.6	0.295	28.453	0.087	0.029
Västerbotten	2.976	3.607	1.736	0.142	13.724	0.045	0.015
Norrbotten	3.203	3.8881	1.868	0.153	14.767	0.045	0.015

[a]Calculated from price elasticities of beef 0.594, pork 0.272, cheese 0.947, milk 0.35, and cream 0.169 from Säll et al (2020), prices in million euro per ktonne beef 11.945, pork 9.534, cheese 8.247, and cream 6.956 from Gren et al. (2020) and quantities presented in Table A1; [b]Calculated from regional price elasticities in Tirkaso and Gren (2020), prices in million euro per 1000 m^3 gasoline 1.513 and diesel 1.527 from SPBI (2020), and quantities in Table A1.

Table A3: Land use in Sweden, 1000 ha, and coefficients in quadratic cost functions

County	Prod. Forest[a]	Arable land[b]	Unmanaged arable land < 5 years[b]	Agriculture on peat soils[c]	Rent, euro /ha[d]	Coefficients in quadratic cost functions; Forest man.	Afforestation	Peat rest.
Stockholm	304	65.9	19.4	11.9	171.8	0.007	0.026	0.144
Uppsala	509	131.6	16.5	18.7	171.8	0.004	0.013	0.092
Södermanland	352	106.1	20.7	16.6	171.8	0.006	0.016	0.103
Östergötland	604	170.7	32.8	17.1	171.8	0.003	0.01	0.1
Jönköping	706	60.9	29.2	11.0	171.8	0.003	0.028	0.156
Kronoberg	670	30.2	19.4	8.0	134.4	0.003	0.045	0.168
Kalmar	738	93.1	30.9	16.5	134.4	0.003	0.041	0.081
Gotland	126	72.6	14.5	12.7	134.4	0.016	0.019	0.106
Blekinge	210	23.8	8.1	5.1	327.9	0.01	0.138	0.643
Skåne	421	401.7	47.6	24.7	327.9	0.005	0.008	0.133
Halland	293	93.4	18.7	5.3	185.5	0.007	0.02	0.35
Västra Götaland	1290	399.4	77.9	30.9	185.5	0.002	0.005	0.06
Värmland	1327	77.1	34.2	1.7	68.3	0.002	0.009	0.402
Örebro	585	88.3	17.6	14	171.8	0.003	0.019	0.123
Västmanland	341	108.5	13.5	11.9	171.8	0.006	0.016	0.144
Dalarna	1969	43.7	19.3	3.8	68.3	0.001	0.016	0.18
Gävleborg	1497	49.0	21.4	4.1	68.3	0.001	0.014	0.167
Västernorrland	1671	31.0	21.6	0.6	44.2	0.001	0.014	0.737
Jämtland	2685	24.6	18.1	2.4	44.2	0.001	0.018	0.184
Västerbotten	3268	49.0	24.7	4.2	44.2	0.001	0.009	0.105
Norrbotten	3937	23.1	14.1	4.4	44.2	0.001	0.019	0.1
Total	22503	2134.5	520.0	225.7				

[a] Riksskogtaxeringen (2020); [b]Pahkakangas et al (2016) Table 1a;[c] Pahkakangas et al (2016) Table 3;
[d] Swedish Statistics 2020b

Table A4: Total minimum costs for achieving 50 % reduction with prob.=0.9 under uncertainty and alternative changes in emission reduction capacities and costs, million euro.

	No uncertainty	Uncertainty	No negative emission, no uncertainty	No negative emission, uncertainty
10 % increase in fuel and food cost	1709	2484	5462	5974
10 decrease in cost of fule and food	1476	2109	4469	4888
10 increase in fuel and food capacity	1592	2297	4920	5323
10 % decreasse in fuel and food capacity	1592	2297	5134	5709
10 % increase in negative emssion	1429	2138		
10 % decrease in negative emission	1786	2476		
10 % increase in cost of negative emission	1635	2339		
10 % decrease incost of negative emission	1549	2254		

Figure A1: Counties in Sweden. Source: www.lansstyrelsen.se

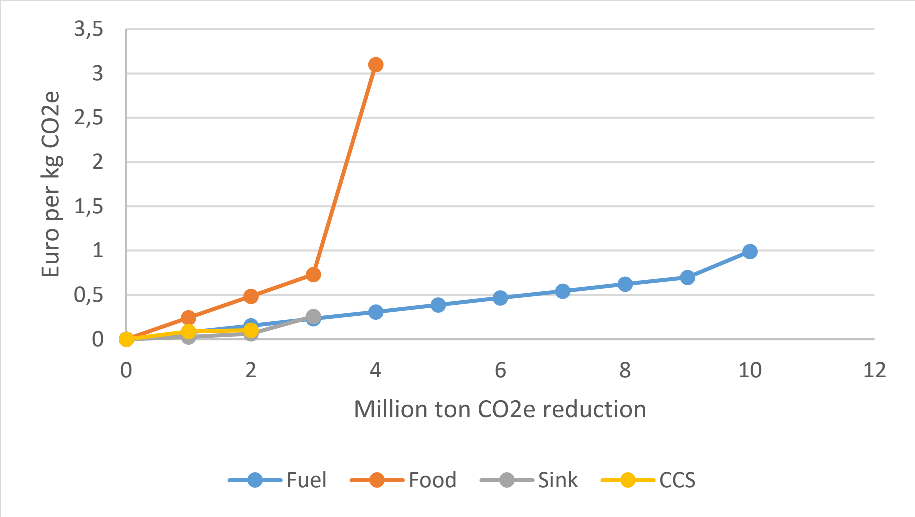

Figure A2: Marginal cost of emission reduction and carbon sequestration under uncertainty with prob=0.9

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