Abstract

Policies for investment in biofuel production facilities and feedstock may be necessary in order to meet climate and renewable energy targets. These policies entail a trade-off between high transportation costs of biomass and economies of scale of production facilities. We develop a spatial optimisation model and investigate the cost-effective localization of production facilities for ethanol from agricultural land in Sweden. Feedstock costs are found to be most important in determining the location, although high feedstock density motivates locating large facilities in areas with high feedstock costs. At higher production, feedstock from the whole country is preferred despite high transport costs.

Keywords: Agricultural land use, biofuel, climate policy, cost-effectiveness, localisation, spatial optimisation

JEL classification: Q10, Q18, Q20, Q42, Q54

1. Introduction

The substitution of agricultural biofuels for fossil fuels has been suggested as a tool to reduce the impact of the transport sector on greenhouse gas emissions. To help achieve this, production of biofuels on agricultural land could be increased (Creutzig et al., 2015). For increased production, investments in production facilities and increased feedstock uptake are needed. However, the introduction of biofuel production on agricultural land is associated with two
major challenges relating to policy design: (i) the choice of location for production facilities and (ii) the competition between feedstock production and food production. Moreover, the biofuel supply chain is characterised by a technology which is generally most efficient when working at large quantities and thus exhibits economies of scale (Leduc, 2009). Costs could therefore be saved by concentrating production to a few facilities. The raw material, which mostly comes from forest or agricultural land, is distributed over a large area and is generally low in energy content, with potentially high transport costs as a result (Lundmark et al., 2018). In particular, this is true if there are only a few, large production facilities in a given area. Therefore, the relation between transportation costs and facility investment costs is important (Yue, You and Snyder, 2014), and the choice of facility location and capacity becomes a first important step towards a cost-efficient production system. Large-scale biofuel production would compete with other types of production on agricultural land, although there is some room for using by-products from agriculture such as straw and food waste (Prade et al., 2017).

The European Union (EU) has developed targets for renewable energy as a means to reach climate targets, set out in the Renewable Energy Directive II (RED II). The common EU-wide target is to reach 32 percent renewable energy as a share of final energy consumption by 2030. However, targets differ between countries with different starting points and possibilities to increase renewable energy use. With transport accounting for a large share of fossil fuel use, a specific part of the target is that at least 14 percent of transport fuels should come from renewable sources by 2030 (European Parliament, 2018). Due to concern over competition with food production, there are restrictions in RED II limiting the possibilities for crediting biofuel production against the targets for renewables. These limitations concern the use of agricultural land otherwise used for food and feed production and contexts where biofuel production negatively affects other sustainability factors such as biodiversity (European Parliament, 2018; European Commission, 2020). At the same time, biofuels for transport are supported by policies: in the EU mostly through biofuel quotas and mandatory blending but also with financial measures such as tax exemptions. Investment support directed towards production facilities is also provided in many cases but has been more common in the bioenergy heating sector (Banja et al., 2019).

In line with the EU’s aims, biofuel use in the transport sector increased from 1 percent of total fuel consumption in 2005 to almost 6 percent in 2018, but with a large regional variation (Eurostat, 2020a). Globally, the share of biofuels in the transport sector is relatively small and equalled 3 percent of energy use in 2017 (World Bioenergy Association, 2020). To reach the current targets, biofuel production in the EU, or imports, must increase. There is therefore a need to understand how a policy for increased domestic biofuel production should be designed when both the scale of production and the location of production facilities and feedstock cultivation are still an open question, as well as the associated costs.
The purpose of this study is to identify a cost-effective supply chain of biofuel from agricultural land, given a policy target for biofuel production. In particular, we examine the trade-offs between economies-of-scale benefits of production facilities and feedstock production and transport costs. We do this using a spatial model that optimises the placement of investment in biofuel production facilities and the location of feedstock production in Sweden. The model is used to investigate how localisation choices are affected by the stringency of a hypothetical biofuel production target and how those choices are influenced by the geographical distribution of fuel demand. With this model setting, we derive the optimal organisation of supply for different production levels, thus obtaining a national supply curve. We compare estimated marginal costs of domestic production to projected world market ethanol prices and examine the cost-effectiveness of the resulting greenhouse gas emission reductions and consequences for the regional production of fodder and hence for livestock production.

The field of location studies is broad, where non-economic location studies often strive to distribute a given number of facilities in space by minimising the distance to demand sites, e.g. Comber et al. (2015). The best sites for location can also be selected by a detailed suitability analysis, as in Sharma, Birrell and Miguez (2017) that locates sites using a GIS suitability analysis.

Many economic studies on optimal localisation of biomass and biofuel facilities have been published in recent years, of which most focus on long-term strategic decisions (Zandi Atashbar, Labadie and Prins, 2018). Some studies analyse decisions concerning a single production facility. Lankoski and Ollikainen (2008) investigate the optimal use of land for feedstock around a given facility, using a von Thünen model. Rentizelas and Tatsiopoulos (2010) consider the best location and design of a single facility in an area, given available feedstock, while Rozakis et al. (2013) account for endogeneity of feedstock supply using a sector model.

Several economic studies have analysed policies over larger regions, which requires consideration of multiple production facilities. Such studies often minimise the cost of the biofuel supply chain, by identification of both the optimal location and the optimal number of facilities. The system boundary can be the biofuel system or, as in De Jong et al. (2017), the whole forestry sector. Most of the studies are static; however, there are some exceptions, such as Santibañez-Aguilar et al. (2015) who apply a dynamic setting for facility investment and production taking seasonality in feedstock supply into account. Some studies analyse biofuel produced with feedstock from the forest sector while others apply their analysis to the agricultural sector. The majority of studies assume restrictions on the availability of feedstock for biofuels and a regional but constant unit cost of feedstock. Bai, Ouyang and Pang (2012) model competition over feedstock as a Stackelberg game where biofuel production facilities are modelled as leaders and the farmers as followers. Britz and Delzeit (2013) couple a sector model with market feedback to their localisation model to get feedstock prices. The regional level is often at the country or state level including a few hundred regions or on e.g. the EU level but then
with fewer regions within each country. Some studies are applied at the country or state level, with a lower spatial resolution, but allowing for other model extensions. For example, Wetterlund et al. (2013) model choices between different technologies for the conversion of feedstock into biofuels, and de Jong et al. (2017) study the impact on overall costs of different cost-reduction strategies. Furthermore, some studies allow for different transport modes: train, truck and ship. Meanwhile, others model the choice between alternative feedstock sources. In addition, some studies perform a suitability analysis that favours factors such as proximity to cities, roads or power lines to choose a subset of possible locations before the optimisation of the model (Wilson, 2009). An overview of some relevant studies referred to in this section can be found in Table A1.a in Appendix A1.

The focus on agricultural feedstock in this study is relevant in light of the more stringent climate policies required by the Paris Agreement, as more biomass must be used for biofuels if they are to be a significant part of the mitigation strategy. Further, the question has been raised whether forests should be used as carbon sinks rather than for bioenergy production (Hedenus and Azar, 2009; Vass and Elofsson, 2016). This suggests that it is important to assess the cost-effective potential of agriculture as an alternative source of biofuel feedstock.

We contribute to the literature on the localisation of biofuel production facilities by focusing on agricultural feedstock, using a model that takes into account regionally increasing opportunity costs that arise due to competition over land with other types of agricultural production. We highlight the trade-off between forces that work in opposite directions: feedstock transport costs motivate decentralised small-scale production facilities, while economies of scale at the facilities have the opposite effect.

The empirical application to Sweden is of particular interest in this context due to its large geographical heterogeneity. A higher feedstock production potential in the south suggests it could be beneficial to locate production facilities there. There could also be cost advantages associated with locating these facilities in the vicinity of major demand centres, typically located where population density is the highest. However, the potential for cheap feedstock production in the north, due to the low opportunity cost of land, is an argument in favour of locating the production facilities there.

The paper continues with a description of the case study in Section 2, the model in Section 3 and the data used in Section 4. Thereafter, results are presented in Section 5, and Section 6 identifies policy implications. Finally, Section 7 provides a discussion and policy recommendations.

2. Case study area

We apply the model to biofuel production with agricultural feedstock in Sweden. There are large geographical differences across the country. In the northern parts, yields are lower and agricultural land scattered. In the southern parts more fertile soils are found, mixed with areas of low-productive land.
Agriculture is concentrated where fertile soils are more abundant. A large share of the agricultural land is used for ley production (Statistics Sweden, 2019). Sweden has a low population density, with most people living in the south (Statistics Sweden, 2020a).

In Sweden, the share of renewables in total fuel consumption was 23 per cent in the year 2018 (Swedish Energy Agency, 2019), and hence the target for renewable transport fuels has already been accomplished. However, Sweden also has a more ambitious target to reduce greenhouse gas emissions in the transport sector by 70 per cent in 2030, compared to 2010 (Government Offices of Sweden, 2017), to which biofuels could contribute (Swedish Climate Policy Council, 2020). Biodiesel, made from forest products and imported oils, is the most produced biofuel in Sweden (Swedish Energy Agency, 2019). Cereals have hitherto been the most used agricultural crops for producing biofuel (ethanol), but the feedstock is mostly imported (Swedish Energy Agency, 2019).

There are several different biofuel technologies which are capable of producing a range of biofuels such as ethanol, biodiesel and biogas. Further, different types of biomass can be used as feedstock in production: for example, forest residues, oil crops, cereals and energy grasses. In this study, we consider one type of second-generation biofuel technology: the production of bioethanol from lignocellulosic material, in this case reed canary grass grown on agricultural land. Although there is no consensus on which is the superior biofuel technology, Börjesson et al. (2013) argue that the largest quantitative potential lies in such lignocellulosic-based biofuels where ethanol is one option; this technology could also perform well in an environmental and cost perspective. Moreover, ethanol is easier to use (Prade et al., 2017). So far, the production technology used to produce ethanol from lignocellulosic material has only been developed to industrial scale in a few places in the world, but its large potential motivates our choice to consider this technology. The choice of reed canary grass is also made because it is possible to grow in most parts of Sweden and on most types of arable lands (Börjesson, 2007).

3. Model description

We develop a static linear programming optimisation model to find the cost-effective number, capacity and location of biofuel facilities, as well as the associated spatial distribution of feedstock production and biofuel consumption, given a national biofuel production target. The model takes regional heterogeneity in feedstock production costs and biofuel demand into account. We assume that the social planner’s objective is to minimise the total supply chain cost to meet a certain production target, and that farmers and production facilities are price takers and strive to maximise profits. In the following sections, the modelling of production, feedstock supply, biofuel demand

1 According to RED II (European Parliament, 2018), second-generation biofuel includes, for example, non-food crops.
and transport, investment and operational costs are described along with the optimisation problem.

### 3.1. Feedstock supply

Feedstock can be produced in all regions \( g \), with \( g = 1, \ldots, G \). Within each region, the opportunity cost for producing feedstock can vary. To represent increasing costs for the feedstock, the supply in each region is divided into three cost categories \( f \), with \( f = 1, 2, 3 \), with different costs as described below. The quantity of feedstock supply for a particular category \( f \) is denoted \( x_{f,g} \). The quantity available for each category \( f \) in each region \( g \) is limited to \( \bar{x}_{f,g} \):

\[
x_{f,g} \leq \bar{x}_{f,g}
\]

The total sales of feedstock of a given category \( f \) from a given production region \( g \), i.e. \( x_{f,g} \), equals the sum of amounts supplied to production facilities in all regions \( i \), with \( x_{TR}^{f,i,g} \), i.e.:

\[
x_{f,g} = \sum_{i} x_{TR}^{f,i,g}, \forall i \in g
\]

where the superscript \( TR \) indicates ‘transportation’.

### 3.2. Biofuel production

Production of biofuel in region \( i \) is indicated by \( y_i \). Similar to Wetterlund et al. (2012), Lin et al. (2013) and Bai, Ouyang and Pang (2012), we assume a constant linear conversion factor \( \alpha \), expressing the volume of biofuel obtained per ton of processed feedstock, equal for all facilities. This assumption is reasonable when we consider only a single type of technology and single feedstock. Other inputs such as labour and energy are assumed to follow the feedstock use and are not modelled. We assume that the total feedstock input to a facility in region \( i \) is the sum of purchased feedstock from all regions. Thus, the production of biofuel \( y_i \) in region \( i \) is obtained by:

\[
y_i = \alpha \sum_{g} \sum_{f} x_{TR}^{f,i,g}
\]

For production to occur, investment in a production facility is necessary. The variable \( I_{v,i} \in \{0, 1\} \) indicates investment in a production facility at location \( i \), taking the value 1 in the case of an investment and 0 otherwise. Facilities can be of different capacities \( v = \{L, H\} \), where \( L \) indicates low capacity and \( H \) indicates high capacity. The production at a facility is restricted by capacity constraints \( y_v \) and \( \bar{y}_v \) specific for the capacity types:

\[
y_v \cdot I_{v,i} \leq y_i \leq \bar{y}_v \cdot I_{v,i}, \text{ for all } v = \{L, H\}, \bar{y}_H = \bar{y}_L
\]

2 A lower capacity constraint on low-capacity facilities is needed to rule out facilities with too small capacities, which would need even higher marginal investment costs. The restriction \( y_H = \bar{y}_L \) is used to have two distinct capacity size choices.
In addition, to facilitate computation, we add the restriction that only one production facility can be built in each region:\(^3\):

\[ \sum_v I_{v,i} \leq 1 \]  \hspace{1cm} (5)

### 3.3. Biofuel demand

Total production of biofuel \( Y \) from all production facilities is

\[ Y = \sum_i y_i \]  \hspace{1cm} (6)

The produced biofuel is distributed from the production facilities to demand points. The variable \( y_{i,h}^{\text{DISTR}} \) denotes the sales of biofuel from the facility in region \( i \) to meet demand in region \( h \). All produced biofuel must be distributed to demand points \( h \) located in the regions of the model, i.e.

\[ \sum_h y_{i,h}^{\text{DISTR}} = y_i, \; \forall h \in g. \]  \hspace{1cm} (7)

We assume that biofuel prices are fixed and equal across the country and thus omit them in the model. This assumption is reasonable as the large fuel companies do not differentiate biofuel prices across space. We assume that in each region there is a maximum demand for biofuel based on possibilities to blend in biofuel in fossil fuel. The lower level is assumed to be zero.

\[ 0 \leq \sum_i y_{i,h}^{\text{DISTR}} \leq \bar{\beta}_h \]  \hspace{1cm} (8)

### 3.4. Costs

The main costs associated with biofuel production are costs of investment in the production facility, operational costs, costs for purchase of feedstock and costs for transport of feedstock from the supplier to the facility and from the facility to the end user. These costs are assumed to be additive.

Investment in building a new facility comes at a fixed cost, increasing with higher capacity levels. Further, investment costs per unit of capacity can be assumed to be lower for larger facilities, see, for example, Akgul, Shah and Papageorgiou (2012). We model the annualised investment cost \( c_{i,\text{INV}} \) with a fixed part \( \delta_\text{v}, \) depending on the size of the facility, and assuming that \( \delta_H > \delta_L \).

In addition, we follow Lin et al. (2013) by including a variable investment cost \( \rho_\text{v} \) per unit of increase in the production capacity level, with \( \rho_L > \rho_H \):

\[ c_{i,\text{INV}} = \rho_\text{v} \cdot y_i \cdot I_{v,i} + \delta_\text{v} \cdot I_{v,i} \]  \hspace{1cm} (9)

The formulation in equation (9) implies that we have a linearised representation of a non-linear concave investment cost function, reflecting economies.

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\(^3\) A positioning of two facilities in the same region would be economically unreasonable in our case, given the small regions and hence small feedstock supply in each region. Further, we never find facilities located in neighbouring regions in the empirical simulations.
of scale. This is illustrated in Figure 1, where the solid and dashed black line depicts the cost of the low-capacity facility, which has a low intercept and a steep slope, compared to the grey line, which depicts a high-capacity facility. The solid parts of the lines show the capacity ranges where each facility type is superior to the other, and in the cost minimisation context they form the piecewise linear and (in this case almost) continuous investment cost function.

![Figure 1](https://example.com/image1.png)

**Fig. 1.** Investment cost as a function of the production capacity level. The black solid and dashed line represents the cost for low-capacity facilities; the grey solid and dashed line represents the cost for high-capacity facilities. Solid lines indicate the minimum investment cost for a given capacity, and capacity spans are indicated by dotted lines.

The operational cost of the production process, $c_{i}^{OP}$, is assumed to depend only on the output level. Most earlier studies assume either a linear cost function which varies across facilities (e.g. Wetterlund et al., 2012) or an identical linear cost function for all production facilities, where instead the economies of scale are modelled in the investment costs (Lin et al., 2013). The latter approach is applied here, and $\sigma$, the cost per unit of produced biofuel, is assumed equal for all facilities:

$$c_{i}^{OP} = \sigma \cdot y_{i}$$

(10)

Earlier studies have made varying assumptions about feedstock costs. Sometimes the feedstock cost is assumed to be a fixed regional unit cost, as in Wetterlund et al. (2012). Alternatively, a supply function with increasing costs is included, as in Apland and Andersson (1996). Here, we take an intermediate approach, where we account for the fact that a larger feedstock production in a region will increase the opportunity cost of production in this region. The profit maximising farmer is assumed to only produce feedstock for biofuel production if the economic gain is equal to or exceeds the opportunity costs. We assume that the marginal cost of feedstock production is stepwise linear. Each category $f = 1,2,3$ represents taking more land into use for feedstock use. Feedstock of each category $f$ is associated with a different unit cost $\vartheta_{f,g}$. 
Consequently, in each region $g$, feedstock of the lowest cost level is chosen until its maximum capacity, given by the land available for the category, is exhausted. The total cost for feedstock of all categories $f$ across all regions $g$ for a given facility in region $i$ is

$$c_i^{FEED} = \sum_g \sum_f \vartheta_f x_{f,g}^{TR}$$  \hspace{1cm} (11)

As feedstock for producing biofuel can be bulky, transport brings important costs. We assume one transport mode (truck) while others, e.g. Akgul, Shah and Papageorgiou (2012), allow for different transport modes: train, truck and ship. The costs include loading and unloading as well as the time and fuel required for transportation. Therefore, transport costs $c_i^{TR}$ increase with the feedstock used and the transport distance $d_{g,i}$ between the supplier at location $g$ and facility at location $i$, given the unit feedstock transport cost $\varphi^{FEED}$. The cost function also has a fixed element $\omega^{FEED}$ per unit transported, reflecting the cost of loading and unloading, similar as in, e.g. Wetterlund et al. (2012) and Akgul, Shah and Papageorgiou (2012):

$$c_i^{TR} = \sum_g \sum_f (\omega^{FEED} + \varphi^{FEED} d_{g,i}) x_{f,g}^{TR}$$  \hspace{1cm} (12)

Similarly, the cost $c_i^{DISTR}$ for transporting biofuel from the facility at $i$ to demand points $h$ is determined by the unit transport cost $\varphi^{FUEL}$ and the unit cost of loading and unloading, $\omega^{FUEL}$:

$$c_i^{DISTR} = \sum_h (\omega^{FUEL} + \varphi^{FUEL} d_{h,i}) y_{i,h}^{DISTR}$$  \hspace{1cm} (13)

### 3.5. Production target

Finally, we assume that there is a policy target for biofuel production at the national level that should be reached, defined as an annual production target $Y^*$:

$$Y \geq Y^*$$  \hspace{1cm} (14)

### 3.6. Objective of the model

The objective of the model is to minimise the costs for meeting the production target $Y^*$, subject to the constraints in equations (1)–(8). The decision to invest in a production facility at a given location will depend on the spatial allocation of all facilities, feedstock production and biofuel demand. The problem includes agglomeration forces, due to the benefit of concentration that follow from economies of scale (equation 9), and dispersion forces from transport costs and increasing costs of feedstock production (equations 11–13). The problem can be described as follows:

$$\arg\min_{y_{i,g}, x_{j,i,g}^{TR}, y_{i,v}, y_{i,h}^{DISTR}} \sum_i \sum_v \left( c_i^{INV} + c_i^{OP} + c_i^{FEED} \right) + \sum_i c_i^{TR} + \sum_i c_i^{DISTR}$$
s.t. \[ \text{Equations (1)} \text{– (14)}, \text{ and} \]
\[ x_{f,g}, y_{i,h} \geq 0 \text{ and } I_{v,i} \in \{0, 1\} \]

In the following, the model is simulated numerically using data relevant for our case study.

4. Data

This section gives a brief overview of the data; more details are given in Appendix A2.

4.1. Spatial structure

In the calculations below, the regional unit used for feedstock supply, location of production facilities and demand for biofuel is the municipality. The regional units are indicated by \( g, i \) and \( h \), when related to feedstock production, biofuel facility location and location of final demand, respectively. We include all municipalities in Sweden, 290 in total. For these, the median total land area is 670 km².

To calculate the transport distances \( d_{g,i} \) and \( d_{h,i} \) between municipalities, we follow Leduc (2009) and Akgul, Shah and Papageorgiou (2012) by multiplying Euclidean distances between regions with a tortuosity factor (Zamboni, Shah and Bezzo, 2009) that accounts for the irregularities of the road network (Zamboni, Shah and Bezzo, 2009).

4.2. Feedstock

We assume that up to 50 per cent of the total agricultural land area in Sweden currently used for ley, and land classified as fallow or other unused land, can be used for the purpose of feedstock (reed canary grass) production. Of this, we assume half can be classified as cost category 1 and half as cost category 2. Moreover, we assume that up to 10 per cent of arable land used for crop production can be used for the same purpose and can be classified into cost category 3. The yield of reed canary grass is assumed to be 5.85 tons dry weight per hectare in Umeå municipality in the northeast of Sweden and differentiated across Sweden in proportion to ley yields, thereby reflecting spatial variations in soil quality and climate. This gives maximum regional supply quantities \( \bar{x}_{f,g} \) with a total potential production of reed canary grass of 5.8 million tons per year in Sweden. The density of the potential feedstock area in relation to the total land area (also including non-agricultural land) is illustrated in panel A of Figure 2.

The conversion rate of biomass to ethanol is set to 0.3 m³ of ethanol per ton of feedstock, which is the same as used by Lin et al. (2013) for another type of bioenergy grass, Miscanthus, for production facilities for ethanol from lignocellulosic material.

4.3. Biofuel demand

Currently, blending of ethanol into gasoline, or E85, is done at fuel distribution terminals, which are spread out at harbours in Sweden, in particular in the southwest. It is also possible to blend in the ethanol in the pump at the retail station. In our
baseline scenario, we assume that the produced biofuel is both mixed with gasoline and used as bioethanol for ethanol vehicles, with blending at retail stations. The upper limit $\bar{\beta}_k$ is assumed to be 38 per cent of current gasoline consumption per region, in ethanol equivalents, and, when also considering ethanol as fuel, corresponds well to a proposed blending target for 2030 (Swedish Energy Agency) of about 28 per cent. For a scenario where all biofuel is used for shipping the spatial distribution of demand is calculated based on passenger and freight traffic at the largest harbours. In a third scenario, it is assumed that all biofuel is used for aviation and biofuel consumption distributed in proportion to the number of passengers per airport. The lower bound on demand is zero. Figure A2.a in Appendix A2 shows the density of fuel use for each end use.

4.4. Costs

All costs are given in EUR 2019. Investment and production costs for biofuels depend on the scale of the production facility, and the amount of biofuel produced. We use cost estimates from Lin et al. (2013), who model production of ethanol from Miscanthus grass in the USA. For our high- and low-capacity spans we use their two low and medium capacity segments (15,000–180,000 and 180,000–360,000 m³ ethanol$^4$), with variable and fixed investment costs $\rho_i$ and $\delta_i$ listed in Table A2.a in Appendix A2.

The current scale of production of reed canary grass is small in Sweden, and production-cost data are not available. Therefore, the production cost $\vartheta_{1,g}$ for reed canary grass for cost category 1 is calculated as the opportunity cost for silage production. This is motivated because both crops are cultivated on similar types of

4 We can note that, thereby, the maximum capacity of the larger facilities exceeds the capacity of the single existing Swedish ethanol production facility, which has a capacity of about 230,000 m³ of ethanol per year (Agroetanol, 2020).
land, using similar production processes. The costs for the second and third cost categories are calculated using the price elasticities for forage products in Sweden for the eight NUTS2 regions. This approach implies that the cost estimates take into account adjustments in other parts of the agricultural sector. The resulting feedstock opportunity costs for cost category 1 are shown in panel B of Figure 2.

Transport costs $c_{TR}^i$ and $c_{DIST}^i$ for feedstock and biofuel, respectively, are based on the amount transported as well as the distance covered. These costs are based on transport costs for wood chips and ethanol in Sweden from de Jong et al. (2017) and are given in Table A1.b.

4.5. Production target levels

We base the levels of ethanol in the hypothetical production targets in our scenarios on the available feedstock. With a total of about 5.8 million tons of available feedstock, which could produce 1.7 million m³ ethanol in Sweden, the highest target $Y^*$ is set a little lower, to 1.5 million m³ ethanol. This gives about 5.8 TWh, corresponding to 21 per cent of gasoline use in Sweden in the year 2018. This is in the same range as was found by Prade et al. (2017) to be a sufficient contribution of the agricultural sector to Sweden’s emission targets for the transport sector.

5. Results

The results obtained from the model consist of locations for production facilities; production capacity levels of these facilities; flows of feedstock supply from regions to facilities and the distribution of biofuel to end users. Further, associated costs and transport distances can be studied. We analyse the effects of increased biofuel production in different scenarios, which are detailed in the next section, and describe the results of these in the subsequent sections and in the policy implications section. Thereafter we perform a sensitivity analysis. The results are calculated using a Mixed Integer Linear Programming model, programmed in the GAMS software (see Appendix A3).

5.1. Scenarios

We examine three sets of scenarios: Target levels, Sequential and Demand distribution.

The first set of scenarios (Target levels) are used to investigate how the location and production of production facilities and the total costs change with the stringency of the production target $Y^*$. The target levels in the scenarios range from 10 to 100 per cent of the maximum target of 1.5 million m³ ethanol. For these scenarios, the regional biofuel demand is allowed to be within a span, as outlined above.

For the remaining two sets of scenarios (Sequential and Demand distribution), the Target level 70 per cent (1.05 million m³ ethanol) is used as a main reference scenario to compare with. This level equals 60 per cent of potentially available feedstock.

In the three Sequential scenarios, we investigate the effects of a sequential increase in the production target $Y^*$. They demonstrate a policy that is gradually introduced, for example, because there is uncertainty about the scale of final biofuel production that would be cost-efficient, given the overall target for renewables, or because the policy maker is budget constrained. Such a sequential implementation could potentially lead to a suboptimal distribution.
Optimal localisation of agricultural biofuel production facilities and feedstock

Fig. 3. Panel A: Production of ethanol at each facility for Target-level scenarios. Blocks representing low- and high-capacity facilities respectively, with production at each site shown by the size of the block. Panel B: Marginal costs in EUR per m³ for different production targets, divided into cost categories.

of production facilities. In Sequential A, we use the result from Target level 30 per cent as the first step in the sequential policy. Holding facility capacities from Target level 30 per cent fixed, the 70 percent target is subsequently optimised. For Sequential B, there is an additional step in the optimisation: First the 50 per cent target is optimised holding facility capacities from Target level 30 per cent fixed, and then the 70 per cent target is optimised holding facility capacities from the previous step fixed. For Sequential C, we take the capacity of the single existing facility in Sweden (with a capacity of 230,000 m³ ethanol, located in Norrköping in the southeast) as the first (fixed) step in the policy, subsequently optimising the system to achieve the 70 per cent target.

In the third set of scenarios (Demand distribution), we compare the role of the geographical distribution of different types of end use of biofuel. There are two scenarios: in Aviation demand, demand is distributed as airport fuel demand, and in Shipping demand, demand is distributed as fuel demand per harbour.

5.2. Stringency of target levels

We illustrate the results for the Target-level scenarios in two figures. Figure 3 summarises biofuel production and costs for the whole range of target levels (Panel A) and shows the associated marginal costs (Panel B). Figure 4 shows the geographical location of facilities and feedstock supply. The blocks in Figure 3, panel A, show the number of facilities of low and high capacity, respectively, as well as the produced quantities at each of these facilities. At the lowest target level, there is one low-capacity facility, while at the highest target levels there are four high-capacity facilities and one of low capacity. The capacity for each facility generally increases with target levels until one additional facility is needed for a higher production level, only then with an increasing number of facilities as a result (see e.g. between 70 and 80 per cent). There are more high- than low-capacity facilities, illustrating the importance of the lower investment cost per unit at these facilities. Thus, investment costs are more important than transport costs. Many low-capacity
facilities would instead have been optimal if the transport distances to the facilities were most important.

Panel B shows the marginal cost at different production target levels, in EUR per m³ ethanol, decomposed into cost items (see Section A2.4.1 in Appendix A2 for the calculations). Marginal costs are increasing, which is mainly due to high and increasing feedstock costs, while there is a tendency towards a decreasing share of transport costs of the total marginal costs when the number of facilities is high. Due to the presence of investment costs, marginal costs are at some instances decreasing locally when production increases.

The maps in Figure 4 show the results for the selected target levels 30, 40, 70 and 80 per cent, with the locations of high- and low-capacity facilities (blue triangles and squares), their respective feedstock catchments areas (black lines) and the highest cost category for feedstock supplied from a region (light to dark green, with a darker shade indicating a higher-cost category). At lower target levels, the facilities are located in the south using feedstock of cost category 1 in the surrounding area. With increasing target levels, the feedstock catchment area increases. Feedstock of cost category 1 is almost solely used across the whole country before using some feedstock in higher-cost categories. This pattern of feedstock use shows that the feedstock costs are of great importance for the location and more important than transport costs. A consequence of the spread of the feedstock catchment area is that transport distances initially increase but then decrease when feedstock of a higher-cost category begin to be used.

The location differs between target levels, but persistently the low-capacity facilities are located in the north and the high-capacity facilities in the south. Some locations are quite stable, such as one high-capacity facility in the southwest and one high-capacity in the east. The southwest region is a suitable location as it is characterised by a relatively low feedstock price and high density of land available for feedstock production (see Figure 2), which decreases the cost of transported feedstock. Low-capacity facilities play a minor role in overall production, but they make up the least-cost method of utilising the more spread out, but relatively cheap,
feedstock in the northern part of the country. These differences affect the unit cost structure for the different facilities, as shown in the 70 per cent scenario in Figure A4.a in Appendix A4.

5.3. Sequential scenarios

In the Sequential scenarios, the facilities from a previous target (Target 30 per cent) remain fixed. These are one low-capacity facility in the south and one high-capacity facility in the southwest (see Figure 4). Figure A4.b in Appendix A4 shows the production for the different scenarios. An increase to 70 per cent (Sequential A) results in a situation with more and smaller facilities than in the direct optimisation at this level (Target 70 per cent). For Sequential B, there are even more and smaller facilities. Consequently, the average distances from supply regions to facilities are lower. In addition, a larger share of the total production is in low-capacity facilities. The new locations are in both cases quite close to those in Target 70 per cent but shift in Sequential A and Sequential B to use the feedstock in the north rather than the south. For Sequential C, the initial facility is one high-capacity facility at a site close to one in Target 70 per cent, and thus the difference between the scenarios is not that large. The total costs are higher in all the sequential scenarios than in the Target 70 per cent scenario, but the difference is less than 1 per cent. One explanation for the small difference is that the important feedstock costs are hardly affected by fixed locations and capacities.

5.4. Spatial distribution of demand

In the Demand distribution scenarios, demand is concentrated to a few geographical points (see Figure A2.a in Appendix A2). However, the results show that the location of facilities is very similar to the main scenario (Target 70 per cent), as transport costs for ethanol are lower than those for feedstock. Nevertheless, the capacity level at each facility is different; in Aviation demand, the facilities close to the large airports, Arlanda in the east and Landvetter in the southwest, are at the highest allowed capacity, and in Shipping demand, the capacities are highest to the south and east where there are a lot of passenger ferries. This shows that the transport of fuel has some impact on the facilities. The less spread-out demand in these scenarios increases the costs relative to the main scenario: for Aviation demand, it is 1.3 per cent higher, while for Shipping demand it is 0.5 per cent higher.

5.5. Sensitivity analyses

Finally, we carry out sensitivity analyses with respect to key parameters. All the sensitivity analyses use the scenario Target 70 per cent and biofuel demand based on current fuel consumption as a base. There are four sets of scenarios: first, variable transport costs change by ±20 per cent; second, feedstock prices change by ±20 per cent; third, fixed investment costs change by ±10 per cent⁵ and fourth,

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⁵ To change the investment costs, the fixed cost component of each of the two capacity levels is changed so that the total investment cost at the intersection of the low- and high-capacity increases (decreases) 10 per cent, while variable costs are left unchanged. Thus, the relative change in fixed investment cost actually differs for high and low capacities; the resulting change
available feedstock changes by ±20 per cent, by changing feedstock of all cost categories.

A reduction in the fixed investment cost has a large effect as it implies more low-capacity facilities—three large and three small, which can be seen in Figure A4.c in Appendix A4. Also, with higher transport costs or a higher feedstock price, there are two rather than one small facility, meaning that these costs are quite important when it comes to localising facilities in areas with lower feedstock availability. For the other sensitivity analysis scenarios, the production per facility and locations are quite stable and similar to the main scenario. However, with decreased transport costs, the facilities are somewhat more spread out. At lower feedstock prices, the catchment area is more to the south, requiring lower transport costs. The total cost difference relative to the main scenario is largest for feedstock cost change as this cost constitutes the largest share of total costs (12 per cent cost increase and decrease, respectively).

6. Policy implications

As investments in biofuel production facilities can receive governmental support (such as is the case for biogas facilities in Sweden (Government Offices of Sweden, 2020)), their capacity and localisation is of relevance for such policy schemes. In addition to this, the results are relevant for the agricultural sector and for the development of policies for more renewables in the transport sector and for mitigation of greenhouse gases. These policy implications are further discussed in the following.

6.1. Animal fodder availability

The land assumed to be available for biofuel feedstock is currently mostly used for ley production. Therefore, fodder production would be affected by increased biofuel production. To measure the impact, we compare hectares of ley per grazing animals (cattle, sheep and goat) measured in livestock units (LSUs), with and without biofuel production. The largest relative and absolute change in hectares per LSU occurs in east Sweden with more than 30 per cent decrease in area per LSU (see Figure A4.d in Appendix A4). In the north, the change is smaller in relative terms but larger in absolute terms due to high initial levels. The decrease in the south is smaller in absolute terms, but the effect is large in relative terms.

6.2. Policies for renewables

A first question is how the modelled biofuel production could contribute to existing targets for renewables. Our maximum target corresponds to 6 per cent of total current (2018) liquid fuel and 21 per cent of gasoline use, which together with the present use of renewables from other sources would be sufficient to comply with the EU target for 2030, that requires 14 per cent renewable fuel for both total liquid fuels and gasoline.

A second question is whether domestic production of biofuels or imports is a cheaper way to meet blending targets. Our results show that the marginal cost of domestic production ranges between 1030 and 1420 EUR per m³, see Figure 2. This can be compared to the projected world ethanol prices of 290 EUR per m³

is greater for low-capacity facilities. The 10 per cent level is chosen as we would otherwise get negative investment costs for the very small facilities.
in 2019 by OECD/FAO (2020) to increase to 360 EUR per m³ in 2029. This suggests that domestic production is not competitive. However, the policy-driven global demand for biofuels could increase beyond the OECD/FAO projections, for example, if further policies put restrictions on the use of first-generation ethanol. Moreover, technology development could lead to decreases in production and investment costs by more than 50 per cent (Brown et al., 2020).

6.3. Climate emissions and policy

The reductions in GHG emissions for reaching the 30 per cent and 70 per cent and production targets in the Target levels scenarios are 0.5 and 1.1 Mt CO₂ eq, respectively. These levels can be put in relation to the Swedish national target to decrease GHG emissions from the transport sector by 70 per cent until 2030, corresponding to a reduction by 11.2 Mt CO₂ eq. At the 30 and 70 per cent production targets in our analysis, the marginal cost per kg CO₂ reduction are EUR 0.23 and EUR 0.26, respectively (see Table A4.a in Appendix A4). This takes into account emissions from the ethanol production process, feedstock production, transports and negative emissions from the replacement of gasoline. Thus, the abatement cost is higher than the Swedish tax on GHG emissions for energy and transport, EUR 0.12 per kg CO₂ in 2021 (Government Offices of Sweden, 2021). However, Sweden also implements several abatement policies for which the marginal costs are higher. For example, the Swedish government applies a combined subsidy-tax scheme for new cars, which is judged to be highly cost inefficient (Brännlund, 2018; NAO (The National Audit Office), 2020). The marginal cost is for a similar subsidy scheme for electric cars in Norway is estimated to EUR 11.5 per kg of reduced CO₂ emissions (Holtsmark and Skonhoft, 2014), where the Norwegian scheme is slightly more ambitious. Moreover, NIER (2017) finds that current Swedish policies for transport fuel substitution imply a cost of EUR 0.5–0.8 per kg CO₂ avoided. See Appendix A2.5.2 for the calculations of the marginal abatement costs.

7. Discussion

This study provides insights regarding the optimal localisation of both facilities and feedstock for biofuel production on agricultural land. We developed a cost-effectiveness model for biofuel production, applied to Swedish data, with which we computed feedstock use, facility location, end use, costs, and greenhouse gas emissions. This enabled us to analyse trade-offs between scale benefits and transport costs, taking into account regional supply and demand differences and derive a national supply curve for biofuel production.

We found that the spatially differentiated opportunity costs of feedstock are the most important for the choice of location. High-capacity production facilities are located in areas combining relatively low feedstock cost and high feedstock density. In Sweden, this was found in the southwest, where most of the facilities would optimally be located. We saw that the significance of feedstock costs made it important to also utilise the cheaper feedstock in the north despite the higher transport costs when higher production targets need to be fulfilled. In that case, some low-capacity facilities were located there. To some degree contrasting with our results, Wetterlund et al. (2013) found that transportation costs can be of great importance for forest feedstock, especially when biomass availability is

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6 World ethanol production is to the largest part first-generation ethanol.
restricted, implying high transport distances. In our case, feedstock availability played a smaller role, whereas transportation costs played a larger role at medium production target levels and a smaller role at higher production targets, which might be explained by a higher importance of increasing feedstock costs. Similar to Natarajan et al. (2014), who focus on the forest sector, we found that the heterogeneous spatial distribution of feedstock played a large role in facility distribution; but contrary to that study, we found that the demand distribution was of little importance. De Jong et al. (2017), also focusing on the forestry sector in Sweden, found that higher production implies a need for feedstock from further afield, which is more costly; this was also true of our results, up to the point when feedstock that was geographically closer but of a higher-cost category was chosen. The producers, as modelled by De Jong et al. (2017), would take all available feedstock from a region at once, as their marginal feedstock costs are constant. This shows the importance of considering regionally increasing costs of feedstock at high production targets, which arise due to competition over land. De Jong et al. (2017) found, similarly to us, that with larger-scale production the facilities were more decentralised. Some general conclusions we draw are that feedstock cost will be of largest importance, and that for high production targets the facilities would be spread out geographically, to compete over land at a low level everywhere rather than be clustered in some regions.

Our study has implications for policies for renewables and climate policies, how to organise production and the impact on agricultural production. The marginal costs we found were not competitive with current gasoline or ethanol prices but provide an indication of the future potential in Sweden. Further, the technology is developing and thus production costs could decrease. The marginal costs for GHG removal is higher than the Swedish CO₂ tax but lower than some other for other policies included in Swedish climate policy.

Energy policies are often developed in several steps. Production targets could, for example, be implemented via stepwise decisions, with targets increasing over time, rather than setting a high target all at once. This could risk incurring additional costs if the outcome deviates substantially from the optimal. We find that such a development would indeed result in suboptimal locations but that the additional cost is small. The presence of policy uncertainty could also imply higher feedstock costs if farmers require a risk premium, and the sensitivity analysis shows that this leads to a higher portion of production in small facilities and a substantial increase in costs.

Our model has limitations related to the scope and the availability of data. The trade-off between detail and a technically well-working model is important, and we use a static model to permit more detail and a clear interpretation of the results. More technologies and feedstock choices could be modelled than in our analysis, such as, e.g. gasification of energy forest into biodiesel or biogas production from agricultural crops and food waste (Börjesson et al., 2016), where biogas would be the most qualitatively different. The use of another technology could imply lower investment costs, and our sensitivity analysis shows that this would in turn result in more and smaller facilities. The use of a single technology and feedstock type allows us to focus on the spatial distribution in the whole country and the effects of different forces on this distribution. Moreover, the yield of reed canary grass that can be obtained under commercial large-scale production, and thus feedstock availability, is uncertain. The sensitivity analysis shows that a lower availability of feedstock implies increased total costs but a similar number of facilities.
Our focus is on the least-cost solution and the calculations assume a competitive market, hence disregarding potential market failures associated with market power, which could be an issue when there are few large production facilities (Bai, Ouyang and Pang, 2012). However, market power can have a significant impact on feedstock prices, and our results showed that feedstock costs are important, suggesting that further analysis of market power, applied to the studied sector, could be relevant. In addition, we abstract from the possibility of policy failure, which could, for example, occur if governments are unable to implement cost-efficient policy instruments.

The trade-off with food production is a potentially serious concern regarding biofuel production. For example, Searchinger et al. (2008) find that large-scale bioenergy production could have a significant negative effect on food production, while on the other hand, Lotze-Campen et al. (2014) do not find any significant effects on food prices. In our scenarios, food production is not directly affected, as land for crop production is almost not used at all. However, we find that the impact of increased biofuel production on animal production can be large, due to a loss of forage area. In addition, ley production could increase on land for crop production, an effect not accounted for in the above analysis.

Potential extensions of the model could be to improve the assessment of the sustainability impact of biofuel production on, e.g. biodiversity, GHG emissions from land use changes and nutrient leakage and comparisons of the cost-effectiveness of agricultural biofuel production with other measures relevant for meeting targets for renewables and climate. Moreover, feedstock and biofuel can be traded across borders, and an extension of the spatial coverage of the model could aid understanding of how increased feedstock use on an international scale might affect the location of production and biofuel prices.

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## Appendix A1: Literature overview

**Table A1.a. Categorised literature**

| Study                                      | Static/dynamic | Single/multiple facility | Facility regions | Feedstock | Feedstock costs | Feedstock choice | Technology choice |
|--------------------------------------------|----------------|--------------------------|------------------|-----------|-----------------|------------------|-------------------|
| Lankoski and Ollikainen (2008)             | Static         | Single                   | One              | Agricultural | Based on transport | Yes              | No                |
| Akgul, Shah and Papageorgiou (2012)        | Static         | Multiple                 | 17               | Forest     | Fixed           | Yes              | Yes               |
| Bai, Ouyang and Pang (2012)                | Static         | Multiple                 | 20               | Agricultural | Stackelberg game | No               | No                |
| Britz and Delzeit (2013)                   | Static         | Multiple                 | 401              | Agricultural | Market model    | Yes              | No                |
| Comber et al. (2015)                       | Static         | Multiple                 | 524              | Agricultural | No              | No               | No                |
| De Jong et al. (2017)                      | Static         | Multiple                 | 366              | Forest     | Fixed           | Yes              | Yes               |
| Leduc (2009)                               | Static         | Multiple                 | >400             | Forest     | Fixed           | Yes              | Yes               |
| Lin et al. (2013)                          | Static         | Multiple                 | 102              | Agriculture | Fixed           | Yes              | No                |
| Natarajan et al. (2014)                    | Static         | Multiple                 | 120              | Forest     | Fixed           | Yes              | No                |
| Rentizelas and Tatsiopoulos (2010)         | Static         | Single                   | Fine grid        | Agricultural | Yes             | No               | No                |
| Rozakis et al. (2013)                      | Static         | Single                   | >300 farm in sector model | Agricultural | Yes             | No               | No                |
| Santibáñez-Aguilar et al. (2015)           | Dynamic        | Multiple                 | 6                | Mixed      | Fixed           | Yes              | Yes               |
| Sharma, Birrell and Miguez (2017)          | Static         | Multiple                 | Fine grid        | Agricultural | Fixed           | Yes              | No                |
| Wetterlund et al. (2012)                   | Static         | Multiple                 | 8 EU regions     | Mixed      | Fixed           | Yes              | Yes               |
| Wetterlund et al. (2013)                   | Static         | Multiple                 | >50              | Forest     | Fixed           | Yes              | Yes               |
| Wilson (2009)                              | Static         | Multiple                 | Fine grid        | Agricultural | Fixed           | No               | No                |
Appendix A2: Detailed data

A2.1. Spatial structure

To calculate the transport distances $d_{g,i}$ and $d_{h,i}$ between municipalities, we first measure the Euclidean distances between regions. We identify the centre points of all municipalities and then measure the distance in kilometres between these centre points. The distance within a region is assumed to be zero. Geospatial data on the geographical extent of each municipality are taken from Esri’s processing of data from Statistics Sweden (Esri, 2012). We construct tortuosity factors at the county level. For this, we use Google Maps (www.google.se/maps) to pick two arbitrary points in opposing ends of each county and then measure both the shortest route via the road network and the Euclidean straight distance and divide the former by the latter. To reduce the risk of possible measurement errors, the average between the county’s calculated tortuosity factor and the average in Sweden, 1.3, is used as tortuosity factor for each county. The result is tortuosity factors in a range between 1.3 and 1.5, with higher levels more common in the north. The average is similar to that for road transport, 1.4, used by Leduc (2009) and Akgul, Shah and Papageorgiou (2012).

A2.2. Feedstock

The available land for feedstock is based on statistics on agricultural land in different municipalities, obtained from the Swedish Board of Agriculture (2020a). We assume that up to 50 per cent of the total land area currently used for ley, and land classified as fallow or other unused land, can be used for the purpose of reed canary grass production. Moreover, we assume that in addition up to 10 per cent of the arable land used for crop production can be used. The land areas in question are calculated as the average area over the years 2015–2019, which yields a total of about 750,000 hectares available for canary grass production. The yield of reed canary grass is assumed to be 5.85 tons dry weight per hectare in Umeå municipality in the north east of Sweden. This equals current yield as observed in field trials plus an expected future yield increase of 30 per cent as suggested by Börjesson (2007). The yield is assumed to be differentiated across Sweden proportionally to standard yield levels for ley in the corresponding agricultural production areas over the years 2014–2018 (Statistics Sweden, 2020b). This gives the maximum regional supply quantities $\bar{x}_{i,g}$ and a total potential production of reed canary grass of 5.8 million tons per year.

A2.3. Biofuel demand

For our baseline scenario, it is assumed that the produced biofuel is both mixed with gasoline and used as bioethanol for ethanol vehicles. Currently most blending is done at fuel distribution terminals. We assume blending is done in pumps at retail stations due to the assumed increase in biofuel use. The upper limit $\bar{\beta}_h$ is assumed to be 38 per cent of current gasoline consumption per region, in ethanol equivalents. This is 10 per cent above the maximum assumed supply target in the model, to make sure that there is enough demand. Further it corresponds well to a proposed blending target for 2030 of 28 per cent (Swedish Energy Agency). We assume the lower limit is zero in each region. To determine fuel use in different municipalities, we calculate the average energy equivalents of liquid fuel used for transport for the years 2014–2018 and multiply it with the average national share of gasoline to calculate gasoline use in each region. These data were obtained from the
Figure A2.a. Spatial demand distribution. From left: fuel, aviation and shipping. Density fuel use per 1000 km².

Swedish Energy Agency (2020). The gasoline use was converted into the equivalent volume of ethanol. For the aviation scenario, the same approach was used, but biofuel consumption is distributed in proportion to the number of passengers per airport, using the average of 2018 and 2019 from the Swedish Transport Agency (2020). For the scenario where all biofuels are used for shipping, the spatial distribution of demand is calculated based on passenger and freight traffic at the largest harbours. The amount of fuel to passenger shipping and freight, respectively, is given by the average of fuel use for these purposes for domestic and international shipping from Sweden from 2003 to 2011 (Swedish Energy Agency, 2013). Of this fuel, the share to each harbour from passenger traffic is calculated based on the average number of passengers per year for the 10 largest harbours. For fuel for freight, consumption is calculated based on tons of goods per year per regional division, with the regional divisions allocated to municipalities with harbours (Transport Analysis, 2019). Together, this gives us an approximation of fuel per municipality with a harbour, from which the shares of total demand can be derived. Figure A2.a shows the density in demand for each end-use type, in total use\(^7\) per 1000 km².

A2.4. Costs

All costs are given in EUR 2019. For the conversion of currencies, we use exchange rates from The Swedish Riksbank (2021) and the consumer price index from Statistics Sweden (2021). We use cost estimates from Lin et al. (2013), who model the production of ethanol from Miscanthus grass in the USA. They base investment cost on observed costs at a single facility and scale these costs to different capacity levels, assuming decreasing marginal costs. They then perform a linear approximation of the costs, in three segments of capacity

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\(^7\) Of the biofuel produced in this scenario.
Table A2.a. Investment and operational costs, technology specification, per year

|                           | High capacity | Low capacity |
|---------------------------|---------------|-------------|
| Capacity, \( y_v - \bar{y}_v \) | 1000 m³ ethanol | 180–360 | 15–180 |
| Operational cost, \( \sigma \) | EUR/m³ ethanol | 145 | 145 |
| Variable investment cost, \( \rho_v \) | EUR/m³ ethanol | 129.7 | 185.7 |
| Fixed investment cost, \( \delta_v \) | Million EUR | 15.4 | 6.0 |
| Conversion, \( \alpha \) | m³ ethanol/ton feedstock | 0.3 | 0.3 |

Source: Lin et al. (2013).

Table A2.b. Transportation costs

|             | Distance-based EUR per km | Loading and unloading EUR |
|-------------|---------------------------|---------------------------|
| Feedstock   | 0.153 per ton             | 4.81 per ton              |
| Biofuel     | 0.120 per m³              | 9.71 per m³              |

levels. The investment costs are annualised assuming a 15-year lifespan. We sum up the costs for pre-processing plants and biofuel production facilities, assuming that the both activities take place in a single type of facility. For our high- and low-capacity spans, we use their two lower-capacity segments, with costs listed in Table A2.a. These approximately give an equal cost at the break between high and low facility. The variable operations costs \( \sigma \) are assumed to be equal for all facilities.

The production of reed canary grass is low in Sweden, and production-cost data are not available. Therefore, the production cost \( p_{f,g} \) for reed canary grass is assumed to equal the opportunity cost for silage production, on the agricultural production region level, from the Agriwise business-calculation database (Agriwise, 2019). This is motivated by the fact of the two crops being cultivated on similar types of lands, using similar production processes. The opportunity cost is based on the costs for silage production and foregone profits for spring barley, when the land is used for biofuel feedstock. Moreover, we assume three cost categories \( f \) in the stepwise linear supply function. For the land currently used for ley production or not being used, which we assume is available for feedstock production, we assume that half can be used to produce feedstock of cost category 1 and half for cost category 2. When land currently used for crop production is used for feedstock production, we assume this is associated with cost category 3. The resulting feedstock opportunity costs are shown in Figure 4. The cost for the second cost category is calculated using the price elasticities for forage products in Sweden at the NUTS2 level from the CAPRI database (CAPRI Modelling System, 2020) (see table PELAGRP), ranging from 0.08 to 1.5. Thus, a 25 per cent reduction in the area of land for forage production would increase feedstock production costs differently for each NUTS2 region. For the third cost category, we use the same price elasticity, calculating the effect of a 50 per cent reduction in the area of forage crops (corresponding to a situation where more than 50 per cent of the area ley and fallow land is used for feedstock production).

For each unit transported, there is both a fixed cost for loading and unloading and a distance-based cost for transportation. These costs are based on transport costs for wood chips and ethanol in Sweden from de Jong et al. (2017) and given in Table A2.b.
A2.4.1. Marginal cost
To approximate marginal cost we take the average total cost increase per extra unit of biofuel between the applied production level and the closest lower production level. The total cost $c_{y}^{TOT}$ for a production level $y$ for a specific scenario in the country is given by

$$c_{y}^{TOT} = \sum_{i} \left( c_{i}^{INV} + c_{i}^{OP} + c_{i}^{FEED} \right) + \sum_{i} c_{i}^{TR} + \sum_{i} c_{i}^{DISTR}.$$  \hspace{1cm} (A2.1)

The marginal cost, $MC_{y}^{TOT}$, is given by

$$MC_{y}^{TOT} = \frac{c_{y}^{TOT} - c_{y-\Delta y}^{TOT}}{\Delta y}.$$  \hspace{1cm} (A2.2)

where $\Delta y$ is the difference in biofuel production between two production targets in the scenarios, i.e. 150,000 m³ ethanol.

A2.5. Emissions
A2.5.1. Emission calculation
Emissions from biofuel production are assumed to be linearly related to the different steps in the production process. We assume emissions from feedstock, $e_{i, g}^{FEED}$, to be differing regionally based on geographic characteristics with emission intensity $\varepsilon_{i, g}^{FEED}$ for each unit of feedstock, while other emissions are equal across the country: $e_{i, g}^{OP}$, for production, $e_{i, g}^{TR}$, for transport of feedstock $e_{i, h}^{DISTR}$, and for transport of biofuel with emission intensities, $\varepsilon_{i, h}^{OP}$, $\varepsilon_{i, h}^{TR}$, and $\varepsilon_{i, h}^{DISTR}$. The emission from transport depends linearly on distances in addition to volume.

$$e_{i}^{OP} = \varepsilon_{i}^{OP} y_{i}$$  \hspace{1cm} (A2.3)

$$e_{i, g}^{FEED} = \varepsilon_{i, g}^{FEED} x_{i, g}$$  \hspace{1cm} (A2.4)

$$e_{i, g}^{TR} = d_{i, g} \varepsilon_{i, g}^{TR} x_{i, g}$$  \hspace{1cm} (A2.5)

$$e_{i, h}^{DISTR} = \varepsilon_{i, h}^{DISTR} d_{i, h} y_{i, h}$$  \hspace{1cm} (A2.6)

The total reduction $r$ in emissions is calculated based on the volume of gasoline that the ethanol, $y_{i, h}^{DISTR}$, could substitute, and the gasoline emission factor $\varepsilon_{i, h}^{GAS}$, less the emission of ethanol:

$$r = \sum_{i} \left( \sum_{h} y_{i, h}^{DISTR} \varepsilon_{i, h}^{GAS} - e_{i}^{OP} - \sum_{g} \left( e_{i, g}^{FEED} + e_{i, g}^{TR} \right) - \sum_{h} e_{i, h}^{DISTR} \right).$$  \hspace{1cm} (A2.7)

A2.5.2. Marginal abatement cost
Marginal abatement cost is given by the marginal cost per marginal abatement at a production level $y$ ($r_{y}$). First, marginal abatement is given by

$$MA_{y}^{TOT} = \frac{r_{y} - r_{y-\Delta y}}{\Delta y}.$$  \hspace{1cm} (A2.8)

Marginal abatement cost $MAC_{y}^{TOT}$ also deducts the forgone marginal costs for gasoline per m³ biofuel, $p_{0}^{GASOLINE}$. The forgone marginal costs for gasoline, $p_{0}^{GASOLINE}$, is based on
the Swedish gasoline price, EUR 1500 per m³ (Swedish Energy Agency, 2021), less the carbon tax, EUR 120 per ton CO₂:

\[ MAC_y^{TOT} = \frac{MC_y^{TOT}}{MA_y^{TOT}} - p_0^{GASOLINE}. \] (A2.9)

A2.5.3. Emission data
Data on emissions from feedstock production, \( \varepsilon_{i}^{FEED} \), was taken from Ahlgren et al. (2011) who give emission intensities in g CO₂ eq/kg dry matter crop, for reed canary grass at the county level in Sweden. Data on emission from the biofuel production, \( \varepsilon^{OP} \), were taken from Bonomi et al. (2019), reporting numbers from the New EC Bioenergy model, with the case of ethanol made from wheat straw in Europe. Emissions for transport of feedstock was taken from Leduc (2009), and \( \varepsilon^{TR} = 48 \text{ g CO₂/km/ton} \). For similarity with \( \varepsilon^{TR} \), emissions for transport of biofuel \( \varepsilon^{DISTR} = \varepsilon^{TR} \frac{\varepsilon_{FEED}^{FEED}}{\varepsilon_{FUEL}^{FUEL}} \text{ CO₂ km/m}^3 \). Data on the emissions from the combustion of gasoline and diesel were taken from Swedish Environmental Protection Agency (2019), given in kg CO₂/l ethanol with \( \varepsilon^{GAS} = 1.5 \).

A2.6. Impact on animal production
Data on ley production and the number of LSUs for grazing animals are used to calculate the potential impact on animal production. To calculate the change in land for ley production, we take the amount of land used for biofuel feedstock production in a region and subtract the initial level of fallow land and land of unknown use, as these are assumed to be used first, and not counted as used for ley production. The number of grazing animals (cattle and sheep) per county were obtained from the Swedish Board of Agriculture (2020b) and transformed into LSUs (Eurostat, 2020b). Dividing change in hectares by the LSU numbers we get the direct change in LSU per hectare.

Appendix A3: Software
Results are calculated using the GAMS software, using version 30.3 for calculating starting values in first simulation that optimises the model without considering demand distribution (GAMS Development Corporation, 2020) and 24.7 when running the full model using the starting values (GAMS Development Corporation, 2016). The optimisation is solved with the OSICPLEX solver. The solutions are calculated with a minimum gap tolerance from optimality equal to 1 per cent for starting values and 2.5 per cent for the full model.

Appendix A4: Results
Figure A4. (a) Unit costs for facilities in the Target levels 70 percent scenario. (b) Sequential scenarios—production of ethanol at each facility. Blocks representing low- and high-capacity facilities respectively, with production at each site shown by the size of the block. Shaded block represents intermediate steps. (c) Production of ethanol at each facility—sequential scenarios. Blocks representing low- and high-capacity facilities respectively, with production at each site shown by the size of the block. (d) Hectares of land for forage production per LSU, with and without biofuel production in Target 70 percent.
Table A4.a. Marginal abatement costs for different Target-level scenarios. EUR per kg CO$_2$

| Scenario | EUR per kg CO$_2$ |
|----------|------------------|
| 10%      | 0.17             |
| 20%      | 0.22             |
| 30%      | 0.23             |
| 40%      | 0.21             |
| 50%      | 0.30             |
| 60%      | 0.29             |
| 70%      | 0.26             |
| 80%      | 0.35             |
| 90%      | 0.42             |
| 100%     | 0.53             |