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RESEARCH ARTICLE

Cost-effective use of abandoned agricultural land for biofuel production

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Abstract

Biofuel can be used to abate greenhouse gas emissions in the transport sector, by replacing fossil fuel. To avoid the problem of competition with food production, the use of abandoned agricultural land (AAL) for production of the feedstock for biofuel has been proposed. AAL has generally low productivity but has also low opportunity costs, and production of perennial bioenergy crops on it can lead to carbon sequestration. A spatially explicit optimization model of biofuel production and transport fuel consumption, applied to Sweden, was used for an analysis of how AAL can alter costs for greenhouse gas emissions abatement. Results show that, compared to the case without AAL, AAL could decrease the costs of reducing greenhouse gas emissions by 29%, for emissions reductions equivalent to 50% of current emissions from gasoline in Sweden. The carbon sequestration from establishing perennial bioenergy crops on AAL is the main driver of the positive results. High carbon sequestration on AAL implies larger emissions reduction for a given volume of biofuel, and the results show that the total biofuel production can be both smaller and larger with AAL. The use of arable land for biofuel production is generally smaller with AAL, but larger at some of the highest analyzed target levels. The low AAL feedstock costs contribute to lower costs of the total biofuel production, which pushes for more total biofuel production and less fuel use reduction and therefore counteracts the reduced use of arable land.

KEYWORDS

abandoned agricultural land, biofuel, carbon sequestration, cost minimization, greenhouse gas emissions, localization, perennial bioenergy crops, spatial model, transport sector

1 | INTRODUCTION

The use of biofuels is a greenhouse gas (GHG) emissions abatement measure that is relatively easy to implement in the transport sector in the near future, as biofuels can be blended into fossil fuel (Debnath et al., 2019). Despite their merits, biofuels are debated, as the production of feedstock competes with other land uses. The debate particularly focuses on the agricultural sector, as the competition can lead to overall higher GHG emissions, lower food production, and increased food prices globally (see e.g., Jeswani et al., 2020; Searchinger et al., 2008). While first generation bioenergy crops such as rapeseed and cereals used for biofuel production lead to the largest competition with food production (Jeswani et al., 2020), second-generation bioenergy feedstock, for example, perennial bioenergy crops (PBC) and forest residues, are potentially less problematic. The PBC plantations have a growing period of several years and require less tillage and fertilizer application than first generation crops. PBCs are high energy yielding crops and can, with relatively good results, be grown on low productive land currently used for fodder production and grazing, and on abandoned agricultural land (AAL) (Valentine et al., 2012). Using such low productive land means there is no direct competition with food production, but it affects meat production, and thus food, indirectly. AAL is commonly defined as land that has been in agricultural use for crops or grazing, is not in use anymore, and is not converted to forest or artificial areas (Perpiña-Castillo et al., 2021). The use of AAL is of special interest to investigate as, since there is no current food production on it, there is little risk of competition with food production.

The PBCs can be used as feedstock for so-called advanced biofuel technologies (Brown et al., 2020). The advanced biofuels, for example, cellulosic ethanol, biogasoline and biodiesel, can, just like first generation biofuels, be used in combustion engines by blending them into fossil fuel. Thus, they reduce the GHG content of the fuel and can be used in existing car fleets without further vehicle investments. The main reason that advanced biofuels are not used extensively yet is that the technologies are not yet fully mature, and thus still too costly for commercialization (Brown et al., 2020). The abatement potential of these biofuels is larger than for first generation biofuels, as the emissions from feedstock production are lower (Valentine et al., 2012).

Policies promote the use of biofuel, for example, the EU's Renewable Energy Directive (II) stipulates that at least 14% of energy used in the transport sector should be renewable by 2030 (European Parliament, 2018). Most EU member states have implemented biofuel blending mandates for fossil fuels (USDA, 2022).

The purpose of this study is to assess the impact of AAL as an additional source of land for production of second-generation feedstock for domestic biofuel on the cost-effectiveness of blending in of biofuel as a GHG abatement measure. First, the study quantifies how much the use of AAL for biofuel feedstock production affects the cost of reducing GHG emissions in the transport sector, compared to only being able to employ arable land that is currently in use. Second, it shows what impact AAL has on the cost-effective level of production of biofuel and on biofuel's contribution to emissions reduction in the transport sector. Thirdly, it investigates what aspects of AAL drive the changes in costs for GHG emissions reduction. A spatial optimization model gives answers to these questions. The model organizes biofuel production spatially, and allocates emissions abatement in the transport sector between replacing fossil fuel with biofuel and reducing transport fuel consumption, to reach emissions reduction targets at the least cost. The model takes into account spatial relationships and regional differences in costs and emissions, and is parametrized with Swedish data.

The cost-effective production of biofuel depends on feedstock costs, investment costs, transport costs, net emissions from biofuel production and avoided fossil emissions, and other related abatement options (e.g., Nordin et al., 2022a). Economies of scale of the production facilities, and large transport costs for feedstock characterize biofuel production, which results in a trade-off between agglomeration and dispersion forces (a land allocation problem described in the von Thünen model; see e.g., Wood & Roberts, 2010, pp. 16–19). Considering AAL as potential land for feedstock production, more feedstock can potentially be produced in each region, which can reduce transport costs. This promotes centralization and makes it easier to exploit the economies of scale by investing in larger production facilities. Feedstock produced on AAL can avoid the high opportunity costs that could arise from large-scale biofuel production on arable land, as there is little or no competition over land on AAL. However, the reason for abandonment is primarily low productivity of land and land degradation, and abandonment occurs most often in remote areas (Perpiña-Castillo et al., 2021). Due to these characteristics, and the fact that the land might have to be cleared before cultivation, production of PBC on AAL can be costlier than on more productive land. However, PBCs can be profitable on AAL when food production is not, as the production costs are comparably lower for PBCs than for other crops. This is because PBCs need less frequent new establishment, and the yields are higher than for fodder and food crops (Valentine et al., 2012).

Cultivation of PBCs leads to direct GHG emissions (e.g., from fertilization), but these are generally lower than for annual crops (Valentine et al., 2012). In addition, planting PBCs on cropland or abandoned cropland can lead to large carbon sequestration (Berndes et al., 2011; Naess et al., 2023). The degree to which carbon sequestration can be accounted for depends on how permanent the land use change is, and if it gives rise to so-called indirect land use changes in other places to compensate the land lost for food production (Berndes et al., 2011).

The relevant literature for this study includes that analyzing the economic potential of using AAL and other marginal land for biofuel production. Marginal land is a diffuse concept but often refers to land that has low productivity and difficulties in making economic profit, and AAL is often seen as one type of marginal land (Khanna et al., 2021). To study the economic potential of using marginal agricultural land, Bryngelsson and Lindgren (2013) build an economic model of agricultural land use for bioenergy purposes. They find that rather than using low productive land for bioenergy, high productive land would be used to a greater extent, pushing away existing agricultural production to low productive land. Choi et al. (2019) model the optimal distribution of supply of biomass for bioenergy to reach an emissions target with an energy model linked to an agricultural land use model. They find significant use of several land types to produce bioenergy crops but only a small proportion of marginal land is used. Both studies also find an impact on food prices when bioenergy is restricted to marginal land, as it increases land rents. Havlík et al. (2011) use a global economic partial equilibrium model for different land uses, to study the impact of meeting the demand for biomass for biofuel. Lee et al. (2023) use a model of the agricultural sector and the fuel market in the US to study consequences of meeting biofuel mandates for ethanol based on PBCs under uncertain parameter assumptions. Weng et al. (2019) introduce an exogenous demand of ethanol into a computable general equilibrium model for China, with a coupled land allocation model, including marginal land. When they allow usage of marginal land, the impact on food consumption decreases, and production on the whole area is steered to more non-grain feedstock. Liu et al. (2017) use bottom-up calculations to estimate economically viable production, and cost of bioenergy from marginal land in Canada. Similarly, Nilsson et al. (2015) estimate the profitability of PBCs on marginal land in Sweden and find a net economic loss.

While other studies have investigated the economic potential of marginal land to contribute to biofuel feedstock production, this study contributes by the specific focus on AAL, and by including the impact of spatial relations between regions in the analysis, where the latter is important for production facility investment. The study improves the understanding of the possibilities of AAL as a previously unused source of feedstock to enhance biofuel as a cost-effective abatement measure. The Swedish case study adds to the knowledge of biofuel in Sweden, and countries with a similar agricultural landscape as Sweden, which is dominated by forest, but with high productive soils in some parts of the country.

The article continues with a description of the model and the data. This is followed with a section outlining the scenarios used to investigate the impacts of AAL, and an analysis of the results. There is then a discussion of the results and, finally, conclusions.

2 | MATERIALS AND METHODS

This study uses a spatial model that optimizes domestic fuel consumption in the road transport sector in order to reach a GHG emissions reduction target. Domestic biofuel production is modelled endogenously. This makes it possible to capture how regionally differing levels and properties of feedstock production on AAL impact on the total cost of reaching a policy target for GHG emissions reduction. Here follows a brief overview of the model, while the subsequent sections describe the explicit modelling of AAL, and emissions, in detail. The interested reader can find a complete documentation of the model in Nordin et al. (2022a) and (2022b).

2.1 | Spatial optimization model for transport fuel consumption and biofuel production

The model is spatially explicit, with 290 regions. It is static, modelling a near-time future for the road transport sector in a small economy, the latter accompanied with an assumption of no fuel price changes. It optimizes localization and quantities of transport fuel consumption, biofuel production, and feedstock production based on regional characteristics and spatial relationships between regions. The objective of the model is to minimize the cost of meeting a countrywide GHG emissions reduction target for the road transport sector. Emissions reduction can be achieved using two abatement measures: (i) blending domestically produced biofuel into fossil fuel, and thus replacing fossil fuel in transport fuel, and (ii) reducing the consumption of transport fuel. Reduced consumption of transport fuel can be realized by reducing travel, changing to more efficient combustion engines, changing travel modes, or such like, where the mix is implicit in the model. The fuel reduction leads to costs in terms of reduced consumer surplus, which is net of the decrease in fuel purchase costs. Empirically, the reduction in consumer surplus is modelled with a fuel demand function with increasing marginal cost, using long-term road transport fuel consumption elasticities.

The modelling of biofuel production includes the discrete choice of the number and localization of production facilities to some regions in the country. Further, the model optimizes the capacity level of each facility, the feedstock uptake of each facility from feedstock producing regions in the country, the transport of feedstock to production facilities, and the transport of biofuel to end users.

Biofuel is blended into fossil fuel, but cannot exceed a certain share of the total fuel product. Facility investment costs are characterized by economies of scale, biofuel operations costs are linear in feedstock volume, transport costs are linear in feedstock and biofuel quantity and transport distance, and feedstock supply costs are increasing, reflecting competition for agricultural land. There is assumed to be one type of feedstock, perennial bioenergy crops (PBC). This can be produced on arable land and on AAL, and is restricted to use less than a given share of total arable land in each region. The marginal cost of feedstock production on arable land increases with the volume in each region, due to competition over land. AAL is described in detail in Section 2.2 and 2.3. The net cost of using biofuel as an abatement measure consists of all the costs for producing the biofuel, a value added tax on the total biofuel production costs, less the avoided costs for the purchasing the replaced fossil fuel.

2.2 | Greenhouse gas emissions

Both abatement by reduction in transport fuel use, and by replacing fossil fuel with biofuel lead to a reduction of fossil fuel use and thus a reduction in GHG emissions. However, biofuel production can also give rise to, or reduce, emissions, depending on the type of feedstock production. Total emissions, e^{TOT} is given by:

$$e^{\mathrm{TOT}} = \sum_h \left(e_h^{\mathrm{die}} + e_h^{\mathrm{gas}}\right) + \sum_g \sum_i e_{i,g}^{\mathrm{TR}} + \sum_h \sum_i e_{i,h}^{\mathrm{DISTR}} + \sum_i e_i^{\mathrm{OP}} + \sum_g \left(e_g^{\mathrm{FEED}} + e_g^{\mathrm{LUC}}\right), \tag{1}$$

where e_h^{die} and e_h^{gas} are emissions from diesel and gasoline use, respectively, $e_{i,g}^{\mathrm{TR}}$ and $e_{i,h}^{\mathrm{DISTR}}$ are emissions from feedstock transport and biofuel distribution respectively, e_i^{OP} are emissions from operations at biofuel production facilities, e_g^{FEED} are emissions from feedstock production due to soil management, and e_g^{LUC} is carbon sequestration due to land use changes (LUC), which is negative. The e_g^{LUC} is described in detail below. All of the indices i, g, and h denote the 290 municipalities in Sweden, where $i = 1, \ldots, 290$ denotes the regions where production facilities are located, $g = 1, \ldots, 290$ denotes the regions where feedstock is produced, and $h = 1, \ldots, 290$ denotes the regions to which the biofuel is delivered and consumed.

A LUC from arable land or AAL to PBC plantation can lead to carbon sequestration, but only carbon sequestration for AAL is accounted for in the model, as the LUC on arable land could lead to so-called indirect land use changes (iLUC). The iLUC take place as PBCs uses the land previously used for for example, food production. Since there is still a demand for food, this can lead to an expansion of arable land for food production at another place, a LUC that releases carbon and counteract the initial carbon sequestration. The net effect is uncertain and can result in low, zero or even high net LUC emissions from PBC on arable land (Mignone et al., 2022; Taheripour et al., 2017). In the model, the assumption is net zero LUC emissions on arable land. Using AAL, food production is not affected by LUC to PBC plantation, as AAL is abandoned, and does not risk causing iLUC, therefore all carbon sequestration is assumed to be valid. These assumptions are relaxed in a set of scenarios. The carbon sequestration in annual emissions per tonne of feedstock, ϑ_g, can differ between regions. The resulting carbon sequestration from LUC, e_g^{LUC}, is

$$e_g^{\mathrm{LUC}} = \vartheta_g x_{a,g}. \tag{2}$$

2.3 | Land use

In this study, AAL is included as land that can be used for feedstock production. This means that both arable land and AAL can be used for feedstock production, extending the available land area, and a choice between land with different properties. Yield differs between AAL and arable land in each region, but the feedstock is a homogeneous product of the same quality, and thus of equivalent use for biofuel production. The variable $x_{b,g}$ denotes the total amount of feedstock produced in any feedstock producing region g, and b denotes land categories, with $b = f, a$. Here, f is the arable land, and a is AAL. The AAL feedstock cost function, $c_{a,g}^{\mathrm{FEED}}$, has increasing marginal costs. This is modelled with a stepwise constant cost function that uses segments of $x_{a,g}$, each having constant costs. AAL is converted to PBC plantation by, for example, clearing for bushes, which comes at a one-time conversion cost. The annualized conversion per tonne of feedstock is denoted θ_a. It is assumed that the AAL that is least expensive to convert is used first, and that the conversion cost increases with the level of $x_{a,g}$, as the land that is more expansive to convert is used. The annual operational cost for feedstock production on AAL, $\omega_{a,g}$, is constant per tonne of feedstock in each region:

$$c_{a,g}^{\mathrm{FEED}} = \theta_a\left(x_{a,g}\right) + \omega_{a,g} x_{a,g}. \tag{3}$$

The amount of feedstock that could be produced on the total area of AAL in each region, $\overline{x}_{a,g}$, restricts the possible feedstock production on AAL:

$$x_{a,g} \leq \overline{x}_{a,g}. \tag{4}$$

Just like feedstock from arable land, all $x_{a,g}$ in one region g is transported to different production facilities i, with $x^{TR}_{a,i,g}$ being the feedstock from AAL transported to each facility. This gives the feedstock use balances:

$$x_{a,g} = \sum_i x^{TR}_{a,i,g}. \quad (5)$$

Each biofuel production facility can use feedstock from different sources and regions to produce biofuel:

$$y_{bio,i} = \alpha \sum_g \sum_b x^{TR}_{b,i,g}, \quad (6)$$

where $y_{bio,i}$ denotes the production of biofuel at facility region i, and α is a conversion coefficient of feedstock into biofuel.

2.4 | Data

Below follows a detailed description of the data on AAL, and related data on arable land. For all other spatially differentiated data that parametrize the optimization model, see Nordin et al. (2022a) and (2022b). Costs are annual or annualized, and at 2019 price levels.

2.5 | Area of abandoned agricultural land and costs of feedstock production

For the area of AAL, the results from a study by Olofsson and Börjesson (2016) is used. They use GIS analysis, and estimate the area of AAL on old cropland in Sweden to be 88,000 ha. The geographical information is used to allocate the areas of AAL to municipalities in the model. This is performed by overlaying polygons of AAL with the geographical extent of the municipalities. The information from the municipality accounting for the largest area of the AAL polygon is attributed to that polygon. The total area of AAL is aggregated to each municipality. About 1.6% of the AAL area was not allocated to a municipality in the original dataset and was therefore distributed to municipalities based on their share of total AAL area (cf. Olofsson and Börjesson (2016) for counties). Abandoned old pasture is omitted from the current study as it often has high nature values, implying that it should be preserved. Use of arable land is restricted in the model; 50% of land used for ley production and 10% used for crop production is allowed to be used for feedstock.

The data on yield per hectare on AAL is on a county level, obtained from Panoutsou (2017). AAL is assumed to have the lowest yield reported in each region. Combining areas and yield levels results in a maximum production of feedstock from AAL of 250 kt, which can be compared to the maximum of 5800 kt from arable land.

Costs for conversion of land to PBC cultivation are from Havlík et al. (2011). The operations cost for feedstock production on AAL are from Panoutsou (2017), using per hectare costs for low productive land at county level, recalculated to costs per tonne feedstock. This results in costs of feedstock, from AAL ranging from €150 to €260 per ton dry matter feedstock, while the span is €83 to €2470 for arable land, although only a few municipalities have feedstock costs above €586 (excluding value added tax). The feedstock production cost on arable land takes into account increases in opportunity costs resulting from competition at higher levels of feedstock use. These are updated in this study to equal Separable costs 4 per hectare in the Agriwise business calculation data base (Agriwise, 2019).

2.6 | Greenhouse gas emissions

Feedstock production gives rise to emissions from crop management, mainly from synthetic fertilization. These emissions are spatially differentiated and are assumed to be equal per hectare for AAL and arable land. Carbon sequestration due to LUC consists of increases in above ground biomass and soil organic carbon (SOC), which is organic carbon in the form of for example, humus and living microorganisms in the soil (Berndes et al., 2011). Land use can be classified into land classes with different properties; some of the main land classes used by the IPCC (Penman et al., 2003) are cropland, grassland and forest. For AAL, the initial land class before it became abandoned is cropland, while a field with PBC is more similar to grassland. Therefore, to calculate the emissions from changes in above ground living biomass, this study uses the assumption that the LUC is from cropland to grassland for old cropland AAL. These emissions are quantified with county level data from Ruesch and Gibbs (2008), who estimate an average of 0.7 t CO_2 sequestered per hectare and year. For SOC, a European average is used for conversion from old cropland AAL to reed canary grass (Iordan et al., 2023), with 5.1 t CO_2 carbon sequestered per hectare and year (annualized over 15 years). The SOC changes are uncertain, but for old cropland AAL they are similar to other studies for conversion of cropland and old cropland AAL for bioenergy purposes: 4–5.7 t CO_2 sequestration per hectare and year (Bell et al., 2020; Ledo et al., 2020; Næss et al., 2023; Qin et al., 2016). In total, the change in emissions due to carbon sequestration is large and negative for AAL that is converted to PBCs, and emissions from crop management are small but positive.

3 | RESULTS

3.1 | Scenario setup

Several sets of scenarios are constructed to analyze the impact of AAL on costs of achieving emissions reduction targets, and on emissions abatement strategies.

Details of the scenarios are given in Table 1. The *R10* to *R100* scenarios are used as reference scenarios. In these, emissions reduction target levels equivalent to 10 to 100% of current gasoline emissions have to be reached. The reduction can take place through reducing transport fuel consumption of gasoline and diesel, and by blending in biofuel with gasoline, thus replacing gasoline in a gasoline-biofuel blend. In these scenarios, AAL cannot be used.

The main scenarios quantifying the impact of AAL are *R10 AAL* to *R100 AAL*. In these scenarios, the same targets as in *R10* to *R100* must be reached, and all AAL can be used for biofuel production. These scenarios are compared to the reference scenarios.

Three aspects of AAL distinguishes it from arable land: (i) the cost for feedstock on AAL is generally lower than on arable land, (ii) the land use change of AAL to PBC fields leads to carbon sequestration, which makes the emissions abatement from biofuel of feedstock produced on AAL greater than that from feedstock produced on arable land, and (iii) the area available for feedstock production in each municipality of the country increases by the area of AAL.

The parameter values of these aspects of AAL are varied in nine scenarios to find out how they affect the cost-effective solution, and how sensitive the results are to the variation, reflecting uncertainties. The emissions reduction target level is set to equal the target level in *R40* for all these scenarios. First, the *Cost high* and *Cost low* scenarios varies the AAL specific feedstock cost by ±50%, respectively. In the *Arable land cost* scenario AAL have the same

TABLE 1 Scenario overview.

Scenario	Target	AAL area	AAL cost	LUC assumption
R10/…/R100	Emissions reduction 10/…/100% of current gasoline emissions	No AAL used	No AAL used	No LUC emissions
R10/…/R100 AAL	As in R10/…/R100	Full AAL area	Base AAL cost	Base LUC emissions
Cost high	As in R40	Full AAL area	150% AAL cost	AAL has base LUC emissions
Cost low	As in R40	Full AAL area	50% AAL cost	Base LUC emissions
Arable land cost	As in R40	Full AAL area	AAL feedstock costs as for arable land, on the high end of the cost function	Base LUC emissions
Emissions high	As in R40	Full AAL area	Base AAL cost	150% of base LUC emissions
Emissions low	As in R40	Full AAL area	Base AAL cost	50% of base LUC emissions
Arable land emissions	As in R40	Full AAL area	Base AAL cost	No LUC emissions
Area high	As in R40	150% AAL area	Base AAL cost	Base LUC emissions
Area low	As in R40	50% AAL area	Base AAL cost	Base LUC emissions
AAL area	As in R40	Full AAL area	AAL feedstock costs as for other feedstock, on the high end of the cost function	No LUC emissions
Arable LUC	As in R70	No AAL used	No AAL used	Arable land has base LUC emissions
Low arable LUC	As in R70	No AAL used	No AAL used	Arable land has 50% of base LUC emissions
Arable LUC AAL	As in R70	Full AAL area	Base AAL cost	Arable land and AAL has base LUC emissions
Low arable LUC AAL	As in R70As in R40	Full AAL area	Base AAL cost	Arable land has 50% of base LUC emissions, AAL has base LUC emissions

feedstock cost function as feedstock from arable land. It is then assumed that the feedstock production costs on AAL equals that on the most expensive arable land in that region, which is considered in the model. AAL still have the AAL specific carbon sequestration, and therefore shows how this aspect of AAL affects the results. Second, the carbon sequestration rate is tested, by varying the carbon sequestration rate by ±50% in the *Emissions high* and *Emissions low* scenarios. In addition, in *Arable land emissions* the AAL does not lead to carbon sequestration, but generates the same emissions as feedstock from arable land. The AAL still have the AAL specific feedstock cost, and thus also show the isolated impact of the AAL cost. Lastly, the focus is on the AAL area: the AAL area is varied by ±50% in *Area high* and *Area low*. The isolated effect of the increase in area available for feedstock production is shown in *AAL area*, where the area available for feedstock production increases by an area equal to that of AAL, but with feedstock costs and emissions equal to that for feedstock from arable land.

PCB production on arable land is not assumed to lead to carbon sequestration in this study, as indirect land use changes (iLUC) can counteract the carbon sequestration. To see the impact of no or partial iLUC, this assumption is relaxed in four additional scenarios, all with the emissions reduction target level equalling the target level in *R70*. First, two new reference scenarios, where AAL cannot be used, are constructed: one in which the carbon sequestration on arable land is the same per tonne feedstock as for AAL (*Arable LUC*), and one in which the carbon sequestration on arable land is half of the carbon sequestration on AAL (*Low arable LUC*). Two new scenarios with AAL are constructed, which should be compared to the new reference scenarios. In the first, the carbon sequestration on both arable land and AAL is the same as the base assumption for AAL (*Arable LUC AAL*). In the second, the carbon sequestration on arable land is half the parameter value for the base assumption for AAL, but for AAL it remains the same (*Low arable LUC AAL*).

The model is optimized for the different scenarios, and solved with GAMS optimization software (GAMS Development Corporation, 2022), using GAMS version 38, with a mixed integer solver (OSICPLX), set to tolerate a relative gap from the objective value of 0.5%. The model version used for this study including data is available in an open repository (Nordin, 2024).

3.2 | Quantified results

This section reports the results from the scenarios in terms of impact of AAL on total cost, marginal costs, biofuel production, what type of abatement measure is applied, feedstock use, and how different aspects of AAL drive the results and are sensitive to variations in their parameter values. Lastly, the impact of different assumptions of iLUC for arable land are described.

3.3 | Impact of AAL on costs

The total costs for meeting the emissions reduction targets decrease significantly with AAL. The orange bars in Figure 1a, show the total costs for achieving the 10 to 100%

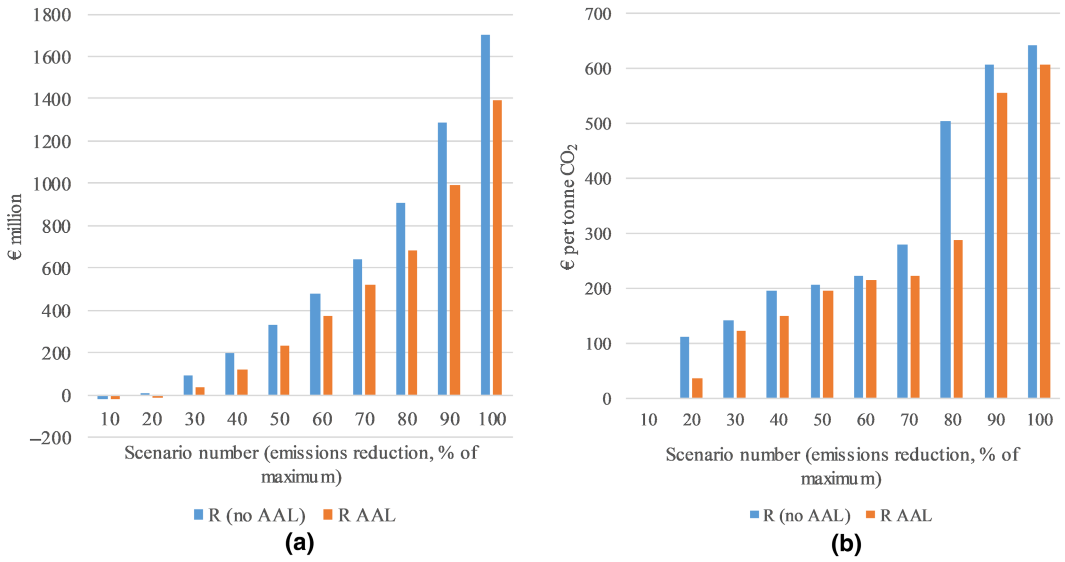

FIGURE 1 (a) Total annual cost in million € and (b) marginal abatement cost in € per tonne CO_2. Both for a set of emissions reduction targets, ranging from 10% to 100% of maximum emissions reduction without AAL: R (blue) and with AAL (orange).

emissions reduction targets with AAL (scenario *R10 AAL* to *R100 AAL*). These are €0 to €314 million lower than the total costs in the reference scenarios *R10* to *R100* (blue bars). That is a rise in the absolute cost differential with the level of stringency in emissions reduction targets. This indicates that AAL contributes to the overall cost savings at high target levels, even though the whole area of AAL is used for feedstock already at low target levels. Conversely, the relative cost differential declines, from 63% to 18%, over the same range of emissions reduction targets (for the lowest target levels, the comparison is between small negative and positive numbers, which makes the relative comparison difficult, and is therefore omitted). This occurs because although the cost for biofuel production is reduced with AAL, the reduction in transport fuel consumption, with associated costs, represents a larger portion of the overall emissions reduction. Figure 1b shows the marginal abatement costs (MAC) for abatement of GHG emissions under the AAL scenarios (orange bars) and the reference scenarios (blue bars). The figure shows not only that the MAC is lower for AAL, but that the marginal cost saving of AAL varies up and down with the stringency in emissions targets. Initially, the MAC for emissions reductions in the scenarios with AAL is converging to the case without AAL, then the MACs of the reference and AAL scenarios diverge at even more stringent emissions reduction targets, to finally converge again. This pattern is due to the interaction of the two abatement measures. The MAC of the reference scenarios is a result of costs for biofuel production and of reduction in fuel consumption. These two measures interact through the blend-in restriction. This reduces the potential of biofuel at higher target levels, as fossil fuel quantities are strongly reduced. The same happens with AAL, but the costs for biofuel are strongly reduced at low targets for AAL. At high targets, the blend-in restriction limits biofuel for both scenario sets. Thus, the costs of biofuel production are reduced, and then the combination of biofuel and fuel reduction costs change, altering the shape of the MAC curve.

3.4 | Impact of AAL on the allocation of abatement measures

The total reduction in emissions in each scenario can be divided into reductions attributed to transport fuel use, and reductions attributed to biofuel replacement. The results, illustrated in Figure 2 (left-hand axis), show that the share attributable to biofuel replacement (blue) is larger for scenarios with AAL (darker colors) than for scenarios without AAL (lighter colors). The large share emissions reduction attributable to biofuel replacement is mostly explained by a greater share of the emissions reduction resulting from carbon sequestration, while other emissions from biofuel have little impact. This impact of AAL on abatement measures also holds for the higher target levels. The difference is smallest for low target levels, where biofuel blend-in is almost exclusively used. For both sets of scenarios, the share of emissions reduction attributable to transport fuel reduction (orange) increases with the stringency in emissions reduction targets. The dots in Figure 2 (units on the right-hand axis) show the amount of biofuel produced, in terms of energy. The total amount of biofuel is generally higher with AAL, but lower with AAL for the 20% target level, implying that the larger emissions reduction with biofuel based on AAL can outweigh lower emissions reduction due to a reduced biofuel volume. The largest differences in production are for the

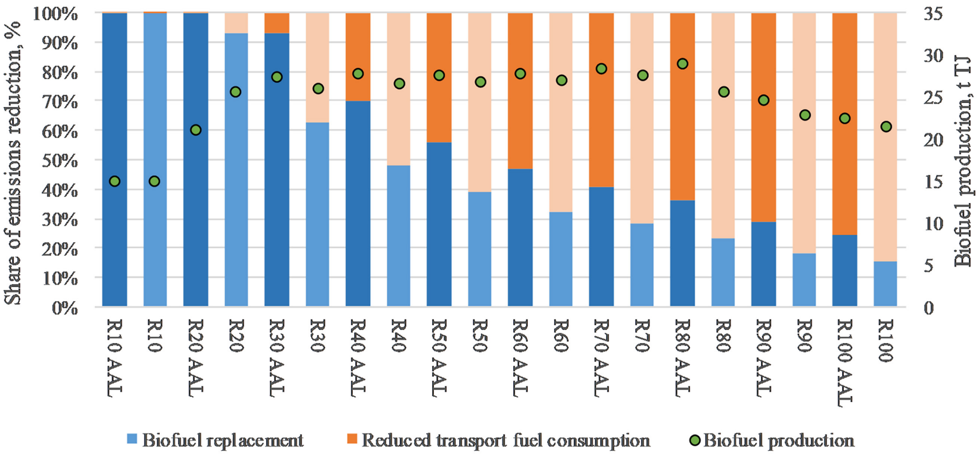

FIGURE 2 Left hand axis: Share of emissions reduction attributed to each abatement measure: Blue bars indicates biofuel replacement, and orange bars indicates reduced transport fuel consumption. Darker colour indicates AAL scenarios. Right axis: Biofuel production in t TJ per year, indicated by green dots.

20% target and the 80% target. For high target levels, the decrease in gasoline is large, and therefore the blend-in restriction limits the use of biofuel, hence biofuel production decreases. For all target levels with AAL except the for 10% and 20% level, biofuel production uses feedstock from 100% of the AAL. The use of feedstock from arable land decreases relative to the reference scenarios, except for the 80% scenario where it increases, and the 30 and 90% scenarios where they are equal (see Figure A1 in the Appendix S1).

Figure 3 shows the organization of biofuel production for *R40 AAL, R40, R70 AAL*, and *R70*, respectively. Blue triangles and squares indicate the production facilities, and the coloured areas indicate feedstock uptake areas. The facilities of the 40% scenarios are almost equal, but *R40 AAL* uses AAL from the whole country, which is transported to the most northern facility. For the 70% target, the scenarios are not equal. *R70 AAL* has one small production facility in the north, which uses the feedstock from the northern regions. The total biofuel production is similar for the 40% and 70% scenarios, but at the higher target, the possibilities to blend-in are restricted, and therefore it a small facility in the north can be important to reduce cost of distributing biofuel to the end users.

3.5 | Disentangling the impacts of AAL

The variation scenarios that show the impact of the lower feedstock costs of AAL, the greater emissions reduction from AAL feedstock, and of the extended area on which to grow feedstock with AAL can be used to determine the most critical factor to measure accurately, understand why results differ for scenarios, and assess the uncertainty of these parameters. The total costs for these scenarios are shown in Figure 4a, where also the results for *R40* and *R40 AAL* are shown with darker color and dotted lines, for comparison. The difference between these two scenarios is €75 million.

Total costs varies equally much in both directions with the AAL feedstock cost: compared to *R40 AAL* costs are higher in *Cost high*, and lower in *Cost low*. With an assumption AAL costs equaling feedstock costs for arable land in *Arable land costs*, costs are much closer to the *R40 AAL* scenario than to the *R40* scenario, implying that the costs for AAL has an impact on cost reductions, but the carbon sequestration in this scenarios leads to results close to *R40 AAL*. The variation in costs is greater for the assumption of carbon sequestration, with a smaller decrease compared to *R40 AAL* in *Emissions high*, than the increase in *Emissions low*. With an assumption of no carbon sequestration in *Arable land emissions*, costs are almost as high as in *R40*, implying that the costs for AAL has little impact on cost reductions. Varying the area of AAL shows similar impacts as varying the carbon sequestration rate: a larger decrease in total costs in *Area high* than the decrease in *Area low*. However, only increasing the available feedstock area, without the characteristics of AAL, results in total costs that are almost equal to *R40*. This means that the impact of carbon sequestration is most important with regards to the total cost.

The share of emissions reduction attributable to biofuel is shown as the blue sections of Figure 4b. In the *R40* scenario, the share is 48%, and for *R40 AAL* the share is 70% (both shown in darker colors). Biofuel production levels, reflected on the right-hand axis, are similar for the scenarios: 26.6 t TJ and 27.8 t TJ, respectively. Varying the cost of AAL by 50% has almost no impact on the share

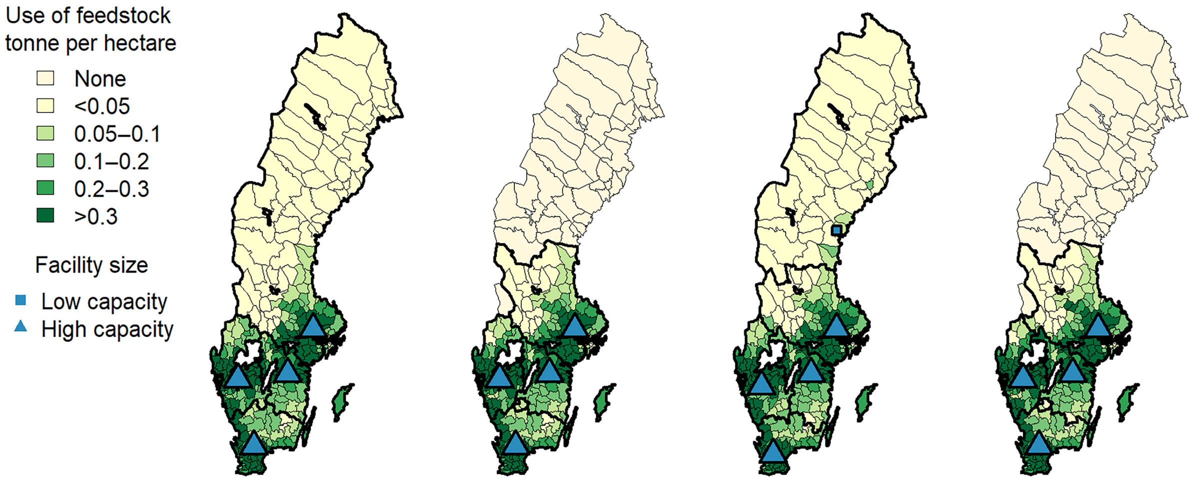

FIGURE 3 Organization of biofuel production. Scenarios, from the left: R40 AAL, R40, R70 AAL, R70. Triangles show facilities with high capacity and squares low capacity. Green areas surrounded by black borders denote areas with supply to a facility. Darker green indicates larger uptake of feedstock.

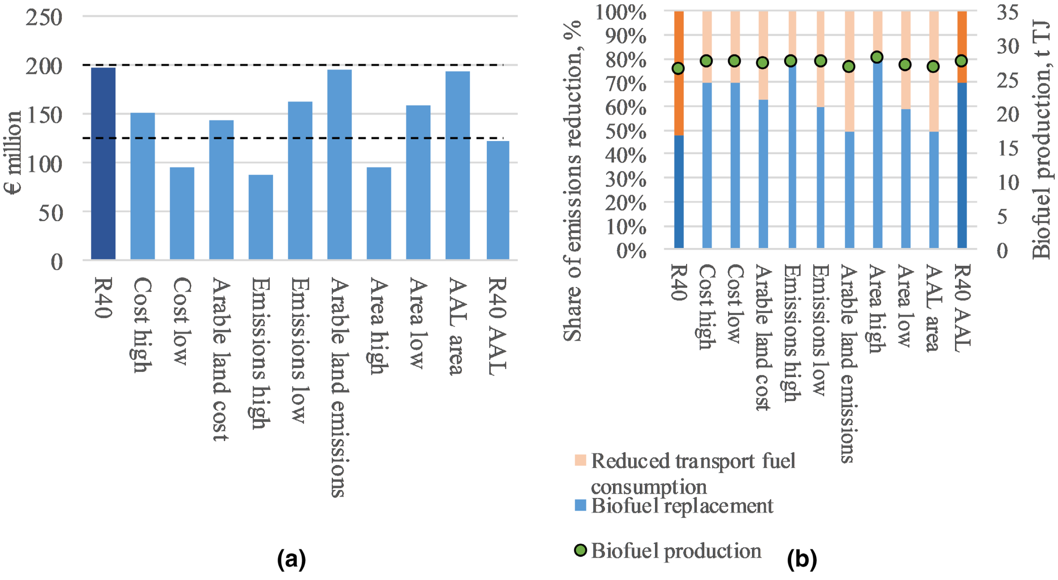

FIGURE 4 Total costs and emissions abatement allocation, for variation scenarios with emissions reduction target 40%. Dark colour indicates reference scenario and AAL main scenario. (a) Total annual cost in million €. Lines indicate reference scenario and AAL main scenario. (b) Emissions abatement allocation and biofuel production. Left hand axis: Share of emissions reduction attributed to each abatement measure: Blue bars indicates Biofuel replacement, and orange bars indicates reduced transport fuel consumption. Right axis: Biofuel production in t TJ per year, indicated by green dots.

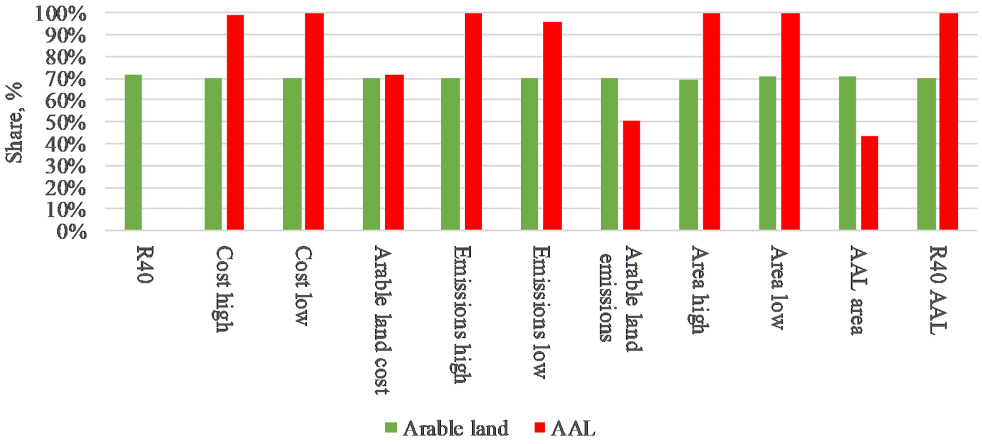

FIGURE 5 Share of total possible feedstock production on arable land (green) and AAL (red), respectively, which is used for the variations scenarios. The total available feedstock on arable land is equal in all scenarios, but for the R40 scenario no AAL is available.

of emissions attributable to biofuel compared to *R40 AAL*, but if AAL feedstock costs are changed to equal the feedstock costs of arable land (carbon sequestration stay the same) the share decreases to 37%. This is explained by the production levels, which stays the same when feedstock costs varies, implying that the AAL is profitable to use also when it increases costs to some degree. This keeps emissions reduction from biofuel the same. The slightly lower production in *Arable land cost*, 27.2 t TJ, is achieved with less use of AAL (see Figure 5 which shows the share of the possible maximum quantity of feedstock that is produced on AAL (red) and arable land (green), respectively, in each scenario), which results in the large difference in allocation of emissions abatement. This suggests that carbon sequestration alone only makes some of the AAL area cost-effective to use. However, the carbon sequestration for AAL makes the net emissions reduction per unit of biofuel much lower than the feedstock from arable land in the *R40*. This increases the total emissions reduction for a given quantity of biofuel, while the lower feedstock costs are needed to reach the full impact of AAL.

Variations in the level of carbon sequestration for *Emissions high* and *Emissions low* plays a large role for emissions attributable to biofuel replacement, which varies from 80 to 60%, while biofuel production levels stay roughly at the level of *R40 AAL*. There is a slight shift to feedstock from arable land instead of from AAL in *Emissions low*, explaining part of the shift in abatement allocation. However, the difference is mostly explained by AAL being used in both scenarios, while the difference in carbon sequestration rates implies differences in emissions reduction for biofuel, and a larger need for emissions reduction from reduced fuel consumption for *Emissions low*. However, without the carbon sequestration altogether, *Arable land emissions* have only 48% of emissions reduction from biofuel replacement. The production level is closer to but still above that for *R40*. 51% of AAL is used since biofuel becomes cheaper with AAL feedstock costs. Hence, it becomes less costly to produce more biofuel than in *R40* than to reduce end fuel consumption, implying that the AAL costs plays a role for production, even though it showed limited impact on total costs.

The variation in AAL area have similar impact on emissions abatement allocation as the carbon sequestration level, showing that it is the total possibility to carbon sequestration that is of importance for allocation of abatement—increasing the AAL area by 50% increases the possibility for abatement by as much as when the carbon sequestration rate is increased by 50%. There is a larger impact on production levels—a large area AAL implies more biofuel has to be produced to realize the carbon sequestration in *Area high*, while there is also a small shift from feedstock from arable land to AAL, and reversely for *Area low*. When only the total land area is extended in *AAL area*, 43% of AAL is still used, and production is larger than in *R40*, while the share emission reduction allocated to biofuel is almost the same.

The variations scenarios have impact on different parts of costs for biofuel, which are indicated in Figure 6. This figure shows the differences in average costs per m^3 biofuel for the modelled cost categories, compared to *R40*. The changes in average total biofuel costs are modest—an increase of about 1% per m^3 biofuel for *R40 AAL*. The largest differences are for feedstock costs, which increases most for scenarios with high AAL feedstock costs and decreases, but less, with low feedstock costs. For other parameter variations the results are similar to for *R40 AAL*, but for *Area high* average feedstock costs are higher since the larger production level requires a larger share more expensive feedstock. Average transport costs are larger for most scenarios with AAL, indicating that transporting feedstock from all AAL in the country increases transports with large distances. These scenarios also have larger production volumes, while scenarios with similar production as *R40* has similar transport costs. Average biofuel distribution costs are smaller for scenarios with AAL, for which reduction of fuel consumption is smaller than for *R40*, and therefore there are larger possibilities to blend in biofuel, potentially at closer distance. Average fixed investment costs are in general lower, as the capacities of the production facilities are larger than in *R40*, and thus benefits from economies of scale. Average variable investment costs are the same for all scenarios as there are only high capacity facilities in all scenarios, and these have the same variable cost. Finally, all production has the same operational costs, and these are therefore equal.

3.6 | Sensitivity to iLUC assumptions

When the assumption of 100% iLUC for arable is relaxed, there is a massive reduction in costs compared to *R70* (shown in Figure A2 in the Appendix S1). Due to the carbon sequestration on arable land, only a smaller volume of biofuel is required to reach the emissions target, and abatement is only made through biofuel replacement. Cost are negative as the reduction in gasoline purchase costs are larger than biofuel production costs at these production

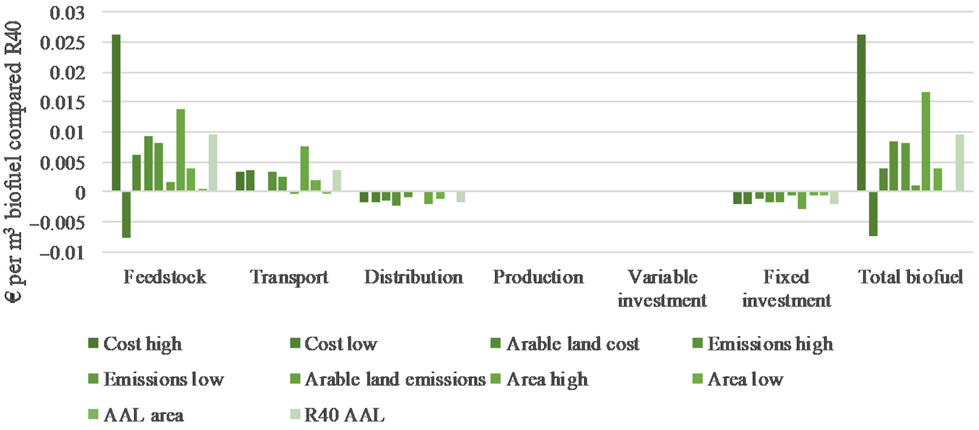

FIGURE 6 Differences in average cost for biofuel, in € per m^3 biofuel, for scenarios compared to the R40 scenario. Costs are divided into different cost categories.

levels. Including AAL, in *Low Arable LUC AAL*, only decreases costs slightly, and in *Arable LUC AAL* there is no change. At this relatively low production levels, the least expensive feedstock is from arable land, and as AAL have no, or limited advantage of carbon sequestration, little AAL is used.

4 | DISCUSSION

Utilizing abandoned agricultural land (AAL) is often proposed as an option for cultivating feedstock for biofuel production, thereby decreasing competition with food production for arable land. The results of this study show that the costs for emissions reduction in the transport sector can be substantially lower when AAL is included as a land use choice for production of second-generation feedstock for biofuel. This was shown with a modelling case study in Sweden, in which the costs of reaching a greenhouse gas (GHG) emissions target in the road transport sector were minimized. AAL decreased the costs of reducing emission equivalent to 50% of current GHG emissions from gasoline in Sweden by 29%, or €97 million, compared to the case without AAL. This happened despite a quite small total area of AAL. This held for a large range of emissions targets and was explained by large carbon sequestration from cultivation of perennial bioenergy crops and relatively low feedstock production costs for AAL. These results suggest that AAL is a cost-effective, currently unused, resource for GHG emissions abatement, in addition to its potential to decrease competition with food production.

While the specific impact of AAL has not been studied extensively in the economics literature, there are several studies investigating the role of the broader category "marginal land", for biofuel production. In line with this study, Havlík et al. (2011) found that the availability of marginal land for biofuel feedstock production decreases competition with food production and the costs to meet a bioenergy production target. Choi et al. (2019) found a lower use of marginal land for production of PBCs to meet an emissions reduction target, than was found in the current study; however, their study does not include carbon sequestration, which is one explanation for the difference in results. Bryngelsson and Lindgren (2013) found that mostly high-productive land, and only some low productive land would be used for bioenergy production. As the objective in their study is to reach a demand for bioenergy crops and not GHG emissions reduction, they did not take into account the positive impact on emissions reduction of carbon sequestration on AAL. Lee et al. (2023) found, in line with the current study, that all marginal land should be used to fulfil a production mandate for cellulosic ethanol at least cost.

Among all the factors that differentiate AAL from arable land, the carbon sequestration potential of PBC had most influence on total cost reduction. The carbon sequestration makes the total emissions reduction for a given amount of biofuel larger. This resulted in reduced biofuel production in some scenarios, while the overall contribution of biofuel to emissions reduction at the same time increased. However, land use change related emissions fluxes, such as carbon sequestration, are associated with large uncertainties. The results showed that with a lower carbon sequestration rate, the impact of AAL on total costs would be lower, but that costs of emissions reduction would still be substantially reduced.

The generally lower feedstock costs on AAL compared to on arable land reduced the total feedstock cost of biofuel, which made biofuel cheaper than reducing fuel use. It resulted in lowered total costs for emissions reduction, and incentivized larger biofuel production. Higher feedstock costs could be anticipated if, for example, some opportunity costs on AAL materialize. This could be the case if much agricultural production is pushed away on arable land. The land might be used for other activities such as recreation (Fayet et al., 2022), and therefore have a value. Further, large scale PBC production is not yet in place and therefore the management costs and the costs of converting AAL to PBC plantations are uncertain. Conversely, increased production could lead to learning effects, and thus lower costs. The results showed that with increased feedstock costs, total costs decreased compared to not having AAL but less than in the main scenario. Therefore, this could be an issue but, qualitatively, the results remain.

The fact that AAL extends the area available for feedstock production only reduced costs slightly. However, it shows an important effect. As biofuel production takes place in a few large production facilities, transport costs will be lower when there is more feedstock in the form of AAL, close to each production facility. This resulted in a slightly increased biofuel production when the area was extended. It shows that the extension of area changed the potential of the whole biofuel supply chain. The spatial mechanism can also explain why AAL could keep decreasing total costs, for increasing stringency of emissions reduction targets. At low target levels, all AAL across Sweden was used, but feedstock had to be transported at greater costs to a few production facilities. With more facilities at the higher target levels, the same feedstock from AAL could be transported to a closer facility at lower cost. This shows the value of explicitly modelling the impact of spatial relationships with scale economies and transport choice for production facilities.

AAL consistently reduced abatement costs, and increased the share of emissions reduction through biofuel replacement relative through transport fuel reduction, for a range of target levels. However, total biofuel production could be either higher or lower with AAL. This depends on what mechanism had most impact in each case: the larger emission reduction per unit of biofuel or the lower cost for each unit of biofuel.

An important assumption in this study is that there is no carbon sequestration of perennial bioenergy crops cultivated on arable land, as this could be counteracted by emissions from indirect land use change. The sensitivity analysis showed that if all carbon sequestration on arable land was accounted for, the impact of AAL on total costs would be small, largely because the total costs without AAL would be much smaller than in the original reference scenario. While an indirect land use change effect is probable at large scale, the size of the effect is uncertain (Mignone et al., 2022; Taheripour et al., 2017). Therefore, there is a risk that the results in this study overestimate the positive impact of AAL, and of the total costs of emissions reduction.

Another concern raised about biofuel is that alternative uses of AAL, and arable land, also would lead to carbon sequestration, and therefore the net emissions gain of using the AAL for feedstock production should be lower (Searchinger et al., 2022). Næss et al. (2023) estimate that for the laissez-faire alternative use of AAL, natural forest regrowth, carbon sequestration is larger than for perennial bioenergy crop cultivation in some regions. As the results showed smaller impact of AAL when carbon sequestration is low, this is a concern.

The main policy implication of this study is that policy needs to account for the different emissions sources when supporting biofuel feedstock production aimed for GHG abatement. Further, in the current EU agricultural policy, only a limited area above the current use is allowed agricultural support, and support is only given to land maintained as suitable for agricultural production (European Commission, 2023), which AAL might not be classified as. It is important that policies facilitate the use of AAL for biofuel production, to realize its potential. However, agricultural land, and in particular AAL, is limited. Additional abatement measures are needed to reach higher targets, such as the Swedish target to reduce transport emissions by 70% by 2030 (Government Offices of Sweden, 2017).

There is need for some caution when AAL is intended to decrease the competition for arable land. In some scenarios in this study, the use of arable land was higher with AAL than without it. This still reduces the cost of emissions reduction, but can have unintended consequences for food production. In addition, PBC plantations on AAL can have both synergies and trade-offs with other environmental problems, such as water quality and biodiversity conservation (Vera et al., 2022).

Some limitations remain in the study. Future better estimates of regional carbon sequestration rates could enhance the results. In addition, the impact on the climate from land use changes (LUC) is uncertain (IPCC, 2022). Including other climate impacts, for example, changes in land use in other regions or albedo (surface reflection of solar radiation), can both reduce and increase the net climate impact. Results would be more precise with updated data on the area of AAL, which is difficult to measure, and local soil conditions and vegetation of AAL.

In future research, more aspects of AAL could be included. For example, perennial bioenergy crops can have lower or higher biodiversity values than other crops (Pedroli et al., 2013), which has to be weighed against any climate benefits. Another aspect to study is the impact on emissions from other agricultural activities. Havlík et al. (2011) found larger total emissions when feedstock for biofuel was restricted to marginal land, as other agricultural activities did not decrease as much as when only agricultural land was used, and therefore did not decrease emissions. Extending the model to cover a global perspective would be valuable, along with a larger case study region that can affect prices. In particular, the opportunity to study indirect land use change emissions explicitly, and thus account for carbon sequestration on arable land, would be valuable. Modelling of the fuel market would make it possible to capture indirect fuel use change emissions, which can arise due to global decreases in fossil prices when fossil fuel demand declines (Rajagopal et al., 2011). As AAL decreases the need to reduce fuel use, it could also imply smaller fossil fuel price changes, and thus less indirect emissions. Further, the developments over time could be more accurately accounted for in a dynamic model. In particular, more land is projected to be abandoned in the future and become AAL (Perpiña-Castillo et al., 2021). However, using AAL for biofuel might reverse the trend, and even cause opportunity costs on AAL.

AUTHOR CONTRIBUTIONS

Ida Nordin: Conceptualization; formal analysis; investigation; methodology; project administration; software; validation; visualization; writing – original draft; writing – review and editing.

CONFLICT OF INTEREST STATEMENT

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The model version used for this study including data is available in an open repository: Idanordin/biofuel_location: Model for biofuel localization with abandoned agricultural land (2024_model_abandoned_agricultural_land). Zenodo https://doi.org/10.5281/zenodo.11105366.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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