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Cost-effectiveness of farm- vs. regional-level climate change mitigation policies

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Abstract

Agriculture is a significant source of global greenhouse gas (GHG) emissions, making reduction targets crucially needed. Worldwide, countries have set agricultural GHG reduction goals and discussed methods to reach them. A crucial aspect is, whether the policy target level is set at the individual farm or at a regional level. In this context, we assess the advantages regarding cost-effectiveness and GHG-reduction potential of targets at the regional level. First, we use the bioeconomic farm-level model FarmDyn to simulate the changes in income and GHG emissions of 65 Swiss dairy farms. Secondly, we develop an optimisation algorithm to compare the efficiency and efficacy of these two target approaches. Our analysis reveals that regional targets, which consider the heterogenous abatement costs of the sector, are more cost-efficient than farm-level ones. Specifically, they enable a 10 per cent GHG reduction at 88 per cent lower costs, suggesting they might be a more cost-effective alternative to taxation.

Keywords: Climate change mitigation, agricultural emissions reduction targets, cost-effectiveness of reduction targets

JEL codes: Q12, Q13, Q18, Q52

1. Introduction

Agriculture contributes significantly to global greenhouse gas (GHG) emissions (Rosenzweig et al. 2020). Accordingly, many countries have set ambitious targets to reduce emissions for the agricultural sector. For example, the European Farm to Fork strategy aims to reduce agricultural GHG emissions to reach the targets of the Paris Climate Agreement. To achieve these targets, farmers need to adopt climate change mitigation measures that effectively reduce GHG emissions. However, effective and efficient policymaking to mitigate climate change in the agricultural sector remains challenging. The most common challenge arises when the heterogeneity among farms is not considered. For example, cost inefficiencies occur when farms are treated uniformly (i.e., when all farms have to meet the same reduction target Pedersen et al. 2020); or if farm heterogeneity is ignored in the design of a policy scheme (e.g., Kreft, Finger, et al. 2023). In this context, the effect of the policy target level, that is, whether GHG reduction targets have to be met at the individual farm or on a higher regional level remain unexplored. Here, we present and apply a simulation approach to quantify the cost-efficiency and cost-effectiveness[1] of climate change mitigation policies when reduction targets are set across farms at the regional level rather than at the level of individual farms. To do so, we compare the changes in income, GHG emissions, and marginal abatement costs per farm when shifting emission-reduction targets from individual farms to the regional level. Our analysis is based on the bioeconomic farm-level simulation model FarmDyn and a sample of 65 dairy farms in a Swiss case study region. Setting targets at the regional level allows the exploitation of heterogeneous abatement costs across individual farms and mitigation measures, thus reducing GHG emissions at a lower cost because all farms are not treated with a one-size-fits-all approach.

Previous literature has focused on assessing the effectiveness of mitigation measures (i.e., the extent to which a policy facilitates the achievement of governmental targets), using marginal abatement cost curves. This approach enables the evaluation of the potential GHG emission reductions of market-based instruments, such as taxation and permit markets, or the support of specific mitigation measures (e.g., MacLeod et al. 2010; Moran et al. 2011; Lengers et al. 2013, 2014; Fellmann et al. 2018). Studies quantifying marginal abatement cost curves show that implementing such policies in agriculture might lead to low levels of GHG reductions (Mosnier et al. 2019), carbon leakage as emissions shift to other countries (Perez et al. 2007; Grosjean et al. 2018; Dumortier and Elobeid 2021), and high transaction costs due to the complexity of administration and measuring GHG emissions (e.g., Bakam et al. 2012; Lengers et al. 2013; Grosjean et al. 2018). In addition, taxes and permits might create political opposition since farmers fear income losses as shown, for example, in New Zealand (Rontard and Reyes Hernández, 2022) and Canada (Olale et al. 2019). Consequently, knowledge about the potential increase in effectiveness and efficiency of alternative policy designs is of high political and societal interest (Pedersen et al. 2020). Other policy approaches, such as setting directives at the farm level to control GHG emission levels or paying farms to implement mitigation measures to reduce their emissions, are assumed to be less cost-effective (i.e., the same targets could be achieved by the government at lower costs) because they do not account for the heterogeneity of farms' costs (Goulder and Parry 2008; Grosjean et al. 2018). One approach that could meet reduction levels while maintaining flexibility across farms and measures would be to set regional instead of farm-level targets. Indeed, studies outside the agricultural sector have shown that there is a considerable opportunity to increase efficiency and effectiveness by considering heterogeneity when reduction targets have to be met (Kotchen and Segerson 2019; Peng et al. 2021). However, regional targets have not yet been considered in the context of climate change mitigation policies in agriculture. Thus, quantifying the potential economic gains when shifting the emission-reduction target level from the individual farm to a regional level is an important research gap.

We address this research gap and contribute to the assessment and design of cost-effective policies for reducing agricultural GHG emissions by developing and applying a new approach that allows us to compare and quantify the effects of regional-level rather than individual farm-level reduction targets. We do so in two steps. First, we conduct individual farm simulations using the bioeconomic model FarmDyn for 65 dairy farms from a Swiss case study. FarmDyn allows us to quantify the costs and emissions associated with four different abatement measures that farms can adopt: (i) replacing concentrate feed with legumes grown on the farm, (ii) increasing the number of lactations per dairy cow, (iii) applying manure using trail hoses, and iv) introducing feed additives to reduce enteric cattle fermentation. We select these four mitigation measures because they allow us to keep production levels constant and thus effectively reduce GHG emissions per kg of produced milk for each farm. The simulation results reveal the changes in income and GHG emissions for each farm, each measure, and each combination of measures compared to a situation in which farms do not apply any of the mitigation measures. Second, we apply an optimisation algorithm to select the most efficient mitigation measures across farms for setting regional- or farm-level targets. This allows us to assess the differences in choices of mitigation measures and to quantify the economic gains from not treating farms with a one-size-fits-all measure under different exogenous emission-reduction targets. Our study contributes to the existing literature on climate change mitigation policies in agriculture by showing how the economic benefits of setting regional targets for GHG emissions can be quantified and what implications the target level has on reduction levels and the adoption pattern of climate change mitigation measures.

The findings show that a regional-level target results in a less costly implementation of climate change mitigation measures in our case study region. For a reduction target of 10 per cent of GHG emissions compared to a baseline (i.e., without adopting mitigation measures), a regional-level target is 88 per cent more cost-effective. This implies that there is considerable economic potential in shifting policy target levels in climate change mitigation policies. Policymakers could exploit this economic potential, for example, by establishing binding regional reduction targets and offering payments through compensation schemes to effectively reduce agricultural GHG emissions.

The remainder of this paper is structured as follows. First, we describe the policy context, introduce the modelling framework, and present the case study in a background section. We then describe the methodology, including a description of the bioeconomic model FarmDyn and the optimisation algorithm used to determine which measures are applied by each farm under different GHG emission-reduction targets. Results are presented in section 4, in which we focus on the changes in cost-effectiveness and cost-efficiency and the adoption pattern of mitigation measures under the two policy design options. Finally, we discuss the results and conclude with policy implications.

2. Background

2.1 Policy context

European policies have formulated ambitious climate mitigation targets. However, the emission-reduction targets in the agricultural sector are not always well defined (Pe'er et al. 2020). Furthermore, the policy measures implemented in Europe so far to reduce GHG emissions have lacked effectiveness (i.e., only small reductions have been made) and efficiency (i.e., policy measures have been expensive in terms of public spending and farms' opportunity costs). In Switzerland, which is not part of the European Union, climate change mitigation in the agricultural sector is a specific policy goal. Switzerland's climate strategy targets a 25 per cent reduction of agricultural emissions by 2030 compared to the baseline year 1990 (BAFU 2022). A longer-term goal for Swiss agriculture is to reduce GHG emissions by 40 per cent by 2050 while maintaining a degree of self-sufficiency of over 50 per cent (BAFU 2022). This implies that the contribution of domestic food production should at least be maintained with a diversified production portfolio (BLW 2022). Given the fact that in Switzerland, until 2020, only a 14 per cent reduction was achieved compared to 1990 levels (BAFU 2022), there is a need to implement further mitigation policies with minimal trade-offs related to domestic food production.

From an economic perspective, a uniform tax for GHG emissions across farms would be optimal to reach GHG reduction targets. However, setting the correct carbon price requires extensive knowledge of marginal damage costs, which are difficult to measure (Oates 1996; Pretty et al. 2000), particularly in the agricultural sector (Bullock 2012; Lankoski et al. 2020), which is highly heterogeneous. Thus, the implementation of a tax could have a negative impact on smaller farms. Additionally, due to the significant costs associated with reducing agricultural emissions, implementing taxation is challenging. Furthermore, the implementation of taxes and other instruments based on the polluter pays principle faces strong political opposition from powerful and influential farmer organisations (e.g., Rontard and Reyes Hernández 2022). In fact, taxation tends to be ineffective, as farmers may choose to pay the tax instead of investing in abatement efforts if tax levels are lower than the abatement costs. In contrast, if the tax is set too high, some farmers may have to leave the sector under such a tax burden. Tradable permit markets, in contrast, offer a combination of quantity- and price-based regulation of GHG emissions (e.g., Breen 2008; Bakam and Matthews 2009). This option offers direct control of emissions regulation, as the authority controls the allowable level of emissions. With this approach, there is no need to calculate the marginal damage costs, making a tradable permit market an attractive solution for heterogeneous sectors like agriculture (Vermont and De Cara 2010; Grosjean et al. 2018). Yet, there are very few cases in which such regulations have been applied in the agricultural sector at a governmental level (see OECD 2019). The downside of tradable permits is potentially high transaction costs, which could significantly decrease the cost-effectiveness of the scheme (Perez et al. 2007).

Given the challenges in implementing first-best policy instruments, other instruments should be considered, such as setting directives at the farm level to control GHG emission levels or compensation schemes like payments for ecosystem services (Engel and Muller, 2016) or abatement payments (OECD 2019). By providing financial incentives to farmers for reducing GHG emissions, a middle ground could be established that increases the acceptability of emission reductions for farmers. However, payment approaches for effective GHG emission reductions also depend on the additionality and conditionality of the measure, requiring clear targets. In other words, the payment should have a positive effect on GHG emissions and at the same time be bound to the implementation of the associated measure (Sattler et al. 2023). In addition, compensation schemes that consider the heterogeneity in abatement costs between farms have the potential to be more cost-effective (e.g., Kreft, Finger, et al. 2023).

One potential approach for effectively reducing GHG emissions in a cost-efficient manner is to shift the targets from individual farms to a regional level. This would allow farms with low abatement costs to contribute more than farms with higher abatement costs. For example, the government could set regional targets and compensate farms for collectively achieving these targets (similar to the cooperative approach for biodiversity conservation in the Netherlands; e.g., Barghusen et al. 2021; Jongeneel and Gonzalez-Martinez 2023; Sattler et al. 2023). This could increase cost-effectiveness, reduce trade-offs with respect to production goals, and thus reduce the opposition toward instruments based on the polluter pays principle (Sterner et al. 2019). The extent to which such approaches could contribute to increasing the cost-efficiency and cost-effectiveness of climate change mitigation remains an empirical question. In the following, we present and apply an approach that quantifies the potential gains from shifting the target level and discuss the policy implications of such a shift.

2.2 Modelling framework

We evaluate the efficiency gains resulting from shifting the target level for GHG emissions from individual farms to the regional level, as illustrated in Fig. 1.

First, we start by simulating the reductions in income and abatement potential of four mitigation measures and their combinations, accounting for interactions[2] with the FarmDyn model for each farm. In this step, we calculate the changes in farm incomes and GHG emissions compared to a baseline (i.e., a counterfactual situation in which farms do not implement climate change mitigation measures).

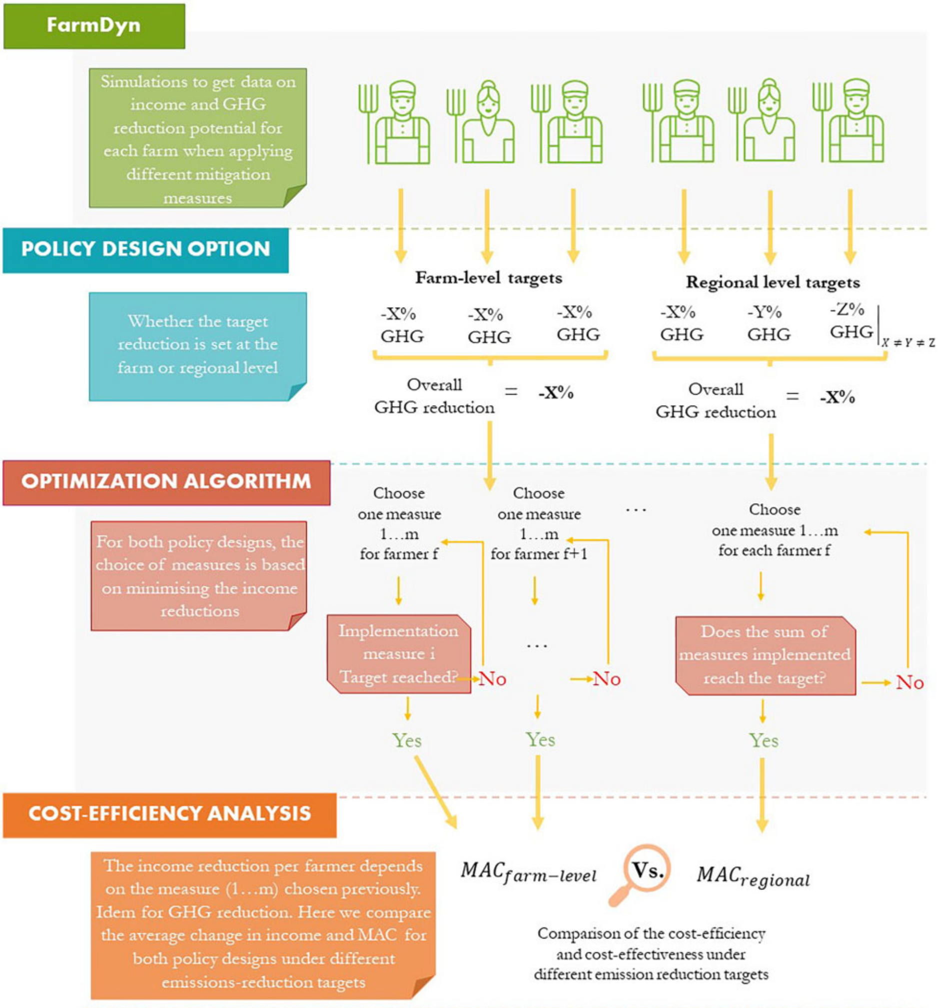

Figure 1. Schematic overview of the methodological approach. MAC stands for marginal abatement cost.

Second, we use the results from the individual farm simulations to calculate which measures must be adopted on each farm with increasing target levels (represented in per cent changes). To do so, we apply an optimisation algorithm that selects the measures with the best cost-efficiency, that is, those with the lowest income reduction, until the same reduction target level is met in both policy options (i.e., regional-level and farm-level design). In the individual farm-level design, each farm has to achieve the same emission-reduction target. Specifically, each farm has to reduce the same amount of GHG emissions compared to its initial baseline emissions. The modelling allows farms to either adopt one stand-alone measure or a combination of measures until the same exogenous emission-reduction target (the percentage reduction with respect to the baseline) is reached by each farm. In the regional-level design, we assume that the imposed emission-reduction target needs to be reached by all the farms jointly, implying that the reduction efforts across farms might differ according to their means of adaptation (i.e., farms that can abate more with lower costs contribute more to the overall reduction target). Thus, the sum of the GHG emission reductions of all farms in the region must be X per cent; the same percentage that all farms must reduce under the farm-level targets.

Finally, we carry out a cost-efficiency and effectiveness analysis and compare the overall changes in income and marginal costs between the two policy design options with increasing reduction levels to quantify the extent of economic gains from setting the target at the regional level.

2.3 Case study

We apply our approach to quantify economic gains from regional-level targets for all dairy farms ($n = 65$) in the Weinland region in the Canton of Zürich (Switzerland). This region is chosen because it has ambitious climate strategies, including pilot projects on climate mitigation (Kreft 2021), as well as for its large heterogeneity in dairy farms and land use, which is a general characteristic of Swiss farm structures (see also Huber et al. 2023). Dairy production is chosen since it is the main contributor to GHG emissions in the case study region. Information on these farms is derived from census data (see Table A1 in the supplementary material for a statistical summary of the 65 farms' characteristics). The average farm size is 40 hectares, and the farms in our sample also have the same number of dairy cows as in the Swiss lowlands on average (approximately 33 cows). Nevertheless, the farms in our sample have larger areas of cultivated and arable land than the average Swiss dairy farm, which is 21 hectares.

We select four mitigation measures that can be applied at the farm level, and we assess their cost-efficiency under different exogenous GHG emission-reduction targets. Table 1 provides an overall description of these measures, explaining their impact on management decisions, the associated implementation costs, and their ability to reduce GHG emissions as well as the associated GHG emissions. Moreover, in the supplementary material, we also provide the distribution of the income reduction associated with each stand-alone measure (see Figure A1. Notice that for most of the farms, the reduction in income for the prolongation of lactation is negative, i.e., cost-saving,[3] meaning that it increases profits while reducing GHG emissions).

These measures are chosen based on their applicability, abatement potential, and relevance to the Swiss dairy farm context (Kreft 2021). Another important aspect of these measures is their ability to reduce emissions without compromising food production. Therefore, we do not consider the switch to other product types but only short-term changes at the farm level, such as a reduction in the number of heifers or shifts in crop production. Our choice is motivated by the Swiss policy goals of reducing GHG emissions while maintaining food production levels as well as providing short-term policy solutions without having to consider demand-side options or carbon-leakage effects, which are often associated with carbon taxes or permit markets. By keeping milk production constant, we can ensure an effective reduction of GHG emissions per kg of milk produced (e.g., Vellinga and de Vries 2018; Huber et al. 2023).

The marginal abatement costs of the mitigation measures are computed per individual farm using the bioeconomic model FarmDyn, which also accounts for the interactions among them. The potential technical abatement of GHG emissions for each measure is calculated based on the emissions from the corresponding farm activities, which are also integrated into FarmDyn. The emission gasses and methodology applied (i.e., emission factors) differ among mitigation measures and are presented in Table 1. Our approach is based on AR5-100 (IPCC) standard values of emission factors (Myhre et al. 2013), which makes it possible to account for direct, indirect, and upstream emissions. Downstream emissions and changes in carbon soil content are not considered.

Table 1. Climate change mitigation measures included in the FarmDyn model and their impact on farm management, the implicit and explicit opportunity costs, the mechanism of GHG emissions reduction, and how the measures are specified in the model. The table also presents the gas emissions associated with each measure and the corresponding methodology applied. Note that the FarmDyn simulations consider all the possible combinations between these four mitigation measures to account for the interactions.

Mitigation measure	Impact on farm management	Implicit and explicit opportunity costs	Mechanism for GHG emissions reduction	Specification in FarmDyn	Emissions	Methodology applied
Replacement of external concentrates with legumes	This measure prohibits the farmer in FarmDyn from purchasing any non-roughage products on the market including e.g., concentrates, grain products, and legumes. Instead, the fodder is replaced by locally or home-grown legumes.	The farmer reduces his purchasing costs for concentrate and at the same time the costs of fodder production on-farm increase. Furthermore, fodder production replaces areas devoted to cash crops.	Replacing concentrate feed such as soybean with locally produced legumes (e.g., peas or horse bean) mitigates up-stream CO2 emissions mainly due to reduced transport and land-use changes (Baumgartner et al. 2008; Hörtenhuber et al. 2010; Knudsen et al. 2014) whereas emissions on-farm can increase when arable land is diverted from cash crop production to fodder production	Upstream emissions (inputs and transport) and emissions of production of domestic legumes (fuels, fertiliser etc.)	NH_3 N_2O NO_x N_2 CO_2-eq	European Environment Agency. 2016; Haenel et al. 2018; KTBL. 2023
Prolongation of lactation periods	Lactations are exogenously extended to at least 5 (from 4) lactation periods per dairy or mother cow for farmers	There are no relevant im- or explicit costs. However, this measure implies a cost-saving, meaning that it increases profits while reducing GHG emissions.	The increased number of lactation periods leads to fewer required replacements in the cow herd, which means fewer heifers and calves on-farm and thus less CO_2-eq. emissions from the herd (Alig et al. 2015.; Grandl et al. 2019; Schader et al. 2014).	GHG reduction based on reduced number of heifers for replacement of old cows. We also assume that there are no changes in milk yield and in fertility or other health issues	CH_4 NH_3 N_2O NO_x N_2	European Environment Agency. 2016; Haenel et al. 2018; IPCC (2006). 2006

Table 1. Continued

Mitigation measure	Impact on farm management	Implicit and explicit opportunity costs	Mechanism for GHG emissions reduction	Specification in FarmDyn	Emissions	Methodology applied
Trail hose for manure application	Mandatory use of trailing hose or trailing shoe for organic fertiliser/manure is linked to new investment in machinery	The farmer faces investment costs for the new machinery.	Applying organic fertiliser close to or directly injected into the soil reduces nitrous oxide and indirect nitrous oxide from other nitrogen compounds (Wulf et al. 2002; Weiske et al. 2006; Thomsen et al. 2010).	Manure application technique is associated with emission factor in FarmDyn and different fuel use is taken into account. We assume 0.2–0.9% N2O reduction with trail hose; costs 2.3 CHF per m^3 and application (Agridea 2019)	NH_3 N_2O NO_x N_2	European Environment Agency. 2016; Haenel et al. 2018
Feed additives	This measure prescribes farmers in FarmDyn the application of feed additives for ruminants to intervene in the digestive system. These feed additives are linked to purchasing costs.	For each unit of feed additives used for cows, the farmer must purchase the feed additive on the market.	The use of feed additives aims to reduce the methane emissions from the ruminant. However, we still don't know their full benefits and impacts. (Hristov et al. 2013; Engelke et al. 2019; Jayanegara et al. 2020)	Reduced enteric fermentation in cattle. For linseed we assume 10–25% CH4 mitigation (e.g., product by Trinova); costs 0.65 Fr./cow/day (Trinova 2023)	CH_4	Haenel et al. 2018; IPCC (2006). 2006

3. Methods

3.1 FarmDyn

The first step in our analysis is to run simulations with FarmDyn, a bioeconomic model that can be used to calculate the reduction in GHG emissions and profits associated with adopting the considered mitigation measures. This mixed-integer linear programming model assumes a fully informed rational decision-maker who optimises profits under different constraints and processes, such as economic, biophysical, and farm characteristics (Kuhn et al. 2019; Mosnier et al. 2019; Pahmeyer and Britz 2020). The data transformation and generation in FarmDyn is carried out in GAMS (General Algebraic Modelling System), and the solutions are found using the MIP (mixed integer programming) solver CPLEX.

FarmDyn contains detailed information about economic and biophysical processes, such as investments and nitrogen and GHG emissions flows. This allows the representation of different farm activities, including land cultivation, feed production, animal husbandry, and feed and manure management (Lengers et al. 2014). At the same time, these activities are directly linked to the GHG emissions accounting module, which enables calculation of the emissions reductions associated with applying mitigation measures. The accounting of farm-level GHG emissions is based on inventory data from IPCC 2006, as described in Table 1 and Lengers et al. (2013).

FarmDyn is adapted to the Swiss agricultural context by including input and output prices, investment prices for crops or machinery, and agricultural factors, such as crop yields, feeding ratios, and product output per animal. Moreover, the model is adapted to the Swiss policy context of direct payments and cross-compliance regulations. The type of direct payments we introduce to FarmDyn are those that support food supply, arable land, biodiversity conservation, and grass-feeding practices for milk and meat production. For the latter, we consider mandatory crop rotations (including cover crops) and levels for biodiversity conservation (see Huber et al. 2023). The data on bio-physical and economic activities and processes are taken from the official planning data (Agridea 2019).

Each farm of our sample is parameterised based on census data containing observed farm characteristics. We use the farm-specific census data on the total amount of land, available working units, types of crops, and the number of animals (i.e., milking cows, heifers, calves) as input parameters for calculating the baseline income. The baseline is a counterfactual situation in which the farms do not implement climate change mitigation measures, and the simulation output mirrors the observed production structure on each farm in the year 2018. Next, we force the different measures into the simulation of each farm. FarmDyn then allocates the land-use and animal production activities under the assumption of profit maximisation. The enforcement of mitigation measures results in costs and economic benefits for each farm. To compute the marginal abatement costs, we then calculate the ratio between the income changes and the changes in GHG emissions between the baseline and each combination of mitigation measures (for a detailed description of the calculation of marginal abatement costs, see Huber et al. 2023).

3.2 Optimisation model and cost-efficiency and cost-effectiveness analysis

After conducting running single-farm simulations with FarmDyn, we write an optimisation model in GAMS to quantify and compare the cost-effectiveness of the two policy designs, (i.e., the same emission-reduction target is either set at the farm level or at the regional level). To do so, we minimise the overall income reduction, considering all the farms in our sample when imposing a certain percentage of emissions reduction. First, we establish a farm-level target, requiring all farms to reduce emissions by the same percentage. Second, for the regional-level target, a group of farmers must collectively achieve a specified level of reduction, allowing for non-uniform and varying reductions among individuals while still meeting the overall percentage set at the individual farm level. To reduce GHG emissions, farms choose mitigation measures or the combination of mitigation measures that lead to the lowest income reduction. To integrate the combinations as a choice option in the model, all possible combinations are modelled as independent measures the farm can choose from. This means that the farm either selects one of the four stand-alone mitigation measures or one of the combinations of different measures. In this way, we ensure that there is no over-counting of the application of mitigation measures[4] (see Figure B1 in the supplementary material for a schematic overview and Table B1 for the description of the variables, parameters, and constraints). This GAMS optimisation model consists of a loop where each farm chooses one mitigation measure, the feasibility of which is assessed based on the policy design and the reduction target. For the individual farm-level design, the mitigation measure chosen is the one that reduces GHG emissions by the same amount as the imposed emission-reduction target. Thus, if the measure chosen does not meet the emission-reduction target, the next measure is taken and evaluated. Once this process is completed, we obtain the reduction in income and GHG emissions for each of the farms based on the chosen mitigation measure. We do this for each mitigation measure sequentially. This allows us to choose one (and only one) measure in each simulation step, which guarantees that we do not double count combinations of measures. We follow the same procedure for the regional-level design, but instead of checking whether each farm reduces its GHG emissions by the set reduction target, we ensure that the sum of emissions reduced by all the farms is at least equal to the emission-reduction target. We test different percentage reduction levels, starting at 1 per cent and increasing by one unit until the maximum possible potential reduction is achieved with the considered mitigation measures.

4. Results

4.1 Income implications of reducing GHG emissions

Evaluating the differences in income reduction based on increasing emission-reduction targets provides an indication of the cost-effectiveness of the farm-level and regional-level policy designs (Fig. 2). We observe that across all the imposed emission-reduction targets, the farm-level targets result in higher average income reductions compared to the income reductions with regional targets. However, for low reduction levels, the difference between the two policy design scenarios is small. Moreover, the income reductions are negative (i.e., they represent a gain in profits). With increasing emission-reduction levels, the average income reduction increases, and the distance between the regional and farm level spreads. When imposing a 10 per cent emission-reduction target, the average income reduction per farm with the individual farm-level policy design is 4,654 CHF, which corresponds to a 3.3 per cent reduction of the original income. For the same reduction level, the total abatement cost with a regional-level target is 545 CHF (i.e., 0.4 per cent reduction of the original income). This indicates that the regional-level target is 88 per cent more cost-effective (i.e., 545 CHF is 12 per cent of 4,654 CHF).

The results presented in Fig. 2 also reflect the heterogeneity of the sample (cf. error bars corresponding to the 95 per cent confidence interval). At low emission-reduction targets, the heterogeneity of the average income reduction is low, and thus the heterogeneity across farms is less relevant to the design of the policy instrument. However, when the imposed emission-reduction targets increase, the differences in income loss among farms also increases, and thus heterogeneity across farms should be considered when designing policy instruments to reduce GHG emissions. This holds true for both policy designs.

The maximum average (over all farms under a regional-level design) reduction that can be achieved with the four measures is 16 per cent of the baseline emissions. This means that the farms in our sample can reduce two-thirds of the target to reduce Swiss agricultural GHG emissions by 25 per cent by 2030. Hence, further measures beyond the four considered here will need to be adopted to reach the short-term policy target in Switzerland (25 per cent

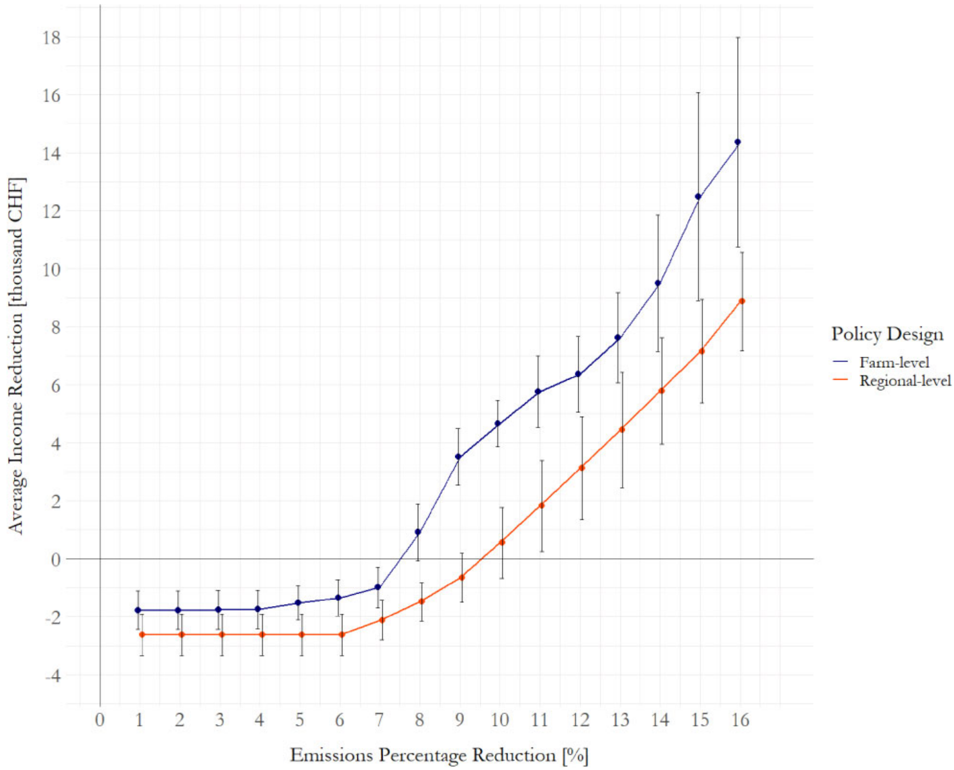

Figure 2. Average income reduction (CHF/farm) resulting from different emission- reduction targets and policy designs. Note: Lines represent the average income reduction over all 65 farms (note that the sample size is reduced once the 10 per cent reduction level is reached; see main text for further explanation). The error bars correspond to a 95 per cent confidence interval across all farms of the corresponding sample. The optimisation algorithm is used to examine reduction targets from 1 per cent to 16 per cent and assess the corresponding income reduction. The dark blue line corresponds to the farm-level design and the orange to the regional-level design. A negative average income reduction (until an emission reduction of 7 per cent for the farm-level design and 9 per cent for the regional-level design) implies an income increase or cost savings.

reduction of agricultural emissions by 2030 compared to the baseline year 1990; BAFU 2022). We also find that not all farms can achieve a reduction level of 16 per cent with the four measures. In fact, more than 60 per cent of the farms could not reduce their GHG emissions levels beyond 10 per cent due to their structural characteristics, including farm size, the amount arable land, and the number of animals. Under the regional-level design, however, such individual farm constraints can be compensated by the remaining farms with higher reduction potential. Thus, in order to ensure a fair comparison between the regional-level and farm-level designs, we adjust the sample of farms once a 10 per cent reduction in emissions is achieved. The adjustment is based on the number of farms that can achieve a reduction of up to 16 per cent under the farm-level design, which is 27.

Second, to evaluate the cost-efficiency of the two policy designs, we analyse the differences in marginal abatement costs across the imposed emission-reduction targets. We find that the average marginal abatement costs follow a similar trend as the reduction in income with increasing emission-reduction levels (Fig. 3). With low reduction levels, the marginal abatement costs are negative, and the difference between the two policy design options is small. With higher emission-reduction levels, there is a difference between the farm-level and regional-level targets. At high reduction levels, the difference between the two policies

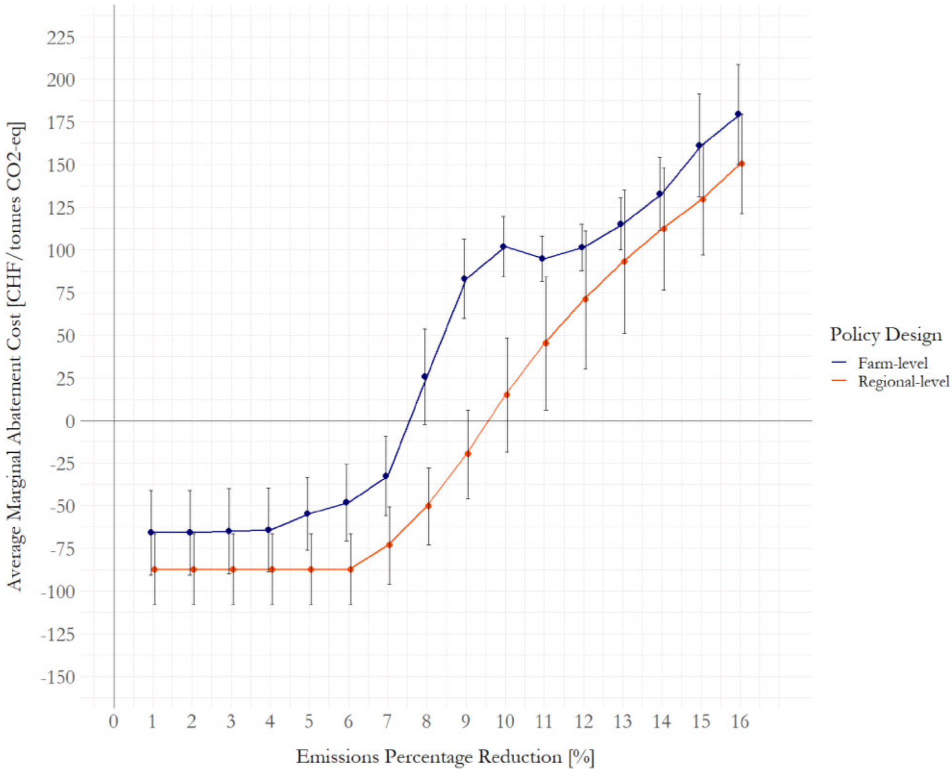

Figure 3. Marginal abatement costs implied by different emission-reduction targets and policy designs. Note: Lines represent the average marginal abatement costs over all 65 farms (note that the sample size is reduced once the 10 per cent reduction level is reached; see main text for further explanation). The error bars correspond to a 95 per cent confidence interval across all farms of the corresponding sample. The marginal abatement cost for each percentage reduction target is computed by dividing the income reduction by the abatement potential (or GHG emissions reduced). The values for the income reduction are those used in the previous figure and obtained using the optimisation algorithm. The dark blue line corresponds to the farm-level design and the orange to the regional-level design. A negative marginal abatement (until an emission reduction of 7 per cent for the farm-level design and 9 per cent for the regional-level design) implies an income increase or cost savings.

decreases, as the sample for the farm-level scenario is smaller. Thus, while the cost-effectiveness for a 10 per cent emissions reduction is tenfold higher in the regional-level scenario (10 vs. 100 CHF per ton of CO2 equivalent), the differences in cost-efficiency are below 20 per cent for emission-reduction targets higher than 13 per cent (see Table C2 in the supplementary material).

4.2 Adoption patterns in the two policy designs

To analyse the adoption pattern of the farms in the two policy design options, we compare the adopted mitigation measures at the 10 per cent and 16 per cent reduction levels (Fig. 4). We assess the contribution of each mitigation measure to the overall average income reduction. Thus, at a 16 per cent emissions reduction, for the farm-level design, we only include the 27 farms that can individually reduce 16 per cent of their emissions with the considered measures.

The main difference for a 10 per cent emissions reduction is that many farms in the regional-level target still profit from cost-saving measures and thus can increase their income

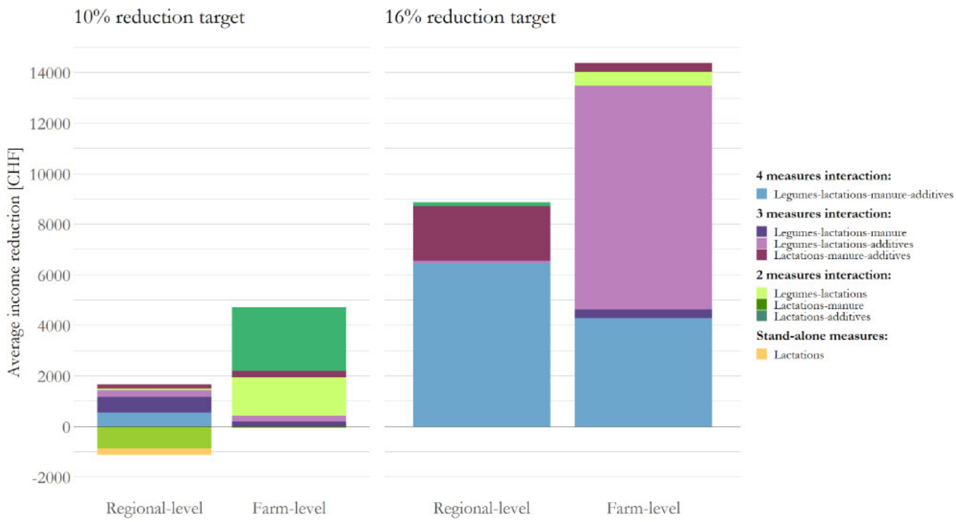

Figure 4. Average income reduction (CHF/farm) by measure for the two policy designs with reduction targets of 10 per cent and 16 per cent. Note: Comparison between regional-level and individual farm-level targets across different emission-reduction targets. The bars represent the average income reduction for each policy design option with two different emissions reduction targets (10 per cent and 16 per cent). Each bar includes the contribution to the income reduction of different mitigation measures, each distinguished in a different colour. The colours in the legend distinguish whether a measure is applied alone or in combinations of two, three, or four measures, respectively, to account for interactions. The abbreviations for each of the measures shown in the legend are as follows: replacement of external concentrates with legumes as 'legumes', prolongation of lactation periods as 'lactations', manure application as 'manure', and feed additives as 'additives'.

when implementing mitigation measures. These cost-saving measures are the combination of the increase in the number of lactations and trail hoses for manure application and the prolongation of lactations as a stand-alone measure. In addition, with a regional-level target, farms with high cost-efficiency apply more measures on their farms, while others do not have to implement any measures (reflected by the higher share of blue and purple colours in the bar).

In contrast, more farms implement fewer mitigation measures with a farm-level target. Table C3 in the supplementary material shows the average income reduction values corresponding to each measure for each policy design and each target. At a 16 per cent emission-reduction level, incomes are reduced for all farms in both policy design options. However, the income reduction at a regional level is lower, and the contribution of the interaction among the four mitigation measures is higher at the regional level (share of colour blue). This implies that the regional-level target allows the farms to choose a more cost-efficient combination of mitigation measures, whereas for the farm-level targets combinations of measures with lower cost-efficiency must be adopted. Thus, this figure shows the importance of accounting for the heterogeneity among farms with different marginal abatement costs to achieve higher cost-efficiency with different mitigation measures. In the regional-level design, farms have more flexibility to choose mitigation measures that are less costly, and the income reductions are lower than with a typical farm-level target (see Table C4 for all results).

5. Discussion

In this article, we present a modelling and optimisation approach to test the cost-effectiveness and cost-efficiency of setting reduction targets on the regional and farm levels, respectively. Our results show that targeting emission reductions at the regional level is more cost-effective, as the total abatement costs are lower compared to targeting emissions at the farm scale. For a 10 per cent emissions reduction, for example, the average income reduction per farm with the farm-level design is 4,654 CHF. For the same reduction level, the total abatement costs on the regional level are 545 CHF, making the latter 88 per cent more cost-effective. At the same time, targets set at a regional level make it possible to achieve higher emission reductions compared to setting targets at the farm level. The higher cost-effectiveness of targets set at the regional level can be attributed to the non-uniform reduction of emissions across farms. Hence, farms can adopt more cost-efficient measures compared to when the reduction target is set at the individual farm level. Our study also shows that the farms in our sample can reduce 16 per cent of their GHG emissions, which represents two-thirds of their reduction target of 25 per cent by 2030 in Switzerland. Hence, additional actions are needed along with changes in production to decrease the demand for animal products such as measures that encourage the adoption of more plant-based diets.

Other studies have also found that accounting for the heterogeneity between agents affects the cost-efficiency of policies' outcomes (Kotchen and Segerson 2019; Peng et al. 2021). In fact, accounting for heterogeneity makes it possible to transfer the burden of emissions reduction to participants with a higher willingness to participate and those who possess better means, such as abatement technology (Peng et al. 2021). Similarly, our results suggest that cost-efficient policy schemes should account for the heterogeneity across farms, and thus regional-level reduction targets could be an interesting policy design option.

However, the regional-level design is only more cost-effective if the efficiency gains are greater than the corresponding transaction costs resulting from a regional-level target. Establishing regional targets and coordinating the mitigation measures across farmers would create costs for the government and the famers. The economic gains from a regional-level design could be used to support the administration needed to set up such policy designs. An example of such a policy design would be collectives (i.e., groups of farmers) with a joint target and governmental support promoting coordination among farmers (e.g., in the Dutch biodiversity program; Barghusen et al. 2021; Jongeneel and Gonzalez-Martinez 2023; Sattler et al. 2023). With such a design, setting binding reduction targets for a group of farms could reduce the income loss by farmers or, in the case of a compensation scheme like direct payments or carbon credits, could reduce the governmental spending needed to achieve the same reduction target.

In this context, regional-level designs not only improve the cost-efficiency of the policy but could also be used to promote stronger social networks and thus increase learning among farmers (see Kreft, Angst, et al. 2023; Kreft, Finger, et al. 2023). This could help improve communication among farms, potentially reducing transaction costs (Burton and Schwarz 2013; Banerjee et al. 2017). Being part of a collective can also reduce the moral hazard problems associated with the monitoring of emission reductions, as a cooperative could play the verification and monitoring roles, similar to the Dutch cooperative approach (Terwan et al. 2016).

Although our results demonstrate how the cost-effectiveness and cost-efficiency of policies can be improved, some limitations of our study need to be considered. First, restricting our choice of mitigation measures to four (and all the combinations) implies that farms under farm-level targets will have higher income losses, as there are few options to reduce exactly the required number of emissions, and farms therefore must choose more costly measures. Including more mitigation measures, but also additional farms and farm types, would make it possible to form more generalisable conclusions about the differences between the two policy designs, especially regarding cost-effectiveness. In addition, we assume that milk production levels remain constant in our simulation such that GHG emissions are effectively reduced per kg of produced milk. Maintaining calorie production is an explicit target of Swiss agricultural policy (BLW 2023). However, this suggests that our results only have short- and mid-term policy implications, as total production would be affected by developments over time, such as structural farm changes or productivity gains. Thus, achieving the long-term Swiss policy goals of reducing GHG emissions by 40 per cent while maintaining constant food production calls for more flexibility in policy designs, including changes in production types, as well as food demand-related interventions (Ammann et al. 2023). An important limitation that should be considered in future research is the inclusion of transaction costs in assessing the effectiveness and efficiency of mitigation policies. This would not only enhance the accuracy of the cost-efficiency estimates but also facilitate consideration of the costs and benefits of such an approach. Finally, our results do not consider individual farmer characteristics, such as resistance to change or non-cognitive skills and social interactions, which also affect the uptake of climate change mitigation measures (e.g., Kreft, Angst, et al. 2023).

6. Conclusion

This paper compares the cost-effectiveness and cost-efficiency of farm-level vs. regional-level policy design options aimed at reducing agricultural GHG emissions. Based on simulations with the bioeconomic model FarmDyn and employing an optimisation algorithm, we find that for our sample of 65 Swiss dairy farms, emission-reduction targets that are set at a regional level rather than a farm level are more cost-effective. Specifically, we find that for a 10 per cent emission reduction target, the regional-level design is 88 per cent more cost-effective.

Despite the limitations discussed in the previous section, our study has two important policy implications. First, establishing regional-level target has the potential to enhance the cost-efficiency of policies aimed at reducing agricultural GHG emissions. Therefore, when it is challenging to implement economically optimal instruments, such as carbon taxes or permit markets, a combination of command-and-control measures (setting binding targets) and a compensation scheme for GHG emission reduction (e.g., in a collaborative setting) could be viable complementary or alternative strategies. Second, the efficiency gains are dependent on the combination of mitigation measures implemented on farms. Therefore, policy instruments that financially reward farms for reducing CO2 should not prioritise specific measures or technologies but instead focus on the potential to decrease GHG emissions. For example, offering payments per ton of reduced CO2 could incentivise farmers to explore different approaches for reducing emissions.

Our approach highlights the increasing cost-effectiveness and cost-efficiency of regional-level GHG reduction targets. The implementation of such an approach requires the consideration of transaction costs and political acceptability. In this context, further research on policy mixes would be helpful (i.e., how combinations of different instruments affect agricultural GHG emissions). Information on how such policy mixes could help to overcome the resistance to climate mitigation policies would be useful for policymakers and stakeholders seeking to effectively reduce agricultural GHG emissions. Moreover, to better generalise our results, future studies should include a higher number of mitigation measures and farms as well as farm types.

Open-source code and data

The replication package for the codes and data used for this paper can be found under:

DOI: http://hdl.handle.net/20.500.11850/632,848 which corresponds to the research collection and archive from ETH.

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Supplementary material

Supplementary data are available at *Q Open* online.

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Data availability

The data supporting this article is accessible in its online supplementary material.

End Notes

1 Cost-effectiveness refers to income reductions required to achieve a specific GHG emission-reduction target. Cost-efficiency refers to income changes associated with implementing mitigation measures (stand-alone or in combination).

2 Interactions account for the changes in marginal abatement costs when measures are applied in combination instead of independently (stand-alone), as the influence of one measure on another impacts the overall marginal abatement cost. For example, when considering the interactions between a measure that reduces the herd (e.g., because of an increase in the number of lactations), this influences the marginal abatement costs of other measures that also depend on the number of animals, such as the introduction of feed additives in their diets.

3 Cost-saving measures contribute negatively to the total income reduction. This means that these measures save money while simultaneously reducing emissions. There are two main reasons why farmers might not yet be adopting the cost-saving measure of prolongation of the lactation period: a lack of information or reluctance to change due to risk aversion (for details, see Kreft, Finger, et al. 2023).

4 By imposing the condition that each farm can only choose one measure (either one stand-alone or any combination of the stand-alone measures) we ensure the prioritisation of the choice of one combination of measures instead of, for example, two stand-alone measures.

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