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Woody Plant Encroachment, Grassland Loss, and Farm Subsidies

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ABSTRACT

The UN Decade on Ecosystem Restoration (2021–2030) aims to prevent the degradation of ecosystems, such as grasslands, which play a key role in the provision of biodiversity, forage, and cultural ecosystem services. However, woody plant encroachment increasingly causes the loss of grasslands, which provide forage, are biodiversity hotspots, and are of high cultural value. In this paper, we evaluate the effect of agricultural policies in the form of farm subsidies on halting the loss of grasslands due to woody plant encroachment. To this end, we assemble a novel panel dataset that connects the farm-level census data of Swiss alpine summer farms and high-resolution remotely sensed woody plant encroachment data. To deal with the endogenous selection of claiming subsidies, we leverage an agricultural policy reform that abruptly and unevenly increased subsidies, allowing us to estimate the causal effect of subsidies at the farm level on woody plant encroachment. Our results show that an increase in subsidies causes a loss of 2% of grassland due to woody plant encroachment, which corresponds to an average loss of 4.7 ha of grassland per farm. Hence, our study highlights that the effect of subsidies can be complex and lead to unintended and not desired policy outcomes, which should be considered by policymakers.

1 | Introduction

The UN Decade on Ecosystem Restoration (2021–2030) aims to prevent the degradation of ecosystems, such as of grasslands, which play a key role in the provision of biodiversity, forage, and cultural ecosystem services, such as heritage and recreational services (Bengtsson et al. 2019; Huber and Finger 2020; Sandström et al. 2022). However, woody plant encroachment (also referred to as bush or shrub encroachment) severely threatens the preservation of grasslands in Europe (Caviezel et al. 2017; Saintilan and Rogers 2015; Van Auken 2009; Venter et al. 2018). Woody plant encroachment is part of a natural succession process and turns grassland into land dominated by shrubs and trees. It is amplified by climatic change, land abandonment, and a reduction in livestock grazing (Anadón et al. 2014; Archer et al. 2017; García Criado et al. 2020; Gherardi and Sala 2015; Van Auken 2009; Venter et al. 2018). Importantly, woody plant encroachment is strongly associated with significant declines in species richness, making it a driver of biodiversity loss (Koch et al. 2015; Ratajczak et al. 2012; Wieczorkowski and Lehmann 2022). These processes also apply to mountain and alpine grasslands (Programme F.a.A.O.o.t.U.N.a.U.N.E. 2023; Straffelini et al. 2024), which are particularly ecologically valuable (Herzog and Seidl 2018) and are threatened by land abandonment (Gellrich et al. 2007).

To stop grassland loss to woody plant encroachment, policymakers can introduce policy tools such as targeted farm subsidies. These subsidies have been implemented in various countries (e.g., Australia, Austria, Germany, and Switzerland)[1] and may be either directly linked to agri-environmental outcomes or indirectly support them by keeping farming viable and thus preventing land abandonment (Convention on Biological Diversity 2022; Elmiger et al. 2023; European

Commission 2020; Key and Roberts 2006; Pe'er et al. 2022). Specifically, farm subsidies aimed at preventing land abandonment seek to maintain production in certain areas, which is critical to reducing woody plant encroachment (Munroe et al. 2013).

Despite the ecological importance of grasslands and the financial expenditure by governments via farm subsidies, the effect of farm subsidies on woody plant encroachment has not yet been assessed. Theoretically, subsidies can have two counteracting effects. On the one hand, farm subsidies are intended to promote land management and stop land abandonment, thus reducing woody plant encroachment. On the other hand, they might entail adversary incentives that lead to a reduction in the maintenance of pastures. The latter might be the case, for example, when farmers have a reference level of income which the subsidies allow them to maintain even when farmers reduce their maintenance effort.

Investigating the effects of farm subsidies on woody plant encroachment is challenging as it requires both long-term information on vegetation dynamics and accounting for the endogeneity that arises from the participation of farms in subsidy schemes—that is, farms' self-selection into the subsidy schemes. In our study, we address both challenges.

In our paper, we assess the effect of subsidy increases received by Swiss farms due to a policy reform. The policy reform in focus was implemented in 2014 and raised subsidies for livestock as well as introduced subsidies for landscape quality and ecological focus areas. Livestock subsidies incentivise farmers to move their livestock to grasslands seasonally. These subsidies therefore facilitate grazing, as well as active and extensive pasture management, thus stopping land abandonment and ultimately woody plant encroachment (Federal Office for Agriculture 2021; Federal Statistical Office 2022b). Subsidies for ecological focus areas require the presence of non-woody indicator plant species in grasslands. Landscape quality subsidies compensate farms for maintaining and enhancing regionally typical landscapes undisturbed by woody plant encroachment. Therefore, all three subsidies share the policy objective of protecting grassland from loss to woody plant encroachment through supporting the viability of farming and preventing land abandonment.

To evaluate the effect of these three subsidies, we compile a unique dataset that runs over two decades. The dataset connects remotely sensed, high-resolution woody plant encroachment data to census farm-level data and therefore enables us to observe the precise amount of encroachment and subsidies for each farm. We use this novel dataset, combined with a semiparametric doubly robust difference-in-differences method to evaluate the effect of these subsidies on woody plant encroachment. Our novel dataset contains alpine summer farms in the Swiss region of Grisons (Figure 1), which are part of UNESCO's world heritage. Our study region resembles the climate conditions of alpine areas across Europe and encompasses the largest share of alpine grassland in Switzerland. These alpine grasslands are becoming increasingly encroached, driven by the expansion of green alder (*Alnus viridis*), which is especially dominant and contributes to a loss of biodiversity and forage in Switzerland and other European countries (Brändli et al. 2020; Caviezel et al. 2017; Koch et al. 2015; Zehnder et al. 2020).

Our research also contributes to two closely related research areas. The first is the literature on the effect of agri-environmental subsidies on environmental outcomes (Baker et al. 2012; Bertoni et al. 2020; Chabé-Ferret and Subervie 2013; Claassen et al. 2018; Feng et al. 2013; Kleijn et al. 2001; Kleijn and Sutherland 2003; Laukkanen and Nauges 2014; Roth et al. 2008; Stetter et al. 2022; Wuepper and Huber 2022), whose findings highlight mostly small positive or no effects of subsidies on these. In this context, our study particularly relates to studies estimating the causal effects of subsidies (Bertoni et al. 2020; Chabé-Ferret and Subervie 2013; Claassen et al. 2018; Feng et al. 2013; Laukkanen and Nauges 2014; Schaub, Pfaff, et al. 2025; Schaub, Roth, et al. 2025; Stetter et al. 2022; Wuepper and Huber 2022; Zimmert et al. 2024). We add to these studies by using measured environmental

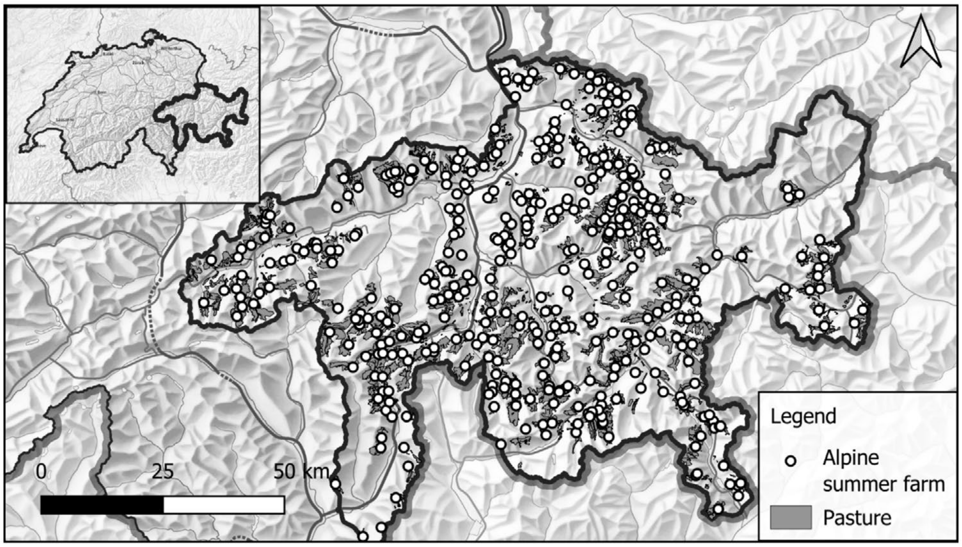

FIGURE 1 | Map of Alpine summer farms (white dots) and pasture locations (grey shapes) in the canton of Grisons, Switzerland. Farms may occupy multiple pastures; however, we cannot show further details due to privacy reasons.

outcomes, which so far have only been done by recent studies in the context of result-based agri-environmental schemes (Schaub, Pfaff, et al. 2025; Schaub, Roth, et al. 2025). However, more commonly, studies use proxies for environmental outcomes, such as the area enrolled in agri-environmental schemes, the carbon footprint index, and fertiliser application intensity. Investigating measured environmental outcomes is a policy-relevant extension of previous work, as the relationship between proxies and environmental outcomes is not always straightforward, given, for example, the landscape dependence of outcome developments (Baldi et al. 2013; Socher et al. 2012) and the quality of action implemented by farmers (Graham et al. 2018; Montgomery et al. 2020).

Second, we contribute to the research on the effect of farm subsidies on land abandonment, such as in less favoured areas and severely disadvantaged areas, a classification used in the EU (Cooper et al. 2006). In this field, studies have reported heterogeneous results with modest effect sizes, ranging from reduction to increases in land abandonment due to farm subsidies (Cooper et al. 2006; Takayama et al. 2019; Zawalinska et al. 2013). These studies so far have focused on different types of subsidies and land under agriculture and farm numbers. Thus, we shed new light on the effect of different types of subsidies on the unintended environmental consequences of land abandonment (i.e., woody plant encroachment). Overall, considering the results of previous studies in both fields, our study adds to a greater picture of agricultural policies that are often not optimally designed.

2 | Study Area and Policy Background

We investigate alpine summer farms in Switzerland, which are seasonal, and their pastures serve as an extension of the forage base during the summer months for, on average, 100 days. This relieves production areas on home farms for winter forage production. Alpine summer farming areas cover 30% of Switzerland's land surface, and the seasonal grazing of these grasslands constitutes an important aspect of the European mountain transhumance[2] (Meyer, Gazzarin, et al. 2024). As of December 2023, the alpine farming season is also part of UNESCO's world heritage (UNESCO 2024), underlining its fundamental importance as a cultural heritage.

Since 1985, land use change in Switzerland has led to the loss of about 10% of summer pastures, and most of this loss, about 75%, was due to woody plant encroachment (Meyer, Contzen, et al. 2025). Expressed in absolute area loss, the feed source loss due to woody bush encroachment amounts to 42,000 ha. 60%–70% of this loss is due to green alder. This encroachment results in a substantial decline in plant species richness as dense green alder has been shown to host 62% less species than open pastures (Bühlmann et al. 2014; Wiedmer and Senn-Irlet 2006; Zehnder et al. 2020). Green alder is rapidly spreading, as shown by Wiedmer and Senn-Irlet (2006), who found an annual biomass increase of 6 tons per ha, predominantly as leaves. Given its modest height of 0.5–3 m (Mauri and Caudullo 2016), this suggests a substantial horizontal expansion across space within a year, despite the lack of exact metrics for expansion speed. Strong encroachment of woody plants to grasslands (0.5%–2% per year) has also been reported in the USA and Argentina, resulting in the loss of animal productivity (Anadón et al. 2014).

Climate change plays a key role in woody plant encroachment. Rumpf et al. (2022) found that reduced alpine snow cover and increased vegetation productivity have led to significant greening in the European Alps, with bush encroachment likely contributing. Gherardi and Sala (2015) observed that greater precipitation variability, including extended droughts, reduces grass productivity while favouring shrub growth, a trend seen in Swiss alpine farms. Van Auken (2009) further highlights that rising CO_2 levels and increasing temperatures, both linked to climate change, contribute to the expansion of woody plants.

Switzerland's government implemented farm subsidies in the 1990s to support alpine summer farms in maintaining the economic viability of farming activities. In 2013, an agricultural policy reform was approved and implemented in 2014. This reform entailed an average increase in livestock subsidies of 17.5% per standardised livestock unit. Furthermore, two additional agri-environmental subsidies were introduced by the policy reform: landscape quality subsidies and ecological focus area subsidies. Landscape quality subsidies aim to compensate farms that maintain and enhance regionally typical landscapes, including meadows, pastures, stone walls, and hedges. Ecological focus area subsidies necessitate the presence of at least six indicator non-woody plant species on grasslands, which must be maintained for a minimum of eight years.

The policy reform has two features that define the control group and enable us to identify the policy effect of farm subsidies on woody plant encroachment. First, the exact increase in subsidies to farmers was previously unclear because of revisions due to public and political debates. The agricultural policy reform was agreed upon in March 2013 by the Swiss Parliament but not without being challenged by a strong political opposition, including the farmers' union (see swissinfo.ch (2011) for details) (OECD 2017). Moreover, the precise adjustments of the subsidies were set by subordinate regulations on October 13, 2013. The official statement explaining the policy to the relevant stakeholders was announced on November 1, 2013 (Meier 2013). As a result, farmers were left with uncertainty regarding the implementation and specifics of the reform, and this uncertainty persisted until shortly before the implementation of the new regulations. This uncertainty in the economic incentives made forward-looking adjustment of farmer strategies unlikely *prior to* the introduction of the reform. Second, not all eligible farmers immediately obtained higher subsidies for different reasons. One reason is that pre-policy subsidies for farmers may be sufficient; thus, they may decide to decrease livestock until they receive the same amount of subsidies as before. This decision may be driven by farmer's opportunity costs, such as off-farm work opportunities or work required at the home farm in the valley. The farmer may work more on the home farm due to less work being required from less livestock on the alpine farm. Another reason is that participation in the payment increase is optional, and an eligible farmer needs to explicitly apply for it. However, we did not investigate the precise reason—we only explored whether the post-policy subsidies were higher than the pre-policy ones. Thus, our control group consisted of a mixture of the two sub-groups described above, which we exploited in our identification strategy, as described below. See S1 for additional information on the policy background.

3 | Methods

3.1 | Data

For our analysis, we constructed a novel dataset that links four different data components from four sources. First, we used annual census data, including information on subsidies for 520 alpine summer farms (white dots in Figure 1) in the canton of Grisons.

Grisons is characterised by the Köppen-Geiger climate classifications *Dfb* and *Dfc*. Besides the European Alps, this climate classification is found among a variety of mountain ranges globally, such as the Rocky Mountains of North America, the Andes of South America, and the Altai Mountains in Central Asia. The annual farm census data are provided by the Agricultural Policy Information System of the Swiss Federal Office of Agriculture from 2004 to 2018. With these 520 farms, we focused on farms in operation throughout our study period (i.e., 2004–2018). This excluded farms that were given up or taken over by a new generation of farmers. This focus enables us to provide a nuanced understanding of the effects of payment on the contemporary agricultural system.

Second, we used spatial pasture perimeter data, which depict the exact extent of the pasture of each farm (grey shapes in Figure 2). We connected farm-level data and pasture perimeters through matching IDs, which we illustrate for a single farm in a motivating example in Figure S3.

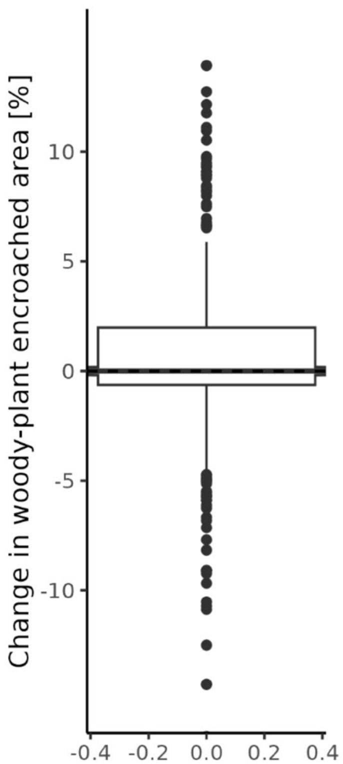

FIGURE 2 | Distribution of change in the share of woody plant encroached area from pre- to post-policy years (i.e., 2009 and 2018, respectively). For improved visibility, we have omitted 11 observations that exhibit changes in woody plant encroachment larger than 15% and lower than 15%.

Third, we used the pasture perimeter to extract spatially explicit information on biophysical covariates that are potentially relevant for woody plant encroachment. These include elevation, if the pasture is on average north-facing, soil water and nutrient capacity, farm accessibility, and share of protected area on total farm area. Farm accessibility is measured as the travel distance of the farm's nearest municipality to the most quickly accessible agglomeration such as a major town or city by car (Federal Office for Spatial Development 2017). Soil water and nutrient capacity are derived from the digital soil map of Switzerland and measured on a seven-point Likert scale from "very low" to "very high", with higher values indicating favourable soil conditions (Federal Office for Agriculture 2024a). We use share of north-facing slopes, as this orientation facilitates encroachment compared to other orientations (Gellrich et al. 2008), which is the focus of our study. We collected these data from the open government data platform *opendata.swiss* and took the mean value at the pasture perimeter of each variable.

Fourth, we constructed our outcome variable (% of woody plant encroached area on total farm area) from remotely sensed and classified aerial images for the years 1998, 2009, and 2018, provided by the Swiss Federal Statistical Office. The spatial resolution of each pixel was 100 m by 100 m (Federal Statistical Office 2019). The Federal Statistical Office (2019) conducts quality control of these classified images through ground truthing, extensive visual expert assessment, and field verification. We calculated the share of woody plant encroached area in relation to the total pasture perimeter area per farm. To match the temporal resolution of the outcome data, we adjusted the temporal resolution of the farm-level data and used the years 2009 and 2018. Further, we used 1998 to assess the conditional parallel time trend assumption.

Combining these four components—farm-level data, pasture perimeters, spatial covariates, and remote sensing woody plant encroachment data—allowed us to study the relationship between subsidies and woody plant encroachment over time, as we explored the precise amount of and changes in subsidies of the farm and the associated woody plant encroachment on the farm's pastures.

3.2 | Notation and Treatment Effects of Interest

We start with an explanation of the notation and treatment effects of interest. Let the random variable D_i indicate the treatment status of the farm i, with $D_i = 1$ indicating that the post-policy subsidies of farm i exceed the pre-policy subsidies and otherwise $D_i = 0$.[3] Therefore, the treatment group is defined as farms that received higher subsidies after the policy reform (=subsidy increase at the farm-level), whereas the farms in the control group received either the same or less subsidies compared to the pre-policy level. The treatment definition also is similar to the one leveraged in Wuepper and Huber (2022).

To define the treatment effects of interest, we use Rubin's causal model (Imbens and Rubin 2010). In particular, for a given treatment status d, let $Y_i(d)$ represent the potential woody plant encroachment outcome of farm i, had the farm been exposed to a subsidy increase d. The measured outcome of farm i is denoted by Y_i. With this notation, we define the treatment effects of interest as $\Delta(1,0) = \mathbb{E}\left[Y_i(1) - Y_i(0) \mid D_i = 1\right]$ where $\Delta(1,0)$ can be interpreted as the average effect of changes in subsidies for farms that obtained them. In the robustness Section 3.5 and in Material S4, we consider two alternative definitions of the treatment. First, we consider a continuous version of the treatment which reflects the total amount of additional subsidies that a farm receives as a result of the reform. Second, we consider the possibility that a farm may adjust its livestock as a result of the reform. To take this possibility into account, we define two further treatment variables: one that measures the increase of livestock and one that measures the increase of subsidies per livestock unit. All three alternative definitions lead to qualitatively very similar estimates for our main findings and the mechanism analysis, implying the robustness of our evidence.

3.3 | Identification Strategy

The main challenge in identifying and estimating $\Delta(1,0)$ is the possibility of farmers selecting the treatment based on their potential outcomes. Specifically, farmers may choose to claim higher subsidies because they expect to be able to improve the management of their grasslands using an additional budget. This may enable them to improve grassland management through additional (contract) labor and the production of additional feed. This type of selection mechanism introduces a correlation between the treatment D_i and the unobserved determinants of encroachment, which potentially induces a bias.

To deal with the endogeneity of D_i, our identification strategy exploits both the multiple time periods of the data as well as the two features of the agricultural policy reform that define the control group (as discussed in Sections 2 and 3.2 above). We utilise these characteristics by adopting the following identification assumption of conditional parallel trends:

$$\mathbb{E}\left[Y_1(0) - Y_0(0) \mid D = 1, X\right] = \mathbb{E}\left[Y_1(0) - Y_0(0) \mid D = 0, X\right]$$

where X includes characteristics of the farms that are relevant to woody plant encroachment (see Section 3.4 and Table S2 for details). In other words, we assume that among farms with similar relevant characteristics X, treated farms ($D_i = 1$) would have had the same trend in woody plant encroachment over time as control farms ($D_i = 0$) (i.e., the counterfactual case in which the treated farms were not exposed to the treatment). Note that this assumption is much weaker than a (conditional) independence assumption as it allows for systematic differences in the unobserved factors, as long as the trends are parallel. In our results (Section 4.3), we provide convincing evidence that this assumption is satisfied.

Two more considerations need to be made with regard to changes in the political system in order to correctly identify the policy effect. First, the abolishment of Switzerland's milk quota system in 2008 could have potentially influenced our results through a legacy effect. However, this is unlikely due to the strong plausibility of the parallel time trend. Second, subsidies for grass-based milk and meat production were introduced in 2014, which could theoretically confound our results regarding the policy reform. However, these subsidies were not paid to the farms in our sample (Mack and Kohler 2019).

3.4 | Doubly Robust Difference-in-Differences Estimation

Following recent developments in the literature on difference-in-differences estimation, we estimated Δ(1, 0) using the semi-parametric doubly robust difference-in-differences (DRDID) approach developed by Sant'Anna and Zhao (2020). The DRDID estimator combines the inverse probability weighting (by the propensity score) approach by Abadie (2005) and the outcome regression approach by Heckman et al. (1998).[4] DRDID is robust to the misspecification of functional forms in either of the aforementioned two approaches. We follow Sant'Anna and Zhao (2020) and use time-invariant covariates in the estimation. The recent econometric literature on parallel trends in the context of self-selection implies that including confounding factors in the difference-in-differences estimator potentially strengthens the validity of the parallel trends assumption. The covariates we consider include average pasture elevation (in meters of above sea level), whether the pastures are on average north facing (dummy), soil water and nutrient capacity (Likert scale), which are bio-physical factors known to have an influence on woody plant encroachment on Swiss summer farms (see e.g., Herzog and Seidl 2018; Gellrich et al. 2008; Gellrich et al. 2007). Further, we include accessibility to the farm (min) (Huber et al. 2021), and whether parts of the pasture are protected areas (share) or part of a wildlife corridor (share), as these factors can may influence the costs of grassland management. An overview of the summary statistics of the time-invariant covariates can be found in Table S2.

3.5 | Robustness Checks

We conduct several robustness checks to investigate the sensitivity of the specification. First, we use an alternative approach to identification that relies on exogenous variations in subsidy increases from an instrumental variable. This instrument is the administratively determined optimal livestock stocking rate of 2000 (Figure S4.2). As a large share of subsidies is made as grazing subsidies for livestock, this regulation can be used as an instrument because it is related to the subsidies (Figure S4.1). Further details can be found in Data S4.

Second, we evaluate the plausibility of the stable unit treatment value assumption (SUTVA). SUTVA states that the potential outcome for any farm does not vary with the treatments assigned to others' farms (Imbens and Rubin 2010). This pertains especially to spatial spillovers from one farm to another. For this, we first look at the neighbourhood relationships of farms, which could make them susceptible to spillovers in bush encroachment and subset the farms that are adjacent to other farms. For these neighbouring farms, we calculate the bivariate Moran's I as a measure of spatial spillovers for woody plant encroachment and lagged subsidies, using an order-one queen contiguity weight matrix as a measure of neighbourhood.

SUTVA also states that there is no hidden variation in treatment. We evaluate this assumption by estimating the ATT from multivalued treatment to account for potentially hidden variation in treatment, using the approach suggested by Callaway et al. (2024). Specifically, we divide the treatment group into two treatment groups: one that had received a subsidy increase below the median subsidy increase, and one that had received a subsidy increase above the median subsidy increase. This evaluates whether different levels of treatment intensity lead to different ATT. If the estimated ATT differs significantly between the two groups, it suggests that treatment effects are heterogeneous and that the assumption of no hidden variation may not hold.

Third, we omit woody plant encroached farms in the upper and lower 5% quantiles and check whether our results were driven by specific quantities of the distribution.

Fourth, we specify two alternative treatment variables. The first one, denoted by $\widehat{D}_i$, measures whether the subsidies per livestock unit of farm i have increased as the result of the policy:

$$\widehat{D}_i = \mathbb{1}\left\{ \frac{S_{i,\text{post}}}{\# LV_{i,\text{post}}} - \frac{S_{i,\text{pre}}}{\# LVi_{i,\text{pre}}} > 0 \right\}$$

where $S_{i,\text{post}}$, $S_{i,\text{pre}}$, denote the total livestock subsidies obtained by farm i in the post and pre-treatment periods, respectively, and $\# LV$ denotes the number of livestock units. Note that since all farmers were eligible for an increase upon claiming it, the control group consists of farmers, who did not claim the increase. This group potentially includes farmers who were either unaware of the reform or who failed to claim the increase on time. The second alternative treatment, denoted by $\widetilde{D}_i$, measures whether the livestock of farm i increased:

$$\widetilde{D}_i = \mathbb{1}\left\{ \#\text{LV}_{i,\text{post}} - \#\text{LVi}_{i,\text{pre}} > 0 \right\}$$

Specifying these two alternative treatment variables is informative about the mechanism of the policy. Specifically, a farmer might reduce the number of livestock as a result of the policy or she/he may adjust other farming practices such as the amount of effort put into manual clearing of woody plants. The three definitions of the treatment—$D, \widehat{D}, \widetilde{D}$—aim at capturing the different aspects of being treated by the policy.

4 | Results

4.1 | Trends in Woody Plant Encroachment

The share of woody plant encroachment increased from pre- to post-policy reform across all farms by +0.6%, equivalent to +2.87 ha per farm. This change exhibits a substantial distribution, as illustrated in the boxplot of changes in woody plant encroached area (Figure 2). Most values are concentrated between approximately −5% and +5%, with an interquartile range from slightly below 0% to about 3%. The mean change of 0.6% suggests a slight overall increase, while numerous outliers—particularly above 5%—indicate that some areas experienced substantial gains, and a smaller number show notable decreases. The cumulative grassland loss caused by woody plant encroachment across all farms amounts to 1491 ha, underlining the ongoing grassland loss dynamics driven by woody plant expansion.

4.2 | Changes in Subsidies

Due to the 2014 policy, farm subsidies increased by, on average, 22,103 CHF per farm, which corresponds to a 53% increase in subsidies compared to the pre-policy period. The increase affected three relevant types of subsidies (Federal Statistical Office 2022a): livestock, ecological focus areas, and landscape quality subsidies. This corresponds to a total increase of 11.5 million CHF for farms within the study area. The number of livestock increased on average by four standardised units of livestock per farm, and subsidies for both ecological focus areas and landscape quality were introduced.

4.3 | Effects of Subsidies on Woody Plant Encroachment

We find that subsidy increases at the farm-level caused woody plant encroachment, thus increasing grassland loss. Specifically, subsidy increases caused an average grassland loss to woody plant encroachment of 1.95% [95% confidence interval = 0.27, 3.63] (Figure 3). To put this result into perspective, the effect corresponds to a grassland loss of 4.7 ha on average per farm[5] between 2009 and 2018, indicating a policy-relevant effect. The results also support the conditional parallel trend assumption, as the point estimate in 1998 was close to the 0 line, with the

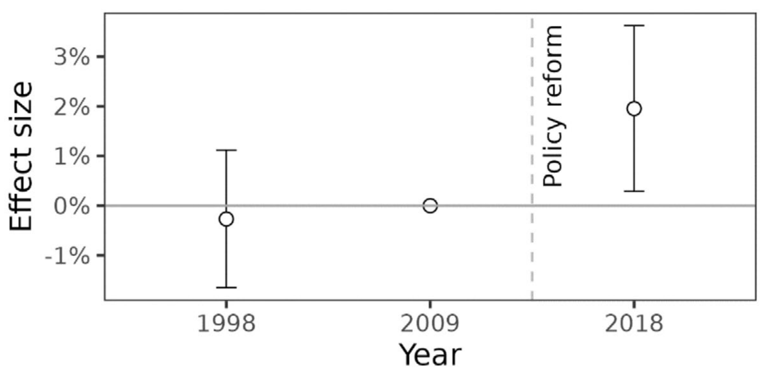

FIGURE 3 | Effect of subsidy increases on the woody plant encroachment share. The bars represent the 95% confidence intervals. 2009 is the reference year in our estimation, which therefore does not have a confidence interval.

confidence intervals symmetrically around it (Figure 3). This also implies that subsidies before the reform had a similar influence on both the treated and control groups, which then does not bias our estimates. Further assumptions are tested and presented in Section 3.5, which supports the validity of our main results.

Turning to the uncertainty of these effect estimates, first we note that we do not test a pre-defined hypothesis but rather evaluate the policy effect. Recent literature on *p*-values and statistical significance suggests different procedures in these two cases (Cox 2020; Imbens 2021; Wasserstein and Lazar 2016). Specifically, we follow Imbens (2021) and report only confidence intervals and their policy implications. The 95% upper and lower bounds of the confidence interval corresponding to our estimate are equal to 0.27% and 3.63% (Figure 3). In policy terms, this means that a realisation at the upper bound would lead to woody plant encroachment about twice as much as our main estimate, while at the lower bound of one that is close to zero. However, the predictive power of the lower and upper bounds is considerably lower than that of the main point estimate. Specifically, as Romer (2020) shows, under some regularity conditions, the upper and lower bounds of the 95% confidence interval are 7 times less likely than the point estimate.

4.4 | Subsidy Mechanisms

To shed further light on our results, we perform an analysis to disentangle the effects of the three components of subsidy increases on woody plant encroachment as potential mechanisms: livestock, ecological focus areas, and landscape quality subsidies.[6] In the first step, we analyse the precise composition of the subsidy increase (the treatment) and calculate the shares of all three components of the total increase in subsidies. Figure 4 shows the histograms of these shares and reveals that primarily, subsidy increases for ecological focus areas (left panel) or livestock (right panel) led to an increase in total subsidies due to the policy reform.

In the second step, we focus our analysis on the share of ecological focus area and livestock subsidy increases. For this, we re-estimate our results for subsets of farms where either livestock or ecological focus area subsidies dominated the total subsidy increase. Domination of one subsidy type means that the total increase in subsidies was primarily due to livestock or ecological focus area subsidies.[7] This analysis is informative about the separate effects of the different policy mechanisms.

We find that woody plant encroachment increases when increases in subsidies for ecological focus areas dominate; that is, the policy effect was similar to the effect of our main results (Figure 5, left panel). When livestock payments dominated the increase in subsidies, the effect tended to decrease woody plant encroachment (Figure 5, right panel). These results suggest an effect of the ecological focus area subsidies that increased woody plant encroachment.

4.5 | Robustness Checks

We conduct a series of robustness checks to investigate the sensitivity of the specification. First, we utilise exogenous variations in subsidy increases using an instrumental variable approach, which supports our findings (see Data S4).

Second, we evaluate the plausibility of the stable unit treatment value assumption (SUTVA). We suggest that spatial spillovers from one farm to another are unlikely as green alder, the dominant woody plant, reproduces and spreads only in local geographical areas. Therefore, only direct neighbour farms may be subject to violation of this assumption. In our case, 35% of farms do not have direct neighbours[8] and are therefore not susceptible to this spillover. For the remaining farms with direct neighbours, we find a low Moran's I as a measure of spatial spillovers and no relevant correlation (Figure S4.3). We further evaluate SUTVA's plausibility and estimate the ATT from multivalued treatment to account for hidden variation in treatment and divide the treatment group into below and above median subsidy increase. These results are consistent with our main results (Figure S4.4).

Third, omitting woody plant encroached farms in the upper and lower 5% quantiles confirmed that our results remained consistent (Figure S4.5).

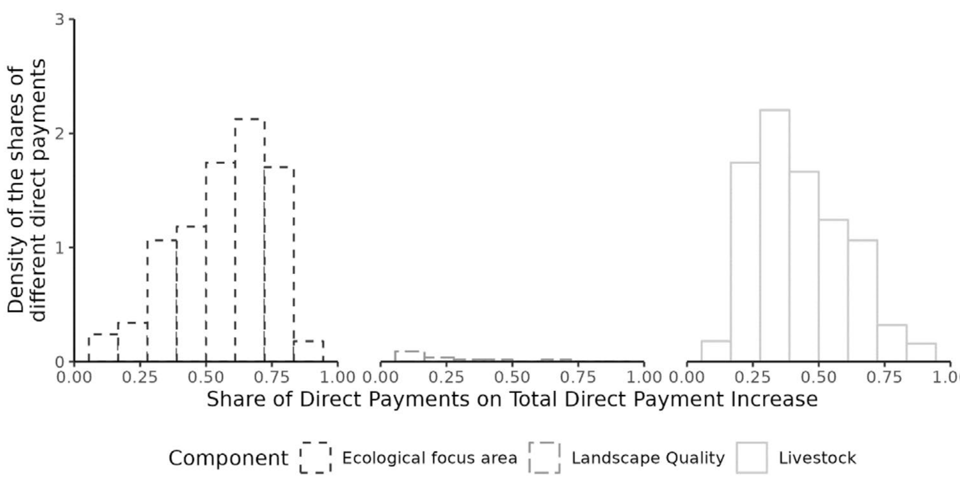

FIGURE 4 | Relationship between farms' increase in subsidies (treated) and the share of subsidy components on the total increase in subsidies.

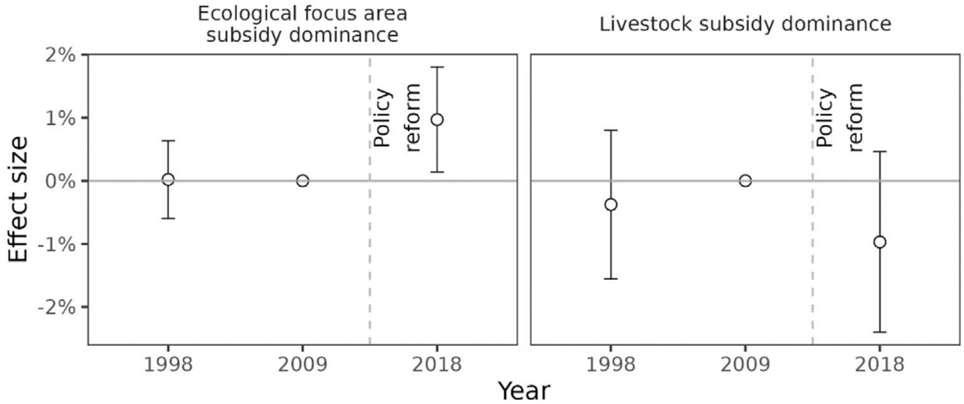

FIGURE 5 | Effect of subsidy increase when ecological focus area subsidies dominate the total increase in subsidies (left panel) and when livestock subsidies dominate the total increase in subsidies (right panel). The dots represent the point estimates, and the bars represent the 95% confidence intervals. The subsidy effects are indicated by the point estimates and confidence intervals in 2018.

Fourth, we re-estimate the treatment effect of the policy under the alternative definitions of the treatment $\widehat{D}$ and $\widetilde{D}$ as defined in Section 3.5. For treatment $\widehat{D}$, that is, when subsidies per livestock unit increased due to of the policy, the results (Figure S4.6) are similar to the estimates where livestock subsidies dominated the total subsidy increase (Figure 5, right panel). For treatment $\widetilde{D}$, that is, when the livestock numbers increase, the effect of the policy on woody plant encroachment is essentially zero (Figure S4.7). This strengthens our conclusion that the policy affects woody plant encroachment through ecological focus areas and not through (the amount of) livestock.

5 | Discussion

One explanation that is consistent with these results is a change in the spatial dispersion of livestock. The literature shows a positive relationship between livestock density and a reduction in woody plant encroachment (Pauler et al. 2022). Thus, farmers may exclude livestock from ecological focus areas to protect indicator plant species,[9] which can have an adverse effect through an increase in woody plant encroachment. This possibility points to a potential conflict of objectives introduced by the subsidies for biodiversity through ecological focus areas. Leaving nature to itself in order to preserve it may lead to biodiversity deterioration through woody plant encroachment. Zabel (2019) highlights an inverse relationship between livestock and biodiversity-based subsidies, which supports this explanation. Similarly, Herzog and Seidl (2018) show a reduction in grazing intensity on marginal grassland.

Another explanation is that farmers might have a minimum profit that they want to earn in reference to previous years (Röder 2007). Farmers may therefore have a reference income (also referred to as target income), meaning they adjust their labour supply based on reaching a specific income level rather than maximising overall profit. As Richards (2020) shows in the context of farm labour, workers may reduce their effort once they achieve their reference income, even if higher pay rates are offered. Similarly, in the case of alpine farming, farmers may decrease labour-intensive management activities once they reach their income goal. Above this reference income, the marginal utility of earning more might be relatively low. Further, in alpine farming, keeping grassland free from woody plants, such as bushes and shrubs, can vary in marginal costs, depending, for example, on distance to the farmhouse (Gellrich et al. 2008).

Finally, farmers have several options to reduce woody plant encroachment, including grazing, mowing, and mulching. While grazing and mowing primarily serve to prevent the establishment of woody plants and are integral to forage-based grassland management, mulching focuses on removing already established woody plants and is not necessarily linked to forage production. These different approaches have important implications for farmers' average costs and the optimal timing of their implementation. Research by Bollmann et al. (2014) and Dux et al. (2009) suggests that mulching is the most effective and cost-efficient method for counteracting woody plant encroachment compared to grazing and mowing. However, the use of mulching on alpine farms is forbidden and may only be allowed with special permits for which farmers have to apply Obtaining these for ecological focus areas is especially difficult. This may exacerbate encroachment issues in these areas.

It is important to note that all three explanations of potential mechanisms are tentative, since we lack the necessary data to test them further. Thus, the precise mechanism remains an exciting open question for future research.

6 | Conclusion

Agricultural policies aim to prevent grassland loss to woody plant encroachment through farm subsidies to ensure the provision of forage for livestock production, conservation of biodiversity, and cultural ecosystem services. However, their actual effectiveness in achieving this goal is unknown. To the best of our knowledge, this is the first study to estimate the effect of farm subsidies on woody plant encroachment, finding an increase in woody plant encroachment due to subsidy increases at the farm level.

Our findings can be explained by a reduction in the management intensity of marginalised grassland and ecological focus areas (Baker et al. 2012; Feng et al. 2013). This reduction could be due to changes in the optimal management intensity resulting from a change in the farmers' income situation and concerns about maintaining the plant species required to obtain subsidies. These explanations align with results by Zabel (2019) and Herzog and Seidl (2018), who showed an inverse relationship between livestock and biodiversity-based subsidies as well as grazing intensity on marginalised grasslands.

Our findings have important policy implications. First, our study shows that subsidies can have unintended adverse effects. Such findings have also been reported in other cases, such as land offered to the Conservation Reserve Program in the USA (Feng et al. 2013). Thus, policymakers should consider unintended behavioural responses by farmers that need to be identified by future research, including income referencing (Dessart et al. 2019; Richards 2020; Schaub et al. 2023). Thus, our results emphasise the importance of the coordinated design of policy measures to achieve environmental sustainability, given the apparent conflict in policy goals highlighted in our study. Finally, the study highlights the need for long-term environmental monitoring programs that measure environmental outcomes directly, as policy uptake rates are insufficient in this case. These data should be made readily available to enhance the evaluation of subsidies, as the inclusion of measured environmental outcomes can provide valuable additional insights into how agricultural subsidies work.

Our study highlights important future research avenues. First, there is a need to explicitly investigate the mechanisms that connect changes in subsidies and woody plant encroachment, including livestock distribution and labour availability (Gellrich et al. 2008). For livestock distribution, this requires spatially explicit measurements of changes in livestock distribution on pastures through GPS collars (Pauler et al. 2020) and their association to changes in subsidies. Second, it is worthwhile exploring optimal policy strategies that consider farmers' behaviours to increase the effectiveness of subsidies in achieving environmental goals. Applicable research approaches include field experiments for different subsidy designs, complemented with in-depth qualitative interviews that uncover the underlying motivations and contextual factors behind farmers' responses. Third, future studies should investigate whether a lack of conditionality (i.e., monitoring compliance and sanctioning detected non-compliance) might be an issue, as woody plant encroachment still occurred in the study area, despite the common objective of subsidies to safeguard grasslands. Wunder et al. (2018) emphasised that the lack of implementation of conditionality in subsidies for environmental services leads to underperformance in environmental conservation due to, for example, including multiple non-environmental objectives. Fourth, as one third of alpine farms and their pastures in Switzerland are collectively managed (Meyer, Gazzarin, et al. 2024), it is worthwhile to explore behavioural differences depending on whether farms are communally or privately managed, as there may be varying degrees of commitment to long-term ecological management (Ostrom 2010).

Author Contributions

Maximilian Meyer: conceptualisation, methodology, writing – original draft preparation, visualisation, data preparation, data analysis, writing – reviewing/editing. Sergei Schaub: conceptualisation, methodology, writing – original draft preparation, writing – reviewing/editing. Petyo Bonev: conceptualisation, methodology, writing – original draft preparation, writing – reviewing/editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The remote sensing data is freely available and can be downloaded at https://data.geo.admin.ch/browser/index.html#/collections/ch.bfs.arealstatistik?.language=en. The survey raw data can be requested from Agroscope. All code used to analyse the data is available in the Supporting Information.

Endnotes

[1] Examples include subsidies for extensive pasture grazing for Swiss alpine farms (described below in detail), the Queensland Vegetation Management Act in Australia, which regulates clearing to preserve grasslands as well as Agri-Environment Schemes in the EU's Common Agricultural Policy, which support farmers in maintaining open landscapes, such as the pastures in Germany's Allgäu region and Austria's traditional grazing areas (Agrarmarkt Austria 2024; Bavarian Academy for Nature Conservation and Landscape Management 2024; Federal Office for Agriculture 2021; State of Queensland 2025). The EU additionally designates areas as 'Severely Disadvantaged Areas' and 'Less Favoured Areas', where farmers receive subsidies to sustain extensive grazing systems in mountainous regions, where alternative land uses are limited and otherwise woody plants would take over grasslands (Cooper et al. 2006; Zawalinska et al. 2013).

[2] Transhumance is a form of pastoralism and is characterised by the seasonal migration of livestock to mountain pastures during the warmer seasons. Farmers move livestock to lower altitudes for the rest of the year.

[3] In our robustness checks we account for different specification of the treatment using the approach suggested by Callaway et al. (2024).

[4] See equation 3.1 in Sant'Anna and Zhao (2020) for a precise definition of the estimator.

[5] As the average farm size is 240 ha.

[6] Ideally, we would also investigate the management decision that ley behind the changes in woody bush encroachment (such as livestock distribution or labor availability), however, such data is not available.

[7] As shown in Figure 4, subsidies for ecological focus areas account for a larger share of the overall increase in subsidies than those for livestock.

[8] We define direct neighbours as farms that share a border with another farm.

[9] In Switzerland, areas such as ecological focus areas that are not to be grazed must be protected from trampling and browsing by grazing animals (Federal Office for agriculture 2024b).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.