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Effects of water protection measures in agriculture on the environmental impacts of the Swiss food sector

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ABSTRACT

European agro-environmental policy aims to reduce agricultural emissions of nutrients and pesticides into water, yet these goals remain unmet. Voluntary direct payments schemes aim to steer farmers towards emission-reducing practices. We assessed the environmental impacts of stricter direct payment regulations: Farmers who want to receive direct payments a) have to produce pesticide-free and b) have to reduce their livestock numbers to their own farm's feed production capacity. We compared the environmental impacts of the Swiss agricultural sector in three direct payment scenarios with the status quo. We addressed the trade-offs between domestic production and imports, and between target and other environmental impacts.

While freshwater ecotoxicity within Switzerland would decrease considerably due to reduced pesticide use, aquatic eutrophication caused by domestic agriculture would remain similar to the status quo. However, increased import amounts would more than offset the domestic environmental improvements. Eutrophication, particularly caused by imported meat, would increase strongly, as would deforestation and water scarcity. Our paper shows that the improvement of water quality in Switzerland has to be bought with partly considerable trade-offs in the countries of origin of imported products, showing the need for complementary measures such as reducing food waste or changing consumption patterns.

1. Introduction

Agriculture remains one of the most important contributors to water pollution with nutrients and pesticides (Kristensen et al., 2018; Parris, 2011). Mekonnen and Hoekstra (2015) found that diffuse sources – mainly agriculture – make up for three quarters of global water pollution with nitrogen (N). In OECD countries, agriculture's contribution to N and phosphorus (P) in surface waters was found to lie between 20 and 80% (Parris, 2011). For water pollution with N and P, the livestock sector is one of the major causes (Leip et al., 2015). Criteria such as regional distribution of animals and nutrient management play a role here. In addition, the amount of imported feed leads to a higher stocking density than would be possible if animals could only be fed with locally produced feed. These factors cause nutrient surplus caused by livestock farming and thus exacerbate pollution in importing countries (Svanbäck et al., 2019; Wang et al., 2018). Pesticides, as important inputs in agriculture to ensure crop yields and product quality (Cooper and Dobson, 2007; Popp et al., 2013), have adverse effects on the environment, especially on water pollution (Mateo-Sagasta et al., 2017; Tudi et al., 2021). De Baan et al. (2020) found that environmental risks caused by fungicides were decreasing over the last years in Switzerland, but this was not the case for herbicides and insecticides. Use restrictions, however, were found have a strong potential to decrease the environmental risk. Ongoing debates exist on banning some pesticides such as glyphosate completely. Those could, however, lead to yield and income losses for farmers, and there would be a trade-off with other measures to protect water quality such as no-till farming (Kudsk and Mathiassen, 2020), which is supposed to prevent soil erosion and related nutrient losses but needs herbicides to prepare the land for the next crop. Environmental policies in Europe aim at reducing the concentration of nutrients and pesticides in water, but these goals have not been reached yet (Kristensen et al., 2018). The Green Deal of the European Union aims at reducing both the amount and the risk of pesticides for human health and the environment by 50% by 2030 (EC, 2020). Likewise, goals exist to reduce nutrient pollution (as in the Water Framework Directive, EC, 2000).

Voluntary direct payments schemes are a tool of agricultural policy to influence farmers towards more emission-reducing management

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(Mack et al., 2023). They can be bound to certain conditions that farmers have to fulfil. In this paper, in an ex-ante analysis we estimated via life cycle assessment the possible environmental impacts of implementing stricter direct payment regulations with the goal of improving water quality. The direct payment regulations that we investigated demand a) that farmers produce pesticide-free and b) that they reduce their livestock numbers to their own farm's feed production capacity. We examined this on the basis of the Swiss agricultural sector. This was motivated by a popular initiative[1] in Switzerland, called the "drinking water initiative", that demanded as a policy measure that only farmers who comply with these restrictions should receive direct payments (Huber and Finger, 2019; Schmidt et al., 2019). Although the initiative was rejected by the voters, it has an ongoing impact on Swiss agricultural policies (Finger, 2021).

We integrate environmental impacts that occur both in domestic agriculture and abroad due to food and feed imports, taking into account changes in the productivity of domestic agriculture under such regulations. For policy measures that lower domestic productivity, it is important to determine the environmental impacts of the entire basket of agricultural products. This is particularly important for countries that are already import-dependent from the start, such as Switzerland, which serves as the focus of this paper. As shown in previous work, imported products have a major influence on the environmental impact of the Swiss basket of agricultural products (Frischknecht et al., 2018; von Ow et al., 2020). Switzerland's gross self-sufficiency rate of food is 57%, and the net self-sufficiency rate is 50%, excluding animal products produced with imported feeds (FOAG, 2021). More favorable environmental impacts of domestic agriculture through extensification measures such as a pesticide ban or lower livestock numbers could lead to a shift or even to an exacerbation of environmental impacts abroad because they decrease productivity (Mack et al., 2023). This can particularly affect environmental impacts that are not the focus of such extensification measures, such as water scarcity or deforestation, which may have much higher characterization factors in other world regions than the region under study, and which also vary highly between countries (Boulay et al., 2018; Chaudhary and Brooks, 2018).

Our analysis is based on data from Schmidt et al. (2019). The authors investigated in an ex-ante analysis how the two direct payment measures "ban on pesticides" and "adapting livestock numbers to each farm's feed potential" would affect economic and structural indicators of the Swiss agricultural sector. According to them, this would cause major changes in Swiss agriculture. Livestock numbers would be reduced by 4–14%, and 70–92% of arable land and 11–52% of permanent crop land would be pesticide-free (Schmidt et al., 2019). Some farmers would opt out of the direct payment scheme, as this would be more profitable for them. Therefore, pesticides would still be used on a portion of the total agricultural land. With such economic and structural consequences, the Swiss agricultural sector's calorie production would decrease by 12–21%. Thus, the dependency of the Swiss food sector on imports would increase further. Environmental impacts might thus be improved domestically, but exacerbated abroad.

The main goal of the "drinking water initiative" was to reduce water pollution with pesticides and nutrients, but the suggested regulations were also expected by the initiators to have a positive impact on ammonia emissions, biodiversity, and global warming. We lay a special focus on the environmental impacts that the investigated direct payment measures aim to reduce, i.e. freshwater ecotoxicity and eutrophication of water with N and P. In addition, we answer the question whether and how other, non-target environmental impacts of the agricultural sector would change and what would be the consequences for environmental impacts abroad caused by changing imports into Switzerland.

2. Material and methods

2.1. Scenarios

Our investigation was based on scenarios from Schmidt et al. (2019), who describe the development of structural and economic indicators for Swiss agriculture under stricter direct payment regulations regarding pesticide use and livestock numbers. The scenarios were modelled over a period of 10 years with the base year 2016. The results of the last evaluation year are presented. In the reference scenario, the direct payment system from 2018 is continued over the whole timespan. In addition, Schmidt et al. (2019) investigated three scenarios for the implementation of the stricter direct payment regulations (they will be called "direct payment scenarios" from now on, as opposed to the reference scenario) (Table 1). Three variables were modified in each of these scenarios: (a) the crop yields that would decrease if no pesticides were used, (b) the total budget for direct payments that could increase for the remaining farmers if some farmers were to leave the direct payment system, and (c) the option of a price premium for pesticide-free products. Among the three direct payment scenarios, the HP scenario represents the optimal situation for farmers from an economic point of view, as they receive higher direct payments and a price premium (Schmidt et al., 2019). Therefore, a high rate of farmers participates in the new direct payment regulations. The IP scenario represents an intermediate economic situation with a medium participation rate. The LP scenario represents the most unfavorable economic situation, with a low participation rate of farmers in the new direct payment regulations. Table 2 shows the yield losses compared to the status quo assumed for pesticide-free production.

In all direct payment scenarios, farms had the option to adopt the new regulations and thus to continue to receive direct payments, or to withdraw from the direct payment system and continue current management practices. For the latter, production methods were assumed to remain the same. Schmidt et al. (2019) calculated the effect of all scenarios on income, land use, livestock numbers and the produced amount of agricultural raw products for each scenario with the agent-based agricultural sector model SWISSland (Möhring et al., 2016). This model is based on 3300 farms from the Swiss farm accountancy data network that are "nearly representative for the Swiss agricultural sector" (Schmidt et al., 2019). It predicts the farmers' response to changing economic conditions and aggregates the results to the sector level. In our case, farmers can decide to adapt their production practice to the new direct payment requirements and to continue to receive direct

Table 1
Definition of direct payment scenarios (cf. Schmidt et al., 2019).

Scenario name	Description	Additional direct payments	Yield losses on complying farms	Price premium
LP (low participation rate)	Unfavorable participation conditions	no	high	none
IP (intermediate participation rate)	Intermediate participation conditions	yes	medium	half of current organic price premium
HP (high participation rate)	Favorable participation conditions	yes	low	current organic price premium

[1] In Switzerland, any citizen can launch a proposal to revise the Federal Constitution. This is done via a so-called "popular initiative" that results in a plebiscite if enough signatures are collected. If an initiative is accepted by voters in a plebiscite, policies according to the initiative have to be implemented. https://www.ch.ch/en/votes-and-elections/initiatives/what-is-a-federal-popular-initiative/#further-information, retrieved December 21, 2023.

Table 2
Yield losses in pesticide-free agriculture. Changes in % of the reference scenario. Source: Schmidt et al. (2019).

Crop	High yield losses			Medium yield losses			Low yield losses		
	Intensive	extensive	organic	intensive	extensive	organic	intensive	extensive	organic
Wheat	−42	−27	−8	−21	0	0	−5	0	0
Barley	−49	−30	−12	−41	−20	0	−26	0	0
Legumes	−41	−29	−23	−24	−8	0	−17	0	0
Sun flowers	−33	−20	0	−25	−10	0	−17	0	0
Rapeseed	−40	−32	0	−23	−12	0	−7	0	0
Soy beans	−35	n.a.	−20	−31	n.a.	0	−19	n.a.	0
Grain maize	−34	n.a.	−12	−29	n.a.	0	−25	n.a.	0
Sugar beets	−40	n.a.	0	−39	n.a.	0	−27	n.a.	0
Fodder beets	−26	n.a.	−2	−25	n.a.	0	−14	n.a.	0
Potatoes	−68	n.a.	−46	−58	n.a.	−29	−50	n.a.	−15
Fruit trees	−60	n.a.	−46	−52	n.a.	−35	−44	n.a.	−24
Grapes	−80	n.a.	−76	−60	n.a.	−53	−40	n.a.	−29
Berries	−80	n.a.	−78	−49	n.a.	−44	−40	n.a.	−34
Silage maize	−34	n.a.	−12	−25	n.a.	0	−17	n.a.	0
Vegetables	−51	n.a.	−29	−23	n.a.	0	−9	n.a.	0
Permanent grassland	0	0	0	0	0	0	0	0	0
Temporary grassland	0	n.a.	0	0	n.a.	0	0	n.a.	0

n.a.: not available.
extensive: Crop production free of fungicides, insecticides, growth regulators, and chemical-synthetic stimulants that is eligible for direct payments in a special Swiss direct payment program. Herbicides are still allowed, as well as other inputs into farming that are prohibited in organic farming, such as mineral fertilizers. "Extensive" can therefore be placed in between conventional and organic farming.

payments, or they can decide to ignore the new requirements and opt out of the direct payment system (Schmidt et al., 2019). The SWISSland model is described in detail in Möhring et al. (2016). We had access to more detailed output data than what is contained in Schmidt et al. (2019) and used them for our analysis of environmental impacts (see section 2.3.1).

2.2. LCA of the agricultural sector

We used the life cycle assessment (LCA) methodology to analyze the environmental impact of the Swiss agricultural sector including imports. The LCA was conducted in accordance with ISO (2006a) and ISO (2006b). We used the SALCA method (Swiss Agricultural Life Cycle Assessment, (Nemecek et al., 2023), which comprises amongst other components set of models for direct emissions from agriculture, a life cycle inventory database for crop and animal products, and a selection of impact assessment methods.

2.2.1. Goal and scope definition

Using comparative LCA, we contrasted the environmental impacts after a possible implementation of the stricter direct payment regulations regarding pesticide use and livestock numbers with a reference scenario. Fig. 1 shows the system boundaries of the agricultural sector as they were regarded in this study, including imported foods and feeds. The selection of products included in the system boundaries comprise the most important food products of the Swiss agricultural sector, the amount of these products that is imported into Switzerland, and the amount of imported feed products needed for animal husbandry in Switzerland. Exported products were subtracted from Swiss agricultural production.

The function of the assessed system, i.e. of the Swiss agricultural sector, is to provide products to feed Switzerland's population. The products under consideration form the content of a "basket of agricultural products", which served as the functional unit in our analysis (as abbreviation, we use the term "basket of products" hereafter). Table SI-1 contains the amounts of products contained in the basket of products. The basket of products – and therefore the functional unit – covers the entire demand of the Swiss population for those agricultural raw products that can be produced in Switzerland. However, the total assessed quantity of these products includes both the quantity produced in Switzerland and the quantity imported. Foodstuffs that are not produced in Switzerland, such as tropical fruits or marine animals, were not considered; these are not affected by the direct payment regulations, and it was assumed that their consumption would remain the same in all scenarios. The temporal system boundary is one year. In the direct payment scenarios, the population and per capita consumption was assumed to remain the same as in the reference scenario. Any changes in domestic production are compensated by imports or exports.

Except for sugar, all agricultural products – both domestic and imported – were considered only up to the stage of the agricultural raw product, *i.e.*, crop products, meat from the slaughterhouse, and raw milk. The transport of imported products to Switzerland was included, but no other downstream processes. SWISSland does not provide information on processed food products. The data therefore do not represent all stages of food production, but covers the part of the agri-food sector that is affected by the changes in direct payment regulations. Food processing and human consumption is outside the scope of this study, since the direct payment system acts exclusively on agricultural production, and processing into consumer products would remain the same with and without implementation of the new regulations.

2.2.2. Life cycle inventory data

We represented the content of the basket of products using life cycle inventory (LCI) data for almost 400 processes (production of crops and feedstuff, processing feedstuff, animal husbandry and slaughtering, production and transport of import products) in Switzerland and abroad. The large majority of these datasets was taken from Agroscope's in-house SALCA database (see tables SI-2 and SI-3), *i.e.*, datasets on crop and animal production and on agricultural buildings. The foreground emissions in these datasets are calculated by SALCA's emission models (Nemecek et al., 2023), while the background data come from the ecoinvent database v3.5 (Wernet et al., 2016). Ecoinvent was also taken as a data source for import products. A smaller amount of datasets was taken from the World Food LCA Database (Nemecek et al., 2019), AGRIBALYSE v1.2 (Koch et al., 2015), and Agri-Footprint (Durlinger et al., 2017). An inconsistency is caused with regard to greenhouse gas emissions: The World Food LCA Database includes CO_2 emissions from land use change, but not the other databases. As this only affects a small number of the datasets used (5 out of 98 data sets for imports, see table SI-3) and climate change was no target impact of this study, this discrepancy was not considered decisive, but it means that the greenhouse gas emissions caused by imported products may be underestimated. We used the Agri-Footprint datasets only for feed processing data and adapted them so that they use ecoinvent v3.5 as background

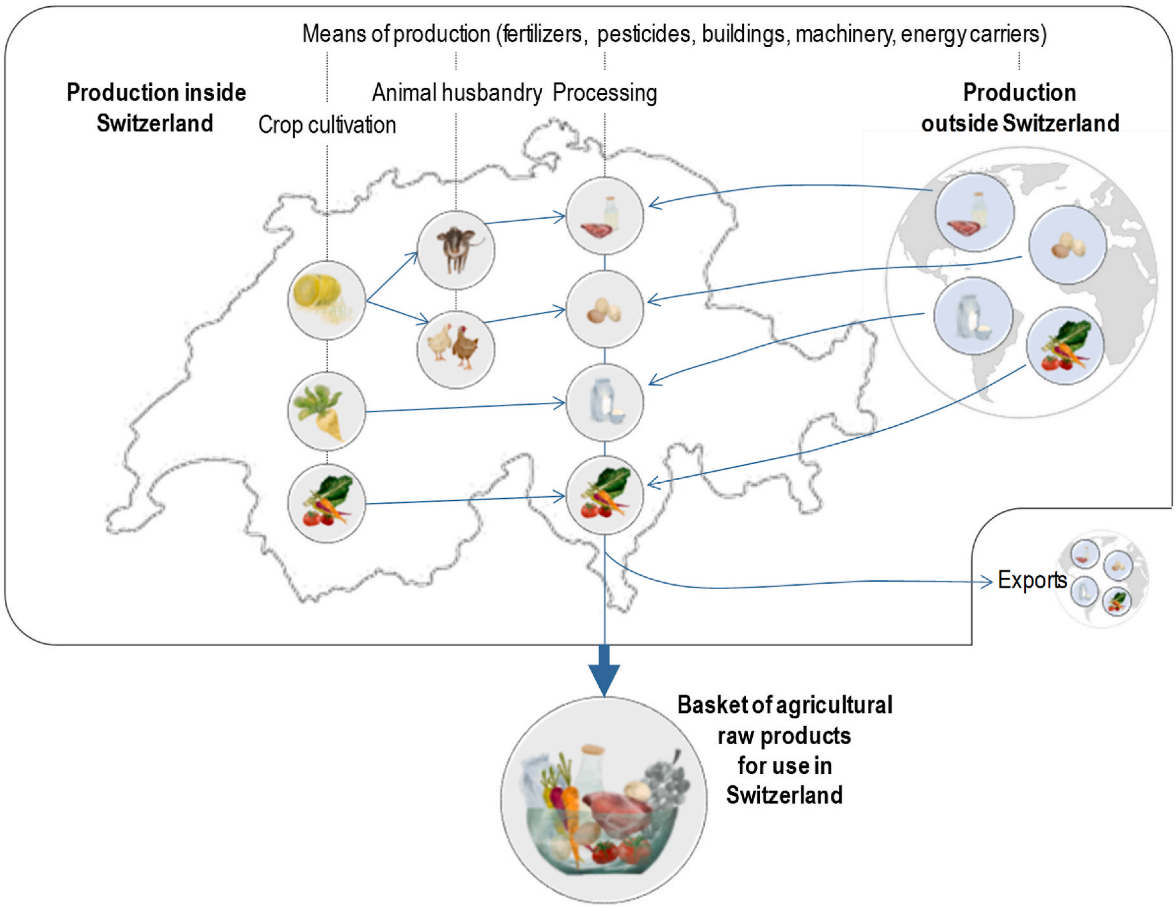

Fig. 1. System boundaries of the LCA of the agri-food sector in this paper.

processes, particularly for agricultural production of the raw products, like all other datasets we used. The data on pesticide use in Switzerland were updated for all major crops using data from the Swiss Agri-Environmental Data network (Gilgen et al., 2023) for the years 2012–2016. Table SI-4 shows which pesticides were used in the LCI datasets. Some products were not available in the databases, so we compiled new LCI datasets using the SALCA methodology. For all inventories, we applied the pestLCI method (Dijkman et al., 2012; Nemecek et al., 2022; Rosenbaum et al., 2015) to estimate losses of pesticides into different environmental compartments. For pesticide-free production, we compiled new datasets with medium yield loss and adapted them for high and low yield loss using the extrapolation approach from Roches et al. (2010). For some countries of origin of imports, no specific LCI data were available. In those cases, we selected other countries as proxies and replaced the background processes with geographically fitting datasets. This comprised all inputs from the technosphere as well as inputs from biosphere such as land occupation and transformation, and emissions such as ammonia, where impact assessment methods require specific information on geography. Tables SI-2 and SI-3 show all LCI datasets that we used. All LCI data were cross-checked against pesticide registers to determine if they contained pesticides that were no longer allowed in the respective countries (cut-off date was June 30th, 2019). If such pesticides were found, they were replaced by others with a similar effect based on consultations with Agroscope experts. The amount of replacement active ingredient was calculated via the respective application rates per passage. For all import products, we used data for conventional production. Therefore, toxicity impacts of imports might be slightly overestimated.

2.2.3. *Impact assessment*

The SALCA methodology contains a set of impact categories, the selection of which is described in (Roesch et al., 2017, 2021) and which is based on recommendations by the Life Cycle Initiative hosted by UN environment[2] and ILCD (International Reference Life Cycle Data System).[3]

We distinguish between target impacts that are given by the goal of the "drinking water initiative" and further environmental impacts that we quantify in terms of a trade-off analysis. With this we want to ensure that improvements in target impacts are not at the expense of other environmental impacts. Target impacts are freshwater ecotoxicity of organic and inorganic substances, and aquatic eutrophication with N and P. As trade-off analysis, we investigated the impact on terrestrial eutrophication, acidification, biodiversity, and global warming, land use and deforestation, water scarcity, non-renewable energy use and use of abiotic resources. Table 3 shows all impact categories used, their short name that we used in figures, and the underlying impact assessment methodology.

Several of these impact categories provide country-specific characterization factors which we used to distinguish between production in Switzerland and abroad. For eutrophication and acidification, we used the Swiss characterization factors for domestic production and the global factors for imported products. For biodiversity impact of land use and for water scarcity, we used individual characterization factors for every import country.

In general, SALCA uses impact categories at midpoint level. No

[2] https://www.lifecycleinitiative.org/, retrieved March 30, 2023.
[3] https://eplca.jrc.ec.europa.eu/ilcd.html, retrieved March 30, 2023.

Table 3
Impact categories analyzed in this paper and sources of the underlying methodology.

Impact category	Name used in figures	Methodology and source
Target impact categories		
Freshwater ecotoxicity of organic and inorganic substances	Freshwater ecotoxicity organic/ inorganic	USEtox (Rosenbaum et al., 2008, 2015), supplemented by characterization factors from the OLCA-Pest project (Nemecek et al., 2022)
Marine eutrophication	Marine eutrophication (aq. eutrophication N)	ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017)
Freshwater eutrophication	Freshwater eutrophication (aq. eutrophication P)	ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017)
Other impact categories used for trade-off analysis		
Terrestrial eutrophication potential, acidification potential	Terrestrial eutrophication, acidification	Accumulated exceedance (Posch et al., 2008; Seppälä et al., 2006), applying different characterization factors for emissions occurring in Switzerland and abroad
Biodiversity impact of land use	Biodiversity impact	Species loss potential through land use according to Chaudhary and Brooks (2018)
Land competition	Land competition	CML (Guinée et al., 2001)
Deforestation	Deforestation	Life cycle inventory results on land transformation
Water scarcity	Water scarcity	AWARE (Boulay et al., 2018)
Global warming potential	Global warming	GWP100 (IPCC, 2021), with climate-carbon feedback, without biogenic CO_2 emissions
Use of non-renewable energy resources	Non-renewable energy use	Cumulative energy demand (Frischknecht et al., 2007)
Abiotic resource use	Abiotic resource use	CML (Guinée et al., 2001)

midpoint method was available for the biodiversity effect of land use and land use change, so this effect was considered at the endpoint level. In addition, we also show results from the LCI stage for land use and deforestation, considering these as resource use impacts.

2.3. Data basis

2.3.1. Production volumes in Switzerland

Table 4 shows the share of farmers who comply with the new regulations in the direct payment scenarios as calculated by Schmidt et al. (2019). A large share of cattle and arable farms would comply with the new regulations, while pork, poultry and specialty crop farms would largely forego direct payments and continue current practice. The exact percentage varies between the scenarios.

Table 4
Percentage of farms of different farm types that comply with the new direct payment regulations in the scenarios with low (LP), intermediate (IP) and high (HP) participation rates. Source: Schmidt et al. (2019).

Farm type	Direct payment scenarios		
	LP	IP	HP
Dairy farms (specialized)	87 %	95 %	97 %
Combined dairy and arable farms	94 %	99 %	100 %
Suckler cow farms (specialized or combined with other productions)	97 %	98 %	98 %
Cattle, sheep, or goat farms	93 %	97 %	98 %
Pork and poultry farms (specialized or combined with other productions)	37 %	58 %	67 %
Arable farms (specialized)	78 %	96 %	99 %
Vegetable farms, orchards, wineries	7 %	30 %	49 %
Other combined farms	83 %	95 %	97 %

Fig. 2 shows the change in agricultural land use in the scenarios, Fig. 3 shows the change in animal numbers, and Table 5 shows the production volume of the main agricultural products within Switzerland. The production volumes of crops do not follow the same pattern for all crops. Particularly remarkable is the production volume of bread and feed grain that increases in the HP scenario, *i.e.*, the scenario with the highest share of pesticide-free arable land. Grain yields do not decrease so much in this scenario compared to the other scenarios, and the area of grain production increases at the cost of other crops, such as sugar beets or oil crops (see table SI-5), which results in higher production volumes. Likewise, the changes in productivity of the other crops are derived not only from yield losses, but also from shifts in the area used per crop.

Not only crop production but also domestic livestock production becomes more extensive in most of the direct payment scenarios. For some animal categories, animal numbers decrease less than meat and milk production, resulting in lower production per animal. In contrast, the number of laying hens and broilers, and therefore eggs and poultry produced is higher especially in the LP and IP scenarios than in the reference. This is due to the fact that farmers who opt out of the direct payment system can increase their stocking density, as they do not have to follow the requirements of the direct payment system any more.

2.3.2. Modelling of imports

We used three different approaches (a – c) to model the amount of imported agricultural products, as we had information on domestic production and consumption at different levels of detail.

a) Modelling import quantities based on data of domestic production volume from SWISSland

Time series of the development of Swiss imports and exports (in tonnes) for the years 2000–2016 were available for the products for which SWISSland provided data on domestic production volume. These time series were projected into 2025. Econometric time series analyses were performed for the projections of import and export volumes (Chatfield and Yar, 1988; Holt, 2004). The time series analyses were performed without additional control variables, such as population growth or gross domestic product per capita. Here we assumed that the development of population or gross domestic product per capita already determined the past development of Swiss imports and exports (Chatfield, 2003). Therefore, the projections of import amounts inherently take into account the same development for the future.

The figures from the projections for import and export volumes (Table 6) were adopted directly for the reference scenario. With this, we calculated the total domestic demand for each of these products in 2025 in the reference scenario by subtracting the export amounts from domestic production and adding the import amounts for each product. In the direct payment scenarios, we assumed that the total domestic demand and the export quantities were the same as in the reference scenario. Thus, the import quantities of the products from Table 6 were calculated for each of the direct payment scenarios as total domestic demand minus domestic production of the scenario plus export quantities.

b) Products for which SWISSland provides information on how much land their cultivation requires in Switzerland

For a number of other agricultural products, e.g. fruit and vegetables, only the area under cultivation in Switzerland and its change in the scenarios was known, but no production quantities (see Fig. 2 and Table 5). For these products, we calculated domestic production using the crop yields from LCI data. No time series projection could be

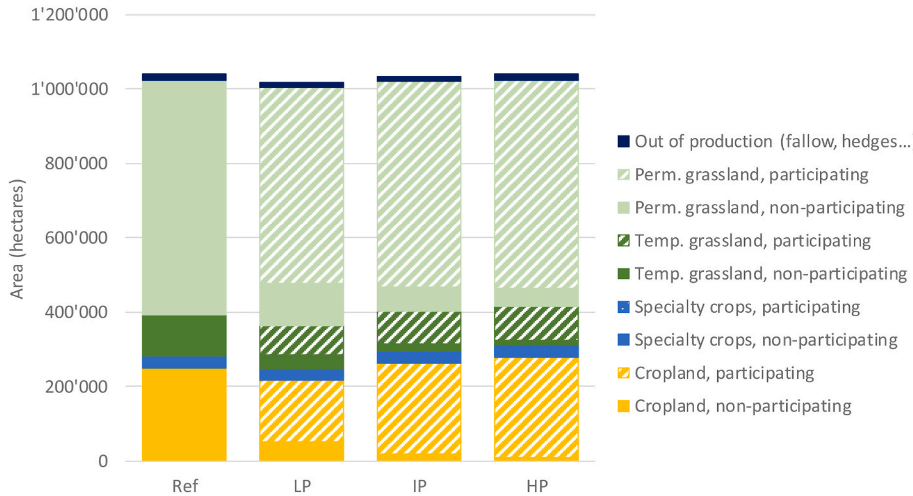

Fig. 2. Agricultural land use in Switzerland in the reference scenario and in the direct payment scenarios with low (LP), intermediate (IP) and high (HP) participation rates in hectares. The figure distinguishes between land cultivated by farmers participating in the new direct payment system (dispensing with the use of pesticides) and by non-participating farmers (continuing to use pesticides). Analysis based on data from Schmidt et al. (2019). Underlying values in table SI-5.

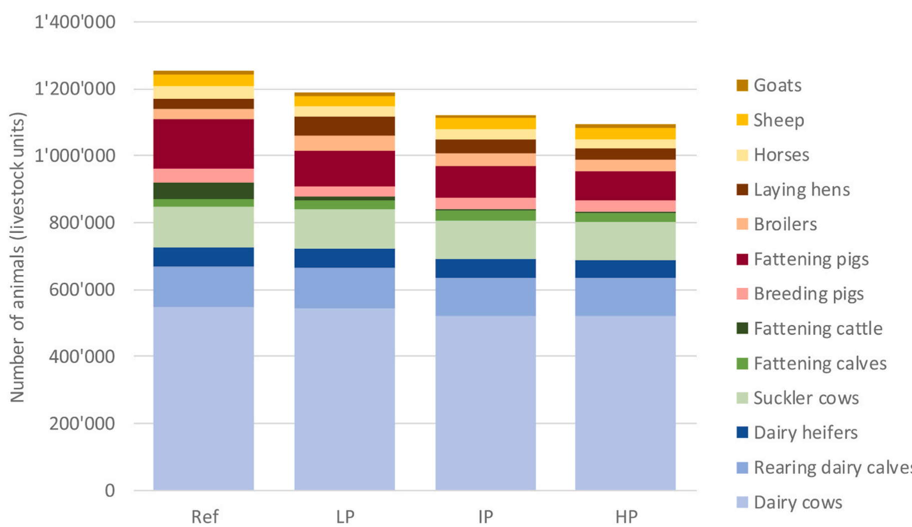

Fig. 3. Animal numbers in Switzerland in the reference scenario and in the direct payment scenarios with low (LP), intermediate (IP) and high (HP) participation rates in livestock units. Analysis based on data from Schmidt et al. (2019). Underlying values in table SI-6.

Table 5
Production volumes of the most important agricultural products in Switzerland in the reference scenario and in the direct payment scenarios with low (LP), intermediate (IP) and high (HP) participation rates. Analysis based on data from Schmidt et al. (2019).

		Reference	LP	IP	HP
Bread grains	1000 t	379	253	435	500
Feed grains		193	117	170	233
Grain maize		133	87	102	117
Oil crops		97	51	66	75
Sugar		234	111	102	130
Potatoes		323	249	203	174
Milk		3437	3281	3110	3109
Beef		114	92	87	85
Veal		27	36	32	26
Pork		239	178	165	158
Poultry		100	175	134	117
Eggs	10^6 pieces	829	1339	956	783

modelled for the import quantities. Therefore, to determine import quantities, we assumed that only the difference in domestic production between the scenarios and the base year (2016) would be compensated by imports or exports. Table SI-7 shows the import quantities of all products included in the calculations for all scenarios.

c) Feed that is produced outside Switzerland, on which SWISSland has no information

For each scenario, we derived the quantities of feedstuffs needed from the figures for animal husbandry from SWISSland. From the LCI data that we used for Swiss animals, we extracted the information on imported feeds and on quantities (table SI-7).

A mix of countries of origin was assigned to each imported agricultural product according to the Swiss import statistics for the years 2012–2015 (see table SI-8). We assumed that in all scenarios, the mix of countries of origin and the production intensity in these countries would be the same as in the base year 2016. The Swiss population represents only about 0.1% of the world population. A change in demand in Switzerland would have only a negligible impact on the world market

Table 6
Amounts of imports and exports in the base year 2016 and modelled for the reference scenario in 2025.

		Exports 2016	Imports 2016	Net trade flow 2016	Exports 2025	Imports 2025	Net trade flow 2025
Bread grains	1000 t	0.2	420.6	420.4	0.2	589.0	588.8
Feed grains		0.4	84.6	84.2	0.9	103.1	102.2
Grain maize		0.2	165.9	165.7	0.2	205.4	205.2
Oil seeds		1.0	46.1	45.1	1.0	30.7	29.7
Sugar		104.3	96.2	−8.1	50.9	95.3	44.4
Potatoes		5.2	104.3	99.1	5.8	69.8	64.0
Milk		3.2	24.8	21.6	5.3	26.1	20.8
Beaf		4.8	22.0	17.2	7.7	29.4	21.7
Veal		0.0	0.7	0.7	0.0	0.8	0.8
Pork		2.2	10.1	7.9	3.3	10.6	7.3
Poultry		1.4	45.2	43.8	1.5	44.5	43.0
Eggs	10^6 pieces	4.3	601.6	597.3	1.7	604.0	602.3

and would therefore not shift import origins or production systems.

The "drinking water initiative" required that farms should reduce their livestock numbers to their own farm's feed production capacity. For Schmidt et al. (2019), livestock numbers were adjusted so that the energy and crude protein needs of the animals could be met solely by the energy and crude protein theoretically available from each farm's own land. This ensures that the livestock numbers or milk yield is adjusted to the farm's own resources. However, it is still possible for farms to buy in feed, freeing up the farm's land for food production. In the modeling of the environmental impacts, this resulted in the continued need for feed imports in the direct payment scenarios.

2.4. Sensitivity analysis

Our assumption in the main scenarios is that when Swiss agriculture becomes less productive due to extensification measures (which is the case for most products, see section 2.3.1), but domestic consumption remains the same, more has to be imported. However, there are levers to improve the environmental impact of imports, such as avoiding food loss and food waste (von Ow et al., 2020). In a sensitivity analysis, we analyzed the effect of avoided food loss and food waste on the overall environmental impact of the Swiss basket of agricultural products (for the sake of brevity, we use the term "food losses" in this paper).

According to Scherhaufer et al. (2018), 18.4% of foods get lost along the food value chain. Beretta et al. (2017) even estimated food loss and food waste of 37% along the food value chain in Switzerland, i.e. from agricultural production up to consumption, including losses of imported products that occur abroad. Food losses have been found to contribute 15–28% to environmental impacts such as greenhouse gas emissions, acidification, eutrophication, water use, land use or biodiversity loss of food systems (Beretta et al., 2017; Jeswani et al., 2021; Read et al., 2020; Scherhaufer et al., 2018). With every step along the value chain, environmental impacts of losses accumulate. Losses at the end of the value chain have higher environmental impacts than losses at the beginning. In general, agricultural production has the highest share of impacts of foods and therefore of food losses (Bernstad Saraiva Schott and Andersson, 2015; Martinez-Sanchez et al., 2016; Oldfield et al., 2016; Read et al., 2020; Scherhaufer et al., 2018).

For our sensitivity analysis, we used the information from Beretta et al. (2017) on how many food losses would be avoidable in Switzerland. We subtracted the respective amounts from the imports in the reference scenario. We included all losses occurring along food value chains, not only those that occur during agricultural production, as our system boundaries would suggest. This is because all losses come down to more agricultural products being needed to compensate for them.

3. Results

3.1. Target impacts freshwater ecotoxicity and aquatic eutrophication

Regarding domestic agricultural production, freshwater ecotoxicity of organic substances decreases by 51% in the LP scenario, by 67% in the IP scenario, and by 75% in the HP scenario(Fig. 4). The most important driver for this effect is the decreasing use of pesticides. This implies that the ban on pesticides in the direct payment system would have the desired effect within Switzerland. However, not all farmers would adopt these new regulations. 51–93% of specialty crop farmers would opt out of the new, stricter direct payment system and continue using pesticides. Therefore, freshwater ecotoxicity of organic substances within Switzerland caused by pesticides won't be reduced to zero. For freshwater ecotoxicity of inorganic substances, crop production has a smaller share in the impact in all scenarios. The most important contributor in the reference scenario is copper use in specialty crops. Conventional wine growing is decisive for the change within Switzerland in the direct payment scenarios: The production amounts are reduced by 23–46% compared to the reference scenario, causing the decrease in domestic impact on freshwater ecotoxicity of inorganic substances.

In the direct payment scenarios, the impact of imported products on freshwater ecotoxicity increases strongly compared to the reference scenario (Fig. 4). In the HP scenario, more farmers comply with the new regulations, keeping fewer livestock and growing fewer fruits, vegetables and grapes than in the LP scenario (table SI-5 shows, that the pesticide-free area for specialty crops in the HP scenario is much larger than in the LP scenario). This implies that less feedstuff has to be imported, but more meat, milk, and specialty crop products, if consumption remains the same. Thus, the impact of the imported products almost compensates for the improvement that occurs domestically. For the whole basket of products, freshwater ecotoxicity of organic substances decreases by 7–8% in the direct payment scenarios compared to the reference scenario. Freshwater ecotoxicity of inorganic substances of the whole basket of products even increases in the direct payment scenarios. The main reason are animal-based foods. Within Switzerland, milk and meat production decreases more strongly than animal numbers, because more extensive production systems are promoted. Thus, more meat and milk have to be imported, while impacts of animal husbandry within Switzerland on freshwater ecotoxicity do not substantially decrease.

Within Switzerland, aquatic eutrophication with N decreases by 16% in the LP scenario, stays the same in the IP scenario, and increases by 8% in the HP scenario compared with the reference scenario. The impact is mainly caused by nitrate emissions from arable crop production. In the HP scenario, arable land area increases compared to the reference scenario, and yield losses are lowest, requiring more N fertilization than in the other two direct payment scenarios. Accordingly, in the LP scenario domestic production scores best. Although the amount of farmyard manure decreases, the nutrient requirement of the total agricultural land remains relatively similar to the reference scenario, so that farmyard manure is replaced by mineral fertilizers.

Freshwater eutrophication shows a similar pattern. Impacts of domestic production decrease only slightly, although this was an important target of the "drinking water initiative". The main contributor are P emissions. These are largely caused by soil erosion and by run-off from agricultural land. Emissions depend not only on the type and amount of

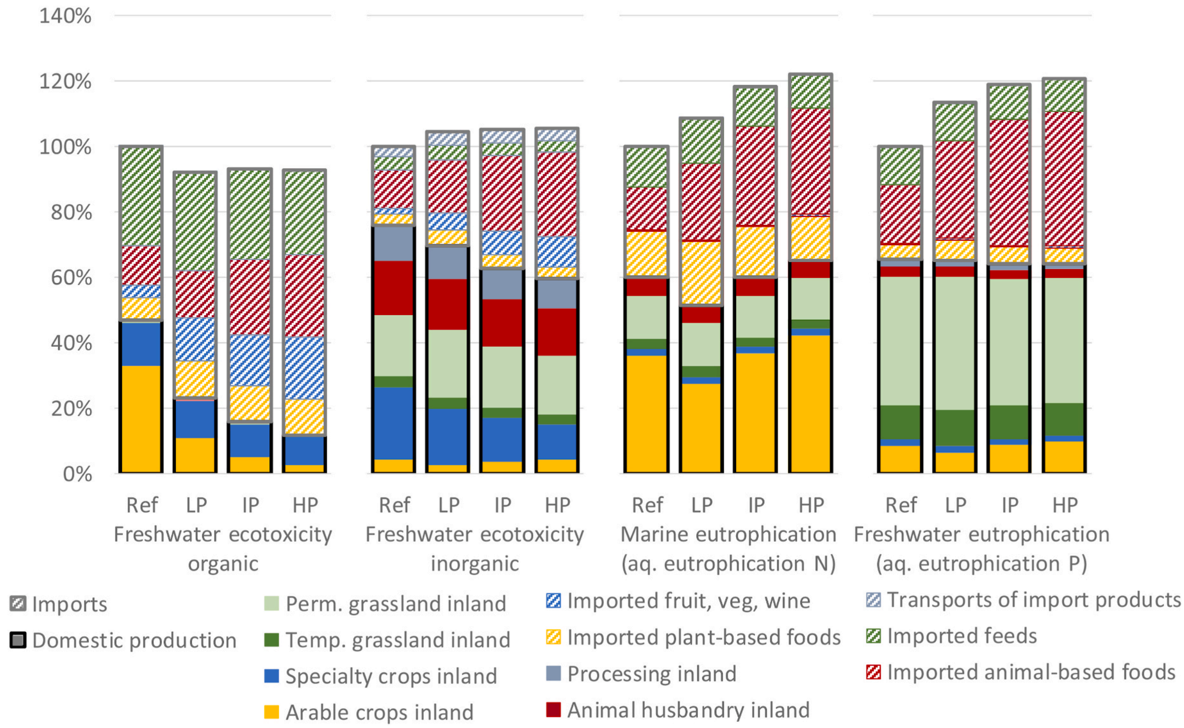

Fig. 4. Target environmental impacts of domestic production and imports in the direct payment scenarios with low (LP), intermediate (IP) and high (HP) participation rates relative to the reference scenario (100%).

fertilizer, but also on the land use type, topography and soil properties. Therefore, the lower livestock numbers and changes in crop production have almost no impact.

Livestock numbers decrease by 4–13%, domestic milk production decreases by 5–10%, beef production by 19–26%, and pork production by 25–34%. Thus, aquatic eutrophication with N and P caused by imported milk and meat increases more than the impact of animal husbandry within Switzerland decreases. Overall, the impact of the whole basket of products is higher in the direct payment scenarios than in the reference scenario.

3.2. Other environmental impacts (trade-off analysis)

For **terrestrial eutrophication** (Fig. 5), animal husbandry and

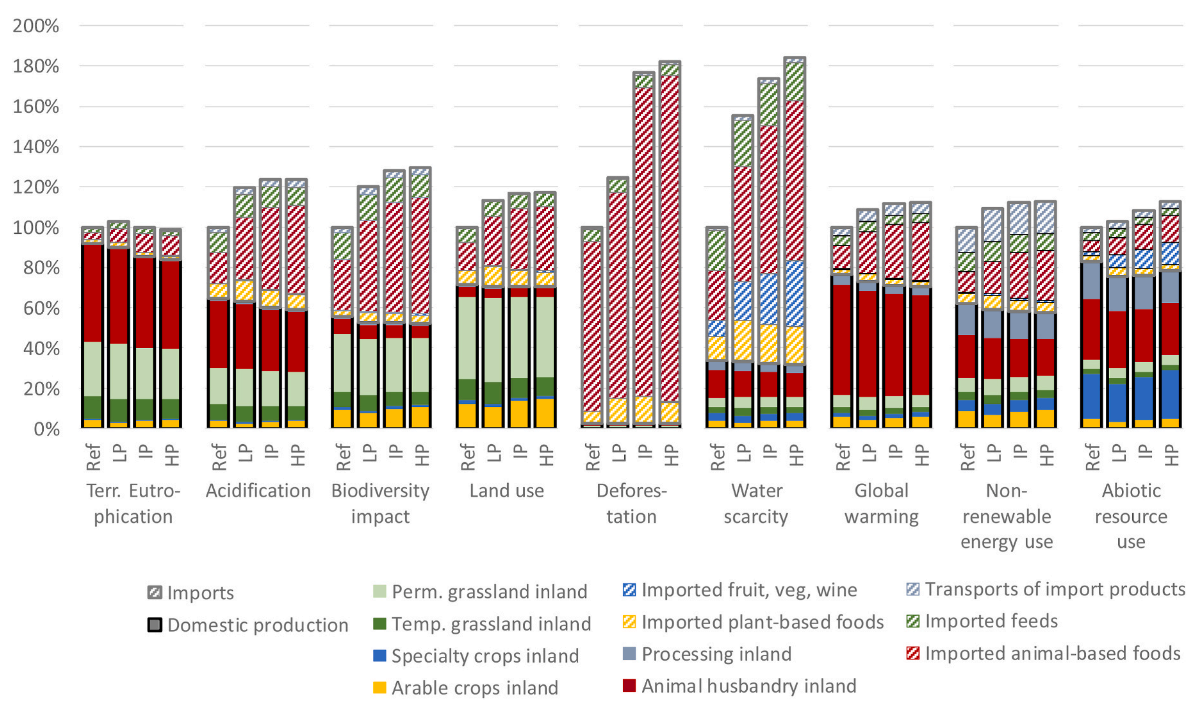

Fig. 5. Other environmental impacts (trade-offs) of domestic production and imports in the direct payment scenarios with low (LP), intermediate (IP) and high (HP) participation rates relative to the reference scenario (100%).

ammonia emissions from fertilization are decisive for domestic production. The effect of domestic production is roughly proportional to animal numbers in the scenarios. This is compensated by the imported animal-based foods, whose emissions increase, but in total the eutrophication of the whole basket of products in the direct payment scenarios remains about the same as in the reference scenario. In this case, the impact assessment method is important. The Accumulated Exceedance method quantifies the area where the carrying capacity of ecosystems is exceeded, and the extent of this exceedance. Therefore, ammonia emissions in Switzerland have a higher impact on terrestrial eutrophication than ammonia emissions in other countries, and the impact of imports is much smaller than that of domestic production.

Ammonia emissions have the largest contribution to **acidification**. For acidification, according to the Accumulated Exceedance method, there is less polluted land and therefore a lower acidifying impact of ammonia in Switzerland. Consequently, imported products, especially animal-based foods, are decisive for the result, with beef from Europe dominating the impact. In total, acidification in the direct payment scenarios is 20–24% higher than in the reference scenario.

The **biodiversity impact** of domestic production decreases by 5–6% in the direct payment scenarios compared to the reference scenario due to extensification as a result of the stricter direct payment regulations. Without greater impact on the overall result, there is a slight shift between the biodiversity impacts of grassland and arable land within the scenarios, because the area used for both land uses shifts. The requirement of the “drinking water initiative” that biodiversity in Switzerland should be conserved is met. However, imported products cause a strong increase in species loss potential in their countries of origin of 41–61 % in the direct payment scenarios compared to the reference scenario. The main impact is caused by beef from South America, even though less than 20% of imported beef comes from there. The land use in these countries per kg of meat is significantly higher than that in European countries (70% of the land use of beef imports occurs in Brazil and Uruguay) due to the more extensive farming systems. In addition, the characterization factor – the species loss potential per m^2 of pasture – is 2–15 times higher there than in the other countries of origin.

Overall **land use** increases in the direct payment scenarios because of higher imports of animal-based foods. The importance of imported products is also evident in the case of **deforestation**. Swiss animal husbandry uses almost only feed from certified production (i.e., from areas that have not been deforested since 2008). Therefore, neither imported feeds nor domestic production cause deforestation, and the whole impact comes mostly from imported animal-based foods. Soybean cultivation for feed used in European countries and the use of pasture land in deforestation areas, but also imported cane sugar as plant-based food, are responsible for the results of the scenarios. There is also a considerable difference in deforestation between the HP and the LP scenarios. Fewer farms complying with the new direct payment regulations, and consequently higher domestic meat production in the LP scenario, leads to lower import quantities and therefore to less deforestation.

Similarly, in the case of **water scarcity**, the effect of domestic agricultural production is rather small and changes little in all scenarios. Again, imported animal-based foods play the most important role for differences in water scarcity. Pork from southern European countries is of particular importance, where the animals are fed with grains from irrigated cultivation and, in addition, the water scarcity according to the characterization factors of the impact assessment method is up to 60 times greater than in Switzerland. Likewise, the impact of imported fruit, vegetables and wine increase in the direct payment scenarios compared with the reference scenario. The higher import amounts in the HP scenario lead to the highest water scarcity of all scenarios.

For **global warming potential**, domestic livestock production plays an important role. Accordingly, the effect of domestic production decreases by 5–8% in the direct payment scenarios compared with the reference scenario. This is in a similar range to the decrease in the cattle population. The effect of imports, on the other hand, increases by 52–79%. In particular, beef and pork from Europe and overseas play an important role. Overall, global warming potential is 9–12% higher in the direct payment scenarios than in the reference scenario.

In terms of **demand for non-renewable energy resources**, various parts of the basket of products contribute to the result. Again, the production of imported animal-based foods is decisive for the change of results in the direct payment scenarios compared to the reference scenario. Additionally, the contribution of transport processes from abroad and of plant-based foods increases. Furthermore, Electricity mixes of imported products use more non-renewable energy than domestic production due to Switzerland’s high share of renewable energy. In domestic production, the energy requirement of roughage conservation plays an important role, but this does not change impacts substantially across the scenarios. The cultivation of specialty crops requires almost as much non-renewable energy resources as arable farming.

Abiotic resource use is dominated by domestic production. Cattle farming, which requires zinc for the construction of barns, is particularly important. The decrease in livestock numbers in the direct payment scenarios therefore causes lower abiotic resource use. This impact, however, is offset by the effect of imported products. Egg imports from Europe make up a comparatively high share in the abiotic resource use of imported animal-based foods. As more eggs are produced domestically in the LP scenario than in the reference scenario, the impact of imported eggs is lower here. Considering both impacts from domestic production and imports, the direct payment scenarios perform similarly to the reference scenario.

3.3. Contribution analysis

Imported animal-based foods are a very important influencing factor for most environmental impacts. In most cases, the more animal-based foods are imported, the less favorable the impact on the environment will be. Imported plant-based foods influence the rating order of the scenarios particularly with regard to freshwater ecotoxicity and water scarcity. While land use and livestock production within Switzerland usually account for a large share of the total impact of the scenarios, their impact changes little between the scenarios. This is because many environmental impacts depend strongly on the area used and change comparatively little as a result of a decrease in farming intensity or crop yields. Domestic crop production influences the scenarios’ ranking only for freshwater ecotoxicity and aquatic eutrophication with N. Domestic livestock production determines the ranking for terrestrial eutrophication, which decreases with lower livestock numbers. Livestock also has a large contribution to other environmental impacts. Its reduction partially counteracts, but cannot offset, the impact of imported products.

For those environmental impacts where the direct payment scenarios differ strongly from the reference scenario, the HP scenario performs least favorably. In this scenario, the proportion of complying farms is high. Thus, it has a comparatively high proportion of farmland that is managed according to the new regulations, the most arable land and the lowest animal numbers. It also achieves higher grain and sugar production and lower potato and animal production than the LP and IP scenarios (cf. Table 5). Accordingly, there are comparatively high import volumes of potatoes and animal-based foods, which have unfavorable impacts. In contrast, the LP scenario, with a larger share of non-complying farms performs most favorably in terms of most environmental impacts. It has the lowest area managed according to the new regulations, the most grassland area and the most animals. It has lower grain production than the other scenarios, but comparatively higher potato and animal production. Furthermore, it has high import volumes of feed grains and grain maize and low import volumes of potatoes and animal-based foods.

In comparison, the yield loss due to the pesticide ban has less impact. It only has a decisive effect where either the intensity or productivity of crop cultivation in Switzerland, or the imported crop products play an important role. This is the case for freshwater ecotoxicity, where high yield losses have an overall unfavorable effect due to the resulting higher quantity of imported plant-based products, and for aquatic eutrophication with N, where low yield losses due to more intensive cultivation entail a higher effect domestically and are thus unfavorable.

3.4. Sensitivity analysis

Minimizing food losses would reduce the environmental impacts of the Swiss basket of agricultural products by 10–44% (Fig. 6). For deforestation, the impact would even decrease by 87%. The available quantities of milk and pork would even be large enough that these products could be exported. The favorable effect of avoiding food losses on the environmental impacts is in a similar range to the unfavorable effect of prohibiting pesticides and reducing livestock in the direct payment scenarios.

4. Discussion

4.1. Influence of policy measures to reduce water pollution

Overall, a pesticide ban and a livestock population that can be fed with the feedstuff produced on the own farm would result in an improvement in most environmental impacts within Switzerland. This improvement is strongest for freshwater ecotoxicity of organic substances. The other target impacts – freshwater ecotoxicity of inorganic substances and aquatic eutrophication with N and P – also decrease, but to a much lesser extent and with the exception of aquatic eutrophication with N in the HP scenario. An improvement also occurs in the non-target environmental impacts. However, this favorable effect is offset by imports. The implementation of the new direct payment regulations results in higher import quantities and thus in an overall unfavorable effect on most environmental impacts of the basket of agricultural product used in Switzerland. Only for freshwater ecotoxicity, the overall effect of the basket of products is favorable.

Of the two direct payment measures suggested, the ban on pesticide use has a pronounced impact only on some of the environmental impacts. Within Switzerland, it is decisive for the strong decrease of freshwater ecotoxicity of organic substances. A slight improvement in

Fig. 6. Sensitivity analysis: Improvement potential of minimizing food losses.

domestic biodiversity can also be attributed to this measure. Regarding the total basket of products, the pesticide ban has a favorable effect on freshwater ecotoxicity of organic substances, but an unfavorable effect on water scarcity. Both impacts are strongly influenced by the imported plant-based foods, because if pesticides are banned in Switzerland, crop yields will decrease and more plant-based foods will have to be imported, e.g. from countries with greater water scarcity.

In contrast, reducing livestock numbers to a number that can be fed with feedstuff produced on the own farm strongly affects most of the environmental impacts. In domestic production, it mainly reduces the effects of ammonia (acidification, terrestrial eutrophication) as well as global warming potential and abiotic resource use. However, when considering the entire basket of products, reduced domestic production of animal-based foods is the main cause of the increase in almost all environmental impacts due to more imports.

4.2. Limitations of assumptions and methods used in this study

Our results show that the **height of yield loss** is important for some environmental impacts of the direct payment scenarios. However, the assumptions on yield losses are subject to large uncertainties. They are mostly based on plot trials and expert estimates (Schmidt et al., 2019). In the direct payment scenarios, we modelled yield losses up to and including harvest. But pesticide treatments also have an impact on losses during storage, processing, transportation, and even consumption (Mathis et al., 2022). It is reasonable to assume that these losses would increase if some pesticides were not used (Mathis et al., 2022), necessitating even more imports with the connected environmental impacts. In addition, with a large-scale conversion to pesticide-free agriculture, the risk of epidemics could probably increase, which would suggest even higher yield losses. To counteract such risks, alternative pesticide-free crop protection measures should increasingly be developed and applied, and more resistant varieties should be cultivated. Appropriate techniques and cropping systems could significantly reduce pest and disease pressure. For these reasons, Schmidt et al. (2019) included three levels of yield losses in the direct payment scenarios. However, the different levels of yield loss in the scenarios do not lead to different conclusions regarding the environmental impact of a pesticide ban compared to the reference situation; the differences only get more or less exacerbated.

Regarding **biodiversity impact**, the method of Chaudhary and Brooks (2018) determines the species loss potential due to land use and land use change in 245 countries worldwide without mapping individual agricultural management measures, such as pesticide applications or soil tillage practices. There is a rough distinction between three intensity levels, but the land use type and the area used are the main drivers of species loss potential. Beyond that, the influence of agricultural management measures such as a ban on pesticides or changes in livestock density on biodiversity cannot be assessed in detail. These effects, however, would be of particular interest in the context of our study.

The **aquatic eutrophication potential** is highly influenced by the amount of fertilizer used on a specific crop. There is currently no data available on the actual amount of mineral and organic fertilizers applied by Swiss farmers in specific crops. Therefore, we assumed that they would not use more fertilizer than is required by the crops. If the amount of organic fertilizer decreases – as it does in the direct payment scenarios due to the restrictions on animal numbers –, it gets replaced by mineral fertilizer, and the overall impact on eutrophication is comparatively small. Assuming that, in reality, more nutrients than needed by the crops are applied in the reference, their amount could decrease in the direct payment scenarios, with a more favorable impact on aquatic eutrophication with N and P.

Our assumption regarding imports is that the **environmental impacts per imported product unit** remain constant in all scenarios. Switzerland accounts only for approximately 0.1% of the world's population and also for 0.1% of grain consumption; grain imports account for 0.3% of world grain trade.[4] The additional import volume required in the direct payment scenarios is marginal compared to global production; the additional land required is less than 1/10,000 of the global agricultural land. Thus, increased imports into Switzerland are not expected to cause any substantial changes in global agricultural production and trade. This approach could not be transferred to larger countries or regions. If, for example, all EU agriculture were to become pesticide-free, the additional imports required would have more drastic effects on global trade and agricultural production, and it should no longer be assumed that production in the countries of origin of the imports would remain the same. Various responses of foreign markets to the increased demand could be expected, especially in the longer term: Production of the additional crop or livestock products could be met by an expansion of cropland on previously unused land. This expansion, in turn, could be at the expense of grassland, fallow land, or natural habitats such as forest or scrubland. In this case, significant negative impacts and thus additional trade-offs from land-use change could be expected in terms of global warming potential and species loss. However, it is also possible that other crops would be displaced, or that other buyers reduce their demand or switch to substitutes. Finally, the production could also be intensified on existing farmland, e.g. through irrigation, or increased pesticide and fertilizer use.

4.3. Levers to counteract trade-offs of extensification measures

Especially in import-dependent countries such as Switzerland, environmental targets have to be evaluated in the context of the whole agri-food sector including imports. Measures on farms can bring a significant, though not sufficient improvement, and regulating consumption patterns and reducing food waste would avoid shifting environmental impacts abroad and thus increasing the overall environmental footprint (Leip et al., 2015).

Consumer behavior was assumed to remain unchanged in all scenarios. Different diets, but also avoiding losses along the food value chain, have been shown to significantly affect the environmental impact of food systems (Nemecek et al., 2016; Poore and Nemecek, 2018; van Dooren and Aiking, 2016; von Ow et al., 2020). Changes in the whole food value chain – up to consumer behavior – have to be targeted together with extensification measures of the agricultural sector to avoid trade-offs.

The effect of **avoiding food losses** was demonstrated in our sensitivity analysis. Priorities along the value chain can be set to translate this into practice: Reducing losses of animal-based foods contributes more to the reduction of environmental impacts than of plant-based foods, and food losses at the end of the value chain have a higher mitigation potential than at the beginning due to the accumulation of environmental impacts (Beretta et al., 2017; Jeswani et al., 2021; Scherhaufer et al., 2018). If food losses cannot be avoided, another option could be recycling (Scherhaufer et al., 2018; Tonini et al., 2018), which, however, would reduce only a small proportion of the total environmental impacts of food losses (Beretta et al., 2017). For products with high calorific value and nutrient content such as cereals, bread or dairy products, feeding to animals is the best recycling option, as it can substitute concentrated feed (Beretta et al., 2017).

Another lever to mitigate the effect of increasing import volumes could be to select **countries of origin** with a lower environmental impact. Usually, in Switzerland, the composition of countries of origin of imports varies only slightly from year to year. However, even slight changes in the composition can be important when there are shifts in the ratio of countries with very different production systems (e.g., Western Europe and South America). Such shifts can affect many environmental impacts. For the EU, 47% of carbon footprint, 85% of water footprint, or 70% of land use for food production could be reduced if import countries

[4] https://www.fao.org/faostat/en/#home, retrieved March 31, 2023.

were chosen according to their impact intensity (de Boer et al., 2019). However, these optimization potentials can only be achieved separately for each environmental impact, not collectively. Also, there is the danger that through a shift to exporting countries with lower environmental impacts, the less favorable countries do not change their behavior but sell their products to other customers, so that in total no improvement would be reached.

Changes of consumer behavior or of import origin are independent of the prevailing direct payment system. They would have to be taken into account both in the reference scenario and in the direct payment scenarios, and the general conclusion on the impact of the new direct payment system would not change. However, avoiding food waste would reduce environmental impacts to about the same extent as the new direct payment system would increase them. So another perspective on the results is that extensification measures in agriculture need to be accompanied by other changes to achieve an overall improvement.

5. Conclusions

The aim of this paper was to demonstrate the environmental impact of policy measures to reduce water pollution caused by agriculture under special consideration of the effects on the whole basket of agricultural products consumed. The direct payment scenarios take into account the two measures "ban on pesticides" and "reduction of livestock numbers to a number that can be fed with feedstuff produced on the own farm". They are characterized by changes in domestic production and import volumes.

We were able to demonstrate that these two measures can reduce water pollution in Switzerland with pesticides and nutrients. In particular, freshwater ecotoxicity of organic substances is significantly reduced. However, aquatic eutrophication, which was supposed to be reduced by restricting livestock numbers, improves by only a few percent. Other environmental impacts, such as biodiversity, global warming, abiotic resource use, or terrestrial acidification, also decrease slightly within Switzerland.

In contrast, the environmental impacts abroad increase due to rising imports if the suggested measures are implemented in Switzerland. In the case of freshwater ecotoxicity, the burden caused by the basket of agricultural products used in Switzerland remains roughly equal to the status quo. The sharp decrease in the domestic impact is offset, but not exceeded, by an increase of impacts in the countries of origin of the imports. The result is similar for terrestrial eutrophication and abiotic resource use. Regarding the other environmental impacts, the reduction in domestic impacts is clearly outweighed by environmental impacts abroad, so that the entire basket of products performs less favorably in the direct payment scenarios than in the reference scenario. This is particularly pronounced for water scarcity and deforestation, where Swiss production has a systematic advantage over other countries, so that any increase in import volumes results in a significantly less favorable assessment. Furthermore, yield losses in Switzerland lead to higher land requirements abroad for the production of imported goods, with the corresponding environmental impacts.

Overall, the improvement of water quality in Switzerland has to be bought with partly considerable trade-offs in the countries of origin of the imports. Different assumptions on the amount of yield losses, producer prices and the redistribution of direct payments – as reflected in our scenarios – do not lead to fundamentally different conclusions. Therefore, if measures such as those examined in this paper are to be implemented, other levers must be applied simultaneously, such as changing consumption patterns or reducing food waste.

CRediT authorship contribution statement

Maria Bystricky: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Cédric Furrer:** Writing – review & editing, Writing – original draft, Validation, Data curation. **Christian Ritzel:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Thomas Nemecek:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization. **Gérard Gaillard:** Writing – review & editing, Writing – original draft, Validation, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142819.

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