Full title

Sustainable and healthy diets: Synergies and trade-offs in Switzerland

Short title

Sustainable and healthy diets

Abstract

Food systems have increasingly strong impacts on the environment and they influence our human wellbeing. In Switzerland, food consumption accounts for one third of the environmental impact caused by total final consumption. At the same time, non-communicable diseases have been linked to a number of dietary aspects. In Switzerland, all non-communicable diseases together are responsible for 80% of total public health care costs annually.

Current assessments that link environmental sustainability and human health-oriented diets for Switzerland lack a transparent representation of the dynamic effects caused by large-scale conversions of the food system. In this study, therefore, a system dynamics model is employed to investigate intended and unintended changes on the food system structure and on environmental impacts. Several human health-oriented scenarios are implemented and tested with different production- and consumption-side intervention strategies. Because all scenarios assuming an increase in the consumption of plant-based products also involve higher consumption of dairy products, consequences for bovine meat need to be considered. The biological link between milk and bovine meat production leads to an unintended increase in bovine meat production as milk production increases.

Intervention strategies at the consumption level thus need to be accompanied by intervention strategies at the agricultural production level. Similarly, intervention strategies that aim at improving health outcomes at the production level need to be accompanied by strategies that affect diets and thus consumption preferences. Avoiding instances of policy resistance requires integrated policy design and implementation across agriculture, the environment, and human health. This integration is a challenge for farmers, the food industry and consumers alike.

Keywords

Agricultural production; diets; food systems; health; sustainability; system dynamics.

1 Introduction

Food systems cause major global environmental impacts (Poore & Nemecek, 2018; Millennium Ecosystem Assessment, 2005) and influence our human wellbeing (Hammond & Dubé, 2012). In Switzerland, food consumption accounts for one third of the environmental impact caused by total final consumption (Jungbluth et al., 2011). At the same time, non-communicable diseases such as cancer, coronary heart diseases, type-2 diabetes, as well as overall mortality have been linked with a number of dietary aspects. These dietary aspects encompass overall high food intake and resulting obesity, low fruit and vegetable consumption, chronic alcohol consumption, high intake of trans-fatty acids, processed meat products and salt (Afshin et al., 2019; Abete et al., 2014; Yusuf et al., 2001); Murray et al., 2012; WCRF & AICR, 2007). In the case of Switzerland, all non-communicable diseases together account for 80% of total public health care costs annually (Wieser et al., 2014).

A recent stream of literature analyzes diets and how they link (environmental) sustainability and human health (e.g., Godfray et al., 2018; Garnett, 2014; Meybeck & Gitz, 2017; Springmann et al., 2018; Tilman & Clark, 2014; Willett et al., 2019). Diets that at the same time improve environmental and human health (Tilman & Clark, 2014) require substantial changes in the types of food that are consumed. These changes constitute, on the one hand, fundamentally different framework conditions to food systems. Alternative options for reducing the environmental effects of food systems, on the other hand, will lead to a different set of products available for consumption (e.g., Frehner et al., 2020; Schader et al., 2015). Diets are thus both outcomes and drivers of food systems (Meybeck & Gitz, 2017).

Food systems comprise activities involved in food production, processing and packaging, distribution and retail, as well as consumption. These activities lead to a number of social, environmental and food security outcomes that, in combination with other drivers, determine how food system activities are performed (Ericksen, 2008). Food systems are characterized by dynamic complexity and thus tend towards unintended consequences of and policy resistance to interventions (Kopainsky et al., 2018). In addition, interventions targeting public health, agricultural production and (environmental) sustainability are typically governed by different national ministries and stakeholders, and therefore lack coordination and integration. Against this background, the purpose of this paper is to test the direct and indirect, short- as well as long-term consequences of healthier and more plant-based diets. More specifically, this paper examines how healthy diets support or conflict with environmental sustainability in the Swiss food system.

In the context of the Swiss National Science Research Programme 69 on Healthy Nutrition and Sustainable Food Production, a consortium of several research institutions built an integrated model that combines, harmonizes and extends existing food system models in Switzerland (Stolze et al., 2019). In this paper, we focus on the system dynamics model. To illustrate the multi-dimensional impacts of human health-enhancing strategies, we also include results from other work packages where appropriate. The model represents the main mechanisms driving food production and trade in Switzerland and how these activities react to changes in food demand, and economic as well as political framework conditions. The main purpose is to trace the production and environmental impacts of possible pathways towards diets that improve the environment as well as human health.

2 Materials and methods

The model spans a time horizon from 2000 to 2050, given that 2050 is used by many agri-food system studies assessing global trends and developing strategies for coping with them (cf., Wood et al., 2010). The model is rooted in a food systems approach (van Berkum et al., 2018). It is an agricultural systems model (cf. Jones et al., 2017), that is, an empirically-based model that includes biophysical relationships complemented by economic content. The biophysical model component represents production functions for different food products in physical units. This model component includes land used for different production activities, livestock as well as nutrient flows. The economic model component maps production costs, prices, profitability, demand and socioeconomic framework conditions, which together provide incentives for shifts in the allocation of land to different production categories. The economic objective function is economic returns to the available agricultural land while respecting a set of biophysical and environmental constraints. Contrary to most agricultural systems model, the level of aggregation of the model is not on the farm or field but on the national level of the agricultural sector at large. This level seemed most appropriate to align public health and sustainability perspectives.

The model is a further development of the model described in Kopainsky et al. (2015). That original model served the purpose of exploring synergies and trade-offs between environmental and economic sustainability in the Swiss agri-food system. Further developments for the purpose of this paper focused on the differentiation of food products that are relevant in light of the environmental and human health impacts of diets (for plant products: food cereals, feed crops, sugar crops, root and tuber crops, vegetables, fruits, grapes, oil crops, pulses; and for animal products bovine meat, pork meat, chicken meat, milk, and eggs; cf. Brombach et al., 2017).

Differentiating between these products entailed substantial changes in the representation of land use and animal husbandry with respect to the original model. The additional structure was derived from literature and iteratively validated with experts and modelers from the other work packages in the overall project. Model calibration was based on a wide range of data sources as well as expert input (cf. section 2.2“calibration and validation”).

2.1 Model structure

Error! Reference source not found. provides an overview of the main subsystems and major feedback loops in the model. **Error! Reference source not found.** also lists a number of exogenous variables. These exogenous variables are used to specify different scenarios. The abbreviation “pc” in many variables in the figure refers to the 15 arrayed product categories (pc) (five animal products and ten plant products). More details about the model sectors with their main processes, conceptual foundations, exogenous inputs and interlinkages are provided in Table 1 and in several figures in the results section, and the full model including documentation is available as supplementary material.

The model calculates domestic production (in the 15 product categories) as well as demand for, and prices of, these products. Production, demand and prices result from and drive changes in profitability of the 15 product categories. They are linked through three major balancing feedback loops (B1a and B1b for production adjustment and B2 for demand adjustment). The processes driving production are grounded in structures from related modeling studies (for livestock e.g. Muller et al., 2017, Schader, et al., 2015) and Zimmermann et al., 2017; for plant products e.g. Gerber, 2016 and OECD,); for land use e.g. Peterson et al., 2019).

The main food production feedback loops are the *supply adjustment plant products (B1a)* and the *supply adjustment animal products loop (B1b)*. Both loops are balancing since more land allocation under normal conditions leads to more production (Schilling, 2000) and a higher supply. A higher supply itself has a decreasing effect on the food price causing reduced farm revenue and profitability, which leads to less allocation of land to the corresponding product category (Peterson, et al., 2019; Varian, 2010). The balancing production feedback loops are complemented by a balancing *demand adjustment loop (B2)*. An increase in food demand causes a lower supply demand ratio which has an increasing effect on the food price and as a result food demand will decrease because people can afford less with their budget. Food demand results from the per capita consumption preferences (dietary preferences; SBV, 2015), the total population, the relative purchasing power (held constant in the model) and the actual affordability of dietary preferences represented by the food price per product category.

An important biological feedback loop is the *reinforcing fertilization loop (R2).* Crop residues add organic nutrients to the soil such as Nitrogen, Phosphorus and Potassium (Scheffer & Schachtschabel, 2010; Schilling, 2000). These organic nutrients are mineralized over time. Manure from livestock is an additional source of organic fertilizer and part of the overall nutrient cycle represented in the model. More fertilizer input leads to higher yields, which in turn increases the amount of plant residues that are left on the field.

Production costs such as related to synthetic fertilizer or feed use (indicated by the solid line between “price” and “production costs”) also lead to shifts in land use and production intensity. The reinforcing feedback loop *cost escalation (R1)* hints at the interlinkages between animal and plant products, where, for example, a decrease in the profitability of animal products leads to a decline in the number of livestock and thus of manure from livestock. In order to maintain plant yield, additional mineral fertilizer needs to be purchased, which increases the production costs and further decreases profitability.

In terms of land use, the model differentiates between arable land, temporary meadows as well as permanent meadows and pastures (which together sum up to total agricultural land) as well as land used for non-agricultural purposes. The mobility between the land use categories is restricted and respects topographic and climatic conditions in Switzerland (e.g., BfS, 2015a). Finally, net imports close the gap between demand and domestic production of goods in the product categories (Listorti et al., 2013).

In terms of environmental impact, the model calculates the high-level indicators of greenhouse gas emissions (global warming potential) and global land use. Greenhouse gas emissions and land use were estimated both for domestic production and for imported products, based on the current share of countries of origin for Switzerland, by the SOL model (Muller, et al., 2017; Schader, et al., 2015) and additional reference values from Poore and Nemecek (2018).

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Table 1 provides a detailed overview of the most important processes and indicators in the model. The table describes the main processes represented in each model sector. It also lists the main inputs (that is, variables from other sectors) as well as outputs (that is, variables that are used in other sectors) per sector and the exogenous parameters used in the sector.

<< Table 1 here >>

2.2 Model calibration and validation

The model was calibrated for the historical time period and for a baseline scenario into the future. The supplementary material provides a detailed overview of data sources as well as a description of the partial model calibration procedure for those parameters for which data was lacking (e.g. supply elasticity to demand). The assumptions underlying the baseline scenario correspond to and extrapolate the assumptions formulated in Möhring et al. (2015) for agricultural parameters, Ecoplan (2015) for the case of economic development, BfE (2013) for energy and BAFU (2017) for climate. In terms of demographic development, the baseline scenario uses the projections by the Swiss Federal Office for Statistics (BfS, 2015b), and more specifically, the coefficients of the reference scenario A-00-2015 for the years 2010 to 2050. In the baseline scenario, population in Switzerland grows to 10.18 million people by 2050. For calculating non-agricultural land demand, the baseline scenario multiplies the population with the average land demand per person according to BfS (2015a). Direct payments continue to be disbursed at today’s per hectare levels, assuming the overall economic development allows for this kind of public policy support. Border protection remains at today’s level (Expert input regarding border protection and direct payments) and, in accordance with OECD/FAO projections (OECD & FAO, 2016; EU Commission, 2015), international prices, on average, change only moderately.

Throughout the modelling process, the model was iteratively validated using a range of structural and behavioral tests (cf., Barlas, 1996; Sterman, 2000). Structural validation was conducted by performing iterative extreme condition, logic and boundary tests. Behavioral validity was tested through extreme condition, sensitivity and behavior reproduction tests. Table 2**Error! Reference source not found.** summarizes Theil inequality statistics (Sterman, 1984) for some of the key indicators in the model. Given that for all indicators, the main source of the root mean square percent error (RMSPE) is concentrated in the error because of unequal covariation (U^C) rather than in a systematic error (U^M or U^S), the model seems capable of capturing the long-term trends in the statistical data.

The table reports Theil statistics for 10 out of the 15 product categories. For the remaining five categories, behavior reproduction testing resulted in the identification of inconsistencies in available statistical data. In the case of oil crops, for example, the division of official data for production (SBV, various years) by official data for land use (SBV, various years) deviates massively from official data for yield (SBV, various years); or pork meat production where official data for consumption, imports and exports do not match data for domestic production (SBV, various years). In such cases, we refrained from comparing model output to statistical data. Similarly, livestock units per livestock category (ALN, 2015) do not add up to total livestock unit numbers (SBV, various years). Total livestock unit numbers are important for calculating livestock density (livestock units per hectare of agricultural land) and thus overall compliance with environmental regulations. In the model, we let livestock density restrict further desired increases in livestock, even though the data suggests that this might not always have been the case in the past for chicken meat. Finally, the data underlying the environmental indicators used to track environmental impact (Poore & Nemecek, 2018), in total, differ from the data reported in the environmental monitoring (Jungbluth, et al., 2011). The differences are in absolute values while the relative developments are similar. We therefore do not report on absolute environmental impact across model scenarios but compare relative changes in environmental impact.

Sensitivity analysis identified a number of assumptions about adjustment times in the livestock sectors that affect model behavior critically. While model behavior in the respective simulation runs is indeed quite sensitive to these assumptions, the relative differences between different simulation runs are not.

<< Table 2 here >>

3 Results

In this section, we first describe the main development trajectories in the baseline scenario (section 3.1). We then introduce a series of scenarios that investigate the production and environmental consequences of alternative diets and compare these consequences to baseline conditions. In terms of alternative diets, we begin with a scenario where we assume that the entire Swiss population eats according to official recommendations (the Swiss Food Pyramid; section 3.2). As this scenario leads to excess meat supply, we explore how the meat composition (chicken versus pork and beef) within the same overall meat consumption quantity can be influenced to avoid excess supply. In a second step (section 3.3), we move towards less comprehensive shifts in diets and investigate the impact of supply- and demand-oriented intervention strategies that aim at decreasing sugar consumption and production (section 3.3.1) as well as increasing vegetable consumption and production (section 3.3.2). Table 3 details the changes in parameter values and in model structure that were implemented in order to perform the different scenario runs.

<< Table 3 here >>

3.1 Baseline scenario

As a result of population and economic growth, total available agriculture land will continue to decline between now and 2050 (Figure 2) but total food consumption will increase by almost 20% (**Error! Reference source not found.**; black bar on the far right). At the same time, productivity increases in plant production and animal husbandry are projected to be too low to fully compensate for land loss (Möhring, et al., 2015). As a consequence, domestic production declines for most products (**Error! Reference source not found.**; the horizontal, dashed black line represents 2019 values), and more imports are necessary. Greenhouse gas emissions and land use increase but less than total consumption does. This is mostly due to decreased exports of animal products. This development is in stark contrast to the climate strategy agriculture (BLW, 2011), which foresees as 60% reduction in greenhouse gas emissions caused by food production and consumption by 2050.

<< Figure 2 here >>

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3.2 Nutrition according to official recommendations

Consumption of high levels of animal products has negative implications both in terms of human health and environmental sustainability (Eker et al., 2019; Mathijs, 2015 ; Vranken et al., 2014; Westhoek et al., 2014; Willett, et al., 2019). In a first set of scenarios, we therefore investigate the implications that a transition towards healthy diets would have. For the definition of healthy diets, we rely on the guidelines formulated by the Swiss Society for Nutrition.

3.2.1 Swiss Food Pyramid

We start with a scenario where we assume that the entire Swiss population complies with the recommendations of the Swiss Society for nutrition by 2050 (Swiss Food

Pyramid, SFP). This means an increase in the per capita consumption of vegetables and plant-based oils as well as nuts/seeds (summarized in the category “oil-bearing crops”), milk/milk products comparable to baseline levels and a reduction of meat consumption.

Figure 4 compares per capita consumption in the SFP scenario to per capita consumption in the baseline scenario. The second bar in the figure represents the relative change in production in the year 2050, that is, the difference in production between the SFP scenario and the baseline scenario in the year 2050. The Figure excludes pulses as SFP consumption is almost 7 times higher than baseline consumption (1.8 for production) and thus makes the results for the other food categories hard to read.

<< Figure 4 here >>

Figure 4 shows that the domestic production of most products follows the changes in consumption, e.g. sugar crops, roots and tubers, fruits, pork. Grape production does not change as much as grape consumption due to the long time delays involved in changes in land conversion to and from vineyards. Vegetable production, as in the baseline scenario (**Error! Reference source not found.**), reacts more to changes in consumption than other plant products. The increase in domestic production allows for a decrease in imports with the corresponding, albeit small, beneficial environmental impacts. The poultry sector with chicken meat as well as egg production reacts strongly to reductions in consumption and profitability.

The impact of consumption changes on bovine meat production seems counterintuitive. Consumption is reduced to around 50% of the reference value. Domestic production, however, remains at much higher levels. The explanation of this behavior lies in the tight biological linkage between milk and bovine meat production.

Error! Reference source not found. describes the herd structures for bovine cattle. The Figure does not show the herd structure for suckler cattle that produces only meat. The number of suckler cows in Switzerland is around 15% that of dairy cows (SBV: Statistische Erhebungen und Schätzungen). Every year, dairy cows breed a certain number of calves (“breeding rate milk cows”). Dairy cows need to bear one calve per year to maintain milk productivity. Once these calves are born, they either grow up into new dairy cows (“allocation to milk line”) or they enter the stock of other bovine cattle (“allocation to meat line”). Only a limited number of calves can grow into dairy cows. First, they need to be female. Second, it is only around every fifth year that a calve is needed to replace a dairy cow. All the remaining calves enter the “Feeder Cattle” stock and they stay in the stock until they are slaughtered.

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Error! Reference source not found. shows that there is a tight physical link between milk production and bovine meat production. Currently, this system is approximately in balance. But this balance is lost if the demand for bovine meat declines considerably and is, at least partially, substituted by demand for dairy products as in the case of the Swiss Food Pyramid scenario. In the short run, the reduced demand for bovine meat will drive bovine meat price down and thus lower the profitability of bovine meat production. However, because consumers start replacing some of the proteins that they previously consumed from meat by dairy products, the demand for dairy products will increase. More calves now enter the dairy cow line. Once the number of dairy cows approximates the desired number of dairy cows, the counterintuitive behavior of bovine meat production emerges. All cows in the dairy cow stock produce one calve per year to maintain their milk productivity. As no more calves are needed to increase the dairy cow stock, only one out of five calves is required to replace the existing dairy cows and to keep the number of dairy cows stable. The remaining four calves enter the feeder cattle stock and even if they are not fattened for a long time, they still generate meat – more meat than before the shift in diets. In total, this excess of bovine meat amounts to more than 50% of the total pork and chicken meat demand in the Swiss Food Pyramid Scenario in 2050. The environmental and human health impacts of this excess meat supply are unclear as long as it remains unclear what happens to the excess meat.

3.2.2 Modifications within the Swiss Food Pyramid

As a reaction to the inconsistencies in the Swiss Food Pyramid scenario, we introduce two alternative scenarios that assume the same overall per capita meat consumption in 2050 as the SFP2050 scenario. The difference to the SFP2050 scenario lies in a modified composition of meat consumption (chicken versus pork and beef). A first modified SFP scenario (SFP2050 mostly bovine) changes the relative shares of bovine, pork and chicken meat in total per capita meat consumption and thus assumes a voluntary shift in diets, an important driver of demand. Specifically, it increases the share of bovine meat in total per capita meat consumption so that no excess bovine meat remains from the dairy stock. Due to health considerations, that is, to avoid even higher consumption of red rather than white meat, increases in the share of bovine meat (0.009 ton/person/year rather than 0.0054 ton/person/year) come at the expense of pork meat consumption (0.0019 ton/person/year rather than 0.0055 ton/person/year) rather than at the expense of chicken meat consumption.

A second modified SFP scenario (SFP2050 penalty pork chicken) aims at reducing excess meat by intervening on the production level. Desired per capita consumption of the different animal products is the same as in the SFP2050 scenario. This scenario introduces stronger regulations for the more land-independent animal production in the poultry and pork sector. Higher land requirements in the poultry and pork sector translate into higher production costs which should reduce the production in these two sectors.

Figure 6 compares animal production (meat production, milk and egg production) to baseline 2050 values for all SFP scenarios. A comparison of the two alternative

SFP2050 scenario reveals that regulating chicken and pork production on the production side (SFP2050 penalty pork chicken) seems to be as effective in reducing chicken and especially pork production as implementing a fundamentally different meat composition in the diet (SFP2050 mostly bovine), that is, as an intervention that changes diets.

<< Figure 6 here >>

3.2.3 Environmental impacts of nutrition according to official recommendations

Agriculture land in Switzerland (cf. Figure 2) comprises two main categories: permanent meadows and pastures on the one hand and arable land on the other hand. Arable land is either used for crop production or it can be used as temporary meadows for bovine cattle. Figure 7 shows changes in temporary meadows relative to baseline 2050 values for all SFP scenarios. None of the SFP scenarios leads to major deviations from baseline 2050 values. As animal production is lower in the SFP scenario, more potentially arable land is used for plant production and temporary meadows decrease a little. As production changes are mostly visible in the pork and poultry sector that do not require meadows or pasture land, and much less in the dairy and bovine meat sectors, the changes in temporary meadows are minor. This result changes with the introduction of the two modifications to the SFP2050 scenario. If meat consumption is concentrated around bovine meat (SFP2050 mostly bovine), the cattle herd size increases marginally and with it the use of temporary meadows. The same is true if the production of pork and chicken is regulated more strongly (SFP2050 penalty pork chicken).

<< Figure 7 here >>

Error! Reference source not found. provides an overview of the total greenhouse gas emissions across all SFP scenarios. The figure compares each SFP scenario value in 2050 with the amount of greenhouse gas emissions under baseline conditions in 2050. Whereas land use in Switzerland does not seem to change much as a result of the three SFP scenarios (Figure 7), the total environmental impact measured in either total greenhouse gas emissions or total land use caused by domestic production and imports declines considerably in the three SFP scenarios compared to baseline conditions. The decrease in consumption of animal products reduces the environmental impact of food consumption and this effect is reinforced by the corresponding decline in imports of animal products (the environmental impact of which is higher for imports than for domestic products). The reductions are, however, not sufficient to reach the climate strategy goal of reducing greenhouse gas emissions in 2050 by 60%.

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3.3 Individual nutrition aspects: sugar and vegetables

Transitioning an entire population to the recommendations formalized in the Swiss Food Pyramid is very ambitious. In a second set of scenarios, we investigate alternatives to voluntary shifts in diets and test the effectiveness of interventions that aim at influencing production and consumption of two plant products that are key from a health perspective (e.g., Brombach, et al., 2017). A first set of scenarios investigates ways of reducing sugar consumption, and a second set of scenarios investigates ways of increasing vegetable consumption. Both sets of scenarios assume reference consumption patterns, i.e., consumption preferences as in the baseline scenario. Shifts in demand will thus be a consequence of changes in price rather than of changes in diets.

3.3.1 How to decrease sugar consumption and production

Error! Reference source not found. compares the effect of interventions that aim at decreasing sugar consumption and production. The first sugar scenario (reference consumption (refcons) sugar tax; reference consumption with sugar tax) introduces a sugar tax that increases the consumer price of sugar. The tax rate is set at 10%, a value used e.g. in Mexico and the United Kingdom. The second sugar scenario (refcons sugar penalty; reference consumption with a penalty on sugar production) eliminates the special support for sugar crop producers. Sugar is considered a strategic crop for food self-sufficiency and the production of it thus receives extra direct payments (Implement Consulting Group, 2019). The final sugar scenario (refcons sugar penalty & tax) combines the first two scenarios and thus intervenes simultaneously on the demand and supply side.

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Error! Reference source not found. indicates that all three scenarios only lead to a temporary decline, both in demand and supply. In the sugar tax scenario, demand recovers after a couple of years as consumers get used to the increased sugar price, with the increased price acting as the new reference price (e.g. Putler, 1992). Supply also recovers as a consequence of the recovery in demand. As long as consumption preferences remain unchanged, the effect of the sugar tax does not last. A more lasting and also substantial decrease in consumption and consequently also in production is only achieved if the sugar tax increases by 10% not once but every year (not shown in **Error! Reference source not found.**). Such an extreme expression of a sugar tax would reduce sugar consumption and production by approximately 25%. At the same time, it is questionable whether the assumption of constant demand elasticities to price is valid under these conditions. This is clearly a limitation in the current version of the model.

Intervening on the production side (refcons sugar penalty) also leads to an only slight decline in sugar production. Direct payments are less important for per hectare revenue from sugar production than they are for other crops. Their removal thus has a limited effect only. With consumption preferences remaining unchanged, the reduced domestic sugar production is replaced by a corresponding increase in imports. The increase in imports is also visible in a slight increase in total environmental impact (not shown in **Error! Reference source not found.**).

The combination of interventions on the demand as well as supply side (refcons sugar penalty & tax) increases the effectiveness of the individual interventions somewhat. The effect, however, is still quite limited. This is in contrast to the SFP2050 scenario that introduced stronger regulations in the chicken and pork sector that increased the production costs in the two sectors (SFP2050 penalty pork chicken) and led to a considerable reduction in production. In the SFP2050 penalty pork chicken scenario, the increase in production costs was accompanied by a steady decrease in desired pork and chicken meat consumption between the years 2020 and 2050. Such a dietary shift is not present in the three sugar scenarios tested in this section, which limits the effectiveness of interventions to the short run.

3.3.2 How to increase vegetables consumption and production

Error! Reference source not found. shows the results for three scenarios for vegetable consumption and production that are conceptually similar to the three sugar scenarios. We start from the consumption preferences used in the baseline scenario (refcons) and test the effectiveness of interventions targeting either the demand or the supply side. The first vegetable scenario (refcons vegetables negtax; reference consumption with subsidized consumer price) reduces the vegetable consumer price by 10%. The second vegetable scenario (refcons vegetable subsidies production; reference consumption with increased production subsidies) doubles the direct payments per hectare of vegetable production. The final vegetable scenario (refcons vegetable subsidies production & consumption) combines the first two scenarios and thus intervenes on the demand and supply side simultaneously.

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Similar to the situation with a sugar tax, consumers get used to the decreased vegetable price and the effect on both consumption and production is only transitory (refcons vegetables negtax). In addition, the Aeppli (2014) study suggests very price-inelastic demand for vegetables. This makes it even more difficult for interventions aimed at making vegetables more affordable to be effective. A more lasting effect on consumption and production could only be established in a scenario with a 50%

reduction of the vegetable consumer price. Under such extreme conditions, however, it seems unreasonable to assume constant demand elasticities of price. As in the sugar scenarios, this indicates a limitation to the current model structure.

The second vegetable scenario that makes vegetable production more profitable by increasing the per hectare direct payments for vegetable production (refcons vegetables subsidies production) leads to minor increases in vegetable production only. Also in the case of vegetable production, direct payments play a relatively minor role in total per hectare revenue. Thus, increases in the volume of direct payments are limited in terms of effectiveness.

Also in the third vegetable scenario (refcons vegetable subsidies production & consumption), where demand- and supply-side interventions are combined, subsidies for vegetable prices show almost no effect. The results are thus the same as in the supply-side only scenario. Overall, the results for the vegetable scenarios are similar to those of the sugar scenarios in that the effect of interventions both on the demand and supply side for vegetables are temporary only as long as dietary preferences remain unchanged.

Differences in environmental impact between baseline development and the sugar and vegetable scenarios as well as within these alternative scenarios are negligible and thus not further reported here.

4 Discussion and conclusions

The purpose of this paper was to examine how healthy diets support or conflict with environmental sustainability in the Swiss food system. For this purpose, a system dynamics model was built and analyzed for several health-oriented scenarios.

An increasing number of studies address the environmental and human health impacts of diets (e.g. Willett, et al., 2019) at different scales (e.g. van Dooren et al., 2014) in a variety of contexts (e.g von Ow et al., 2019), and using a multitude of approaches (e.g. Frehner et al. 2020). This study combines national dietary guidelines of Switzerland with a modelling approach that represents the structure and time-dependent processes of the Swiss agricultural sector. By calibrating the model to Switzerland, local circumstances, such as eating habits that may influence dietary guidelines, as well as geographical contexts that influence agricultural production, can be captured in great detail.

In the recent EAT-Lancet study (Willett et al. 2019), an encompassing review of healthy diets resulted in a global healthy reference diet, with ranges per product categories allowing for adapting the reference diet to local circumstances. On the production side, Willett et al. (2019) defined a safe operating space for food systems, which would allow to keep the contribution of food systems in the safe operating space of the planetary boundaries' concept (Rockström et al., 2009). These two quantifications allow for general guidelines for pathways towards more sustainable food systems. Approaches such as the one at hand provide important results for local contexts, which can serve as a complement to global assessments such as Willett et al. (2019).

Thus, the global healthy diet from sustainable food systems outlined in the EAT-Lancet study (Willett, et al., 2019) needs translations to national and regional contexts. The special role of dairy cows and bovine cattle in Switzerland calls for trade-offs between healthy diets and environmentally sustainable production that are not easy to resolve, and these trade-offs are exacerbated by further trade-offs within environmental sustainability. This makes the translation of global diets to a specific national context challenging and increases the importance of substantiating such translation with sound, model-based evidence about the multi-dimensional consequences of well-intentioned policies.

Although the present study provides new insights on possible transformation pathways towards more sustainable food systems in Switzerland, several limitations should be mentioned. First, consumer behavior is not modeled in detail. The model does not operationalize the endogenous nature in which culture, lifestyles and attitudes interact to change diets over time. Dietary guidelines, for example, serve as orientation for consumer behavior but they are generally not implemented as such. A variety of additional economic, social, cultural and psychological processes determine what people eat. Similarly, intervention strategies such as a sugar tax provide financial incentives to steer consumer behavior in the intended direction. However, to what extent financial incentives ultimately result in the intended consumption changes depends on a variety of additional processes that were excluded from the model.

Second, the long time horizon and high level of aggregation of the model imply that model analysis focuses on intervention types (e.g. sugar taxes), rather than on individual policy and management actions (e.g. differentiation of tax rate according to food product). The simulation model provides an evidence base for strategic decisions (i.e., relative calibration and temporal sequencing of interventions). It can, however, not be used for an absolute calibration and timing of individual policy and management actions and for formulating operational implementation plans.

Swiss agricultural policy is already supported by a variety of agricultural sector models (e.g., Listorti, et al., 2013; Möhring et al., 2016; von Ow, et al., 2019) that provide decision support at a much higher level of detail than the system dynamics model does. The specific contribution of the system dynamics model, however, is that it ensures operational consistency and coherence between agricultural production, trade, the environment and food consumption.

This became particularly obvious in the case of intervention strategies that aim at changing consumption patterns towards more plant-based diets but that result in unexpected increases in meat production. All the scenarios assuming an increase in the consumption of plant-based products, for example, involve higher consumption of dairy products. A simple herd structure for dairy cows reveals that an increase in the production of milk is biologically linked to an increase in meat production, which contradicts the low bovine meat recommendations.

This contradiction between intended consequences of dietary recommendations and system reaction is not unique to Switzerland. The literature relating to sustainable diets shows additional examples of proposed diets that only take health outcomes into consideration without accounting for the agronomic realities how the foods that promote health outcomes are produced (e.g. Tilman & Clark, 2014, and to some extent also Willett, et al., 2019).

The link between milk and bovine meat production is a biological one that cannot be weakened by market mechanisms, policy interventions or changes in farmers' decision making. Producing the recommended amount of milk in the SFP scenario while at the same time avoiding over-production of meat products can be realized in different ways, all of which pose implementation challenges:

- Export of the excess bovine meat. The main implementation challenge is that Swiss production is not competitive on international meat markets, so that exports would have to be supported financially.
- Replacement of at least parts of milk and dairy products by calcium-enriched soy milk. The main implementation challenge here is most likely consumer acceptance.
- Substantial reduction of pork and chicken meat production to accommodate the production of bovine meat without overshooting desired consumption levels. Substantial reductions in the production of pork and chicken meat most likely faces implementation challenges such as consumer acceptance and potential health implications with a shift towards more red and less white meat.

Intervention strategies aiming at influencing diets thus need to be accompanied by intervention strategies at the agricultural production level. Similarly, intervention strategies that aim at influencing production need to be accompanied by strategies at the level of diets. The sugar- and vegetable-oriented scenario runs indicated that, in the absence of changes in diets, interventions aiming at changing production and consumption are effective only for a short period of time. Avoiding instances of policy resistance thus requires integrated policy design and implementation across sectors, such as agriculture, the environment, and human health (cf. also Muller & Bautze, 2017). This integration is a challenge for farmers, food industry and consumers alike. The necessary changes in diets, especially towards increased health, are so substantial that no single policy measure will be sufficient. Instead, they require a combination of instruments ranging from voluntary measures to food pricing (e.g., Afshin et al., 2017) and food environments (e.g., Sisnowski et al., 2017).

Aligning agricultural production and consumption also implies that optimal diets are not static but change over time. This has not been considered in the existing literature yet (e.g., Baur, 2013). The amount of available agricultural land in Switzerland will determine the amount of animal products that can be produced domestically. The differences in environmental impacts between domestically produced animal products and imported animal products are substantial and clearly favor domestic production (Poore & Nemecek, 2018). Agricultural land is, however, not constant, but changes as a result of population and economic development.

Given its specific topographic and climatic characteristics, Switzerland is able to produce a higher amount of pasture-based livestock products than other countries. This favors milk and bovine meat production over alternative animal products as the large amounts of pasture land in the mountains cannot be used for plant production. Bovine meat and milk production have a substantially higher global warming potential than alternative animal products (Poore & Nemecek, 2018). On the other hand, pasture-fed animals do not compete with the production of food for human consumption, something that the feed needed in the pork and poultry sector does. Additionally, grasslands provide a range of ecosystem services beyond forage provision such as climate regulation, pollination, biodiversity conservation and outdoor recreation. In general, extensive management, especially in pastures, favors all ecosystem service provision with the exception of forage production (Le Clec'h et al., 2019). This is particularly relevant in mountain areas with no arable land suitable for crop production. The trade-offs within environmental sustainability are exacerbated by social considerations such as the contribution of agriculture to decentralized settlement and the maintenance of the productive capacity (cf. article 104 in the Swiss Constitution) as well as a high willingness to pay for cultural ecosystem services from extensively used grasslands (Huber & Finger, 2020).

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Tables

Table 1: Most important processes represented in the model.

***Model sector* and conceptual foundation**	**Most important processes**	**Most important inputs from other model sectors**	**Most important exogenous inputs**	**Important outputs**
Livestock – cattle Conceptual foundation: Muller, et al., 2017; Schader, et al., 2015	Herd structure cattle where calves are allocated either to the milk line or to the feeder cattle stock Separate herd structure for suckler cattle Adjustment of livestock numbers and allocation to the different lines according to changes in relative profitability	Change in profitability milk Change in profitability bovine meat Change in demand milk Change in demand bovine meat Limit to livestock expansion	Average lifetime milk cows; average lifetime suckler cows Supply elasticity of milk and bovine meat to profitability Meat yield per livestock category Cattle livestock adjustment time; suckler cattle livestock adjustment time	Milk production Bovine meat production Grass demand dairy cows Grass demand other bovine cattle Feed demand dairy cows Feed demand other bovine cattle
Livestock – pigs Conceptual foundation: Muller, et al., 2017; Schader, et al., 2015	Herd structure pigs Adjustment of breeding stock according to changes in relative profitability	Change in profitability pork production Change in demand pork meat Feed availability Limit to livestock expansion	Average lifetime breeding pigs; average fattening time mature pigs Supply elasticity of pork meat to profitability Supply elasticity of pork meat to demand Meat yield per mature pig and per breeding pig Adjustment time breeding pigs stock	Pork meat production Feed demand pigs
Livestock – poultry – eggs production Conceptual foundation: Muller, et al., 2017; Schader, et al., 2015	Herd structure laying hens Adjustment of laying hen stock according to changes in relative profitability	Change in profitability eggs production Change in demand eggs Feed availability Limit to livestock expansion	Average lifetime laying hens Supply elasticity of eggs production meat to profitability Supply elasticity of eggs production to demand Eggs production per hen per year Meat per slaughtered hen	Eggs production Feed demand laying hens

			Adjustment time laying and breeding hens	
Livestock – poultry – chicken meat production Conceptual foundation: Muller, et al., 2017; Schader, et al., 2015	Herd structure broiler poultry Adjustment of broiler poultry stock according to changes in relative profitability	Change in profitability chicken meat production Change in demand chicken meat Feed availability Limit to livestock expansion	Average fattening time broiler poultry Supply elasticity of chicken meat to profitability Supply elasticity of chicken meat to demand Meat yield per broiler poultry Adjustment time broiler poultry stock	Chicken meat production Feed demand broiler poultry
Total livestock and land balance Coeffcients from from ALN, 2015	Conversion of all livestock to livestock units Comparison of current livestock units to maximum allowable livestock units per ha and limit to expansion of livestock	Livestock numbers from other sectors Total agriculture land	Conversion factors animals – livestock units	Limit to livestock expansion
Animal nutrition Coefficients from Zimmermann, et al., 2017	Total fodder demand (fodder: grass-based) Total feed demand (feed: animal feed from forage crops; concentrate feed)	Livestock numbers for the different livestock categories	Fodder demand for the different livestock categories Feed demand for the different livestock categories	Fodder (grass) demand Feed demand
Desired food consumption Coefficients from SBV, 2015	Calculation of dietary patterns		Population Relative purchasing power	Target total milk products for human consumption Target total eggs consumption Target total meat consumption (bovine meat, pork, chicken) Target total plant products (10 categories)
Yield and production Conceptual foundation: Gerber, 2016; Scheffer & Schachtschabel, 2010; Schilling, 2000	Calculation of yield plant products resulting from changes in water and nutrient availability	Total per ha nitrogen input arable land and temporary meadows	Nitrogen uptake efficiency Genetic yield potential plant products Impact of climate change on water availability	Yield plant products (10 categories) Production plant products (10 categories)

Nutrient dynamics Conceptual foundation: OECD, ; Scheffer & Schachtschabel, 2010; Schilling, 2000	Nitrogen balance; ammonium emissions Affordability of synthetic fertilizer	Animals from different livestock categories Land in different land use categories	Per unit nitrogen input (from atmospheric deposition; manure from different livestock categories; pulses and green manure) Per unit ammonium emission factors (different livestock categories) Fertilizer unit costs Price perception adjustment time Profitability perception adjustment time	Synthetic fertilizer use
Land use Conceptual foundation: Peterson, et al., 2019	Land use changes resulting from - population growth/non-agricultural land use - shifts in profitability that lead to shifts within agricultural land use categories (arable land, temporary meadows, permanent meadows and pastures) - pasture abandonment	Change in profitability plant products; change in profitability milk products; change in profitability meat Change in demand plant products; change in demand milk products; change in demand meat Yield plant products	Population Elasticity of plant production to plant demand; elasticity of plant production to profitability Yield temporary meadows; Yield permanent meadows and pastures Non-agricultural land demand per person Fractional afforestation rate	Land shares in different land use categories Grass-based fodder production
Prices and imports – plant products Conceptual basis: Varian, 2010	Calculation of price of plant products resulting from demand supply ratio; international prices; and production costs. Calculation of demand for plant products resulting from changes in price but also from changes in price of substitutes. Calculation of imports of plant products and resulting demand supply ratio of plant products	Target total plant products Production plant products Relative prices meat Relative price raw milk Relative price eggs Relative production costs plant products	Demand elasticity of price Cross price elasticities Import availability Elasticity of price to production costs; elasticity of price to international prices Price perception adjustment time	Price plant products Demand plant products Change in demand plant products Net imports plant products
Prices and imports – milk products and eggs Conceptual basis: Varian, 2010	Calculation of price of milk products and eggs resulting from demand supply ratio; international prices; and production costs. Calculation of demand for milk products and eggs resulting from changes in price but also from changes in price of substitutes.	Target total milk products and eggs for human consumption (domestic and export) Milk production; eggs production Relative prices meat	Demand elasticity of price Cross price elasticities Import availability Elasticity of price to production costs; elasticity of price to international prices	Price raw milk; price eggs Demand milk products; demand eggs Change in demand milk products; change in demand eggs

	Calculation of imports of milk products and resulting demand supply ratio of milk products	Relative prices plant products Relative production costs milk products; relative production costs eggs	Price perception adjustment time	Net imports milk products Net imports eggs
Prices and imports – meat Conceptual basis: Varian, 2010	Calculation of price of meat resulting from demand supply ratio; international prices; and production costs. Calculation of demand for meat resulting from changes in price but also from changes in price of substitutes. Calculation of imports of meat and resulting demand supply ratio of meat	Target total meat consumption Meat production Relative prices plant products Relative price raw milk Relative price eggs Relative production costs meat	Demand elasticity of price Cross price elasticities Import availability Elasticity of price to production costs; elasticity of price to international prices Price perception adjustment time	Price meat Demand meat Change in demand meat Net imports meat
Profitability – plant products Conceptual foundation: Peterson, et al., 2019	Calculation of changes in the relative profitability of plant products	Yield plant products Price plant products Synthetic fertilizer use	Profitability perception adjustment time Other per ha production costs Per ha direct payments	Change in profitability plant products Relative production costs plant products
Profitability – milk products and eggs Conceptual foundation: Peterson, et al., 2019	Calculation of changes in the relative profitability of milk products and eggs	Milk production per livestock unit per year; eggs production per livestock unit per year Price raw milk; price eggs Price plant products (feed)	Profitability perception adjustment time Other per ha production costs Per ha direct payments	Change in profitability milk products; change in profitability eggs Relative production costs milk products; relative production costs eggs
Profitability – meat Conceptual foundation: Peterson, et al., 2019	Calculation of changes in the relative profitability of plant products	Meat production per livestock unit Price meat Price plant products (feed) Price raw milk	Profitability perception adjustment time Other per ha production costs Per ha direct payments	Change in profitability meat Relative production costs meat
Environmental impact Coefficients from Poore & Nemecek, 2018	Calculation of global warming potential (greenhouse gas emissions) and land use	Production per product Imports per product	Emission coefficients Land use coefficients	Greenhouse gas emissions per product Land use per product

Table 2: Theil inequality statistics for key model indicators (baseline scenario vs. historical data)

	Indicator	**RMSPE**	**$U^{(M)}$**	**$U^{(S)}$**	**$U^{(C)}$**	**R^2**
Plant production	food cereals	0.04	0.00	0.00	1.00	0.99
	feed cereals	0.35	0.07	0.00	0.92	0.63
	roots and tubers	0.07	0.00	0.02	0.98	0.90
	vegetables	0.07	0.29	0.45	0.26	0.99
	fruits	0.11	0.01	0.05	0.94	0.94
Animal production	milk production	0.01	0.01	0.01	0.98	0.99
	bovine meat production	0.04	0.01	0.00	0.99	0.99
	chicken meat	0.08	0.08	0.21	0.71	0.97
	eggs production	0.04	0.02	0.00	0.98	0.87
	pork meat	0.05	0.00	0.04	0.96	0.89
Land use	Temporary meadows	0.02	0.00	0.00	1.00	0.99

RMSPE: root mean square percentage error

U(M): error because of bias; U(S): error because of unequal variation; U(C): error because of unequal covariation

Table 3: Implementation of scenarios in the model

Simulation run name	**Rationale**	**Settings**
Baseline		
Ref consumption sugar tax	Reference consumption Evaluation of impact of sugar tax Intervention on the demand side	Sugar tax 10% as e.g. in Mexico and the UK Prices and imports plant products → relative taxes plant products[sugar crops] 1.1 as of 2020
Ref consumption no sugar subsidies	Reference consumption Evaluation of impact of removal of direct payments for sugar production Intervention on the supply side	Profitability plant products → Direct payments per ha[sugar crops] 0 as of 2020
Ref consumption sugar tax no subsidies	Reference consumption Combined intervention on demand as well as supply side	(combination of settings from the two individual sugar simulations)
Ref consumption vegetable subsidies consumption	Reference consumption Evaluation of impact of reduced consumer price vegetables (negative tax) Intervention on the demand side	Prices and imports plant products → relative taxes plant products[vegetables] 0.9 as of 2020

Simulation run name	**Rationale**	**Settings**
Ref consumption vegetable subsidies production	Reference consumption Evaluation of impact of higher direct payments for vegetable production Intervention on the supply side	Profitability plant products → Direct payments per ha[vegetable] 2600 as of 2020
Ref consumption vegetable subsidies consumption and production	Reference consumption Combined intervention on demand as well as supply side	(combination of settings from the two individual vegetable simulations)
SFP2050	Population eats according to the guidelines by the Swiss Society for Nutrition	Desired food consumption → per capita consumption SGE2050 Prices and imports → demand elasticities to price 0 to enforce changes in dietary preferences
SFP2050 mostly bovine	Population eats according to the guidelines by the Swiss Society for Nutrition. To avoid meat waste, meat composition is adjusted such that there is no excess bovine meat from dairy stock. Increases in bovine meat consumption are at the expense of pork meat consumption due to health considerations. Intervention on the demand side	Desired food consumption → per capita consumption SGE2050 alternative Bovine meat: 0.009 ton/person/year rather than 0.0054 ton/person/year (SGE2050 value) Pork meat: 0.0019 ton/person/year rather than 0.0055 ton/person/year Prices and imports → demand elasticities to price 0 to enforce changes in dietary preferences
SFP2050 penalty pork and chicken	Population eats according to the guidelines by the Swiss Society for Nutrition. To avoid meat waste, this intervention introduces a penalty on the more land-independent animal production in the poultry and pork sector.	Desired food consumption → per capita consumption SGE2050 Prices and imports → demand elasticities to price 0 to enforce changes in dietary preferences Profitability → per GVE production costs with penalties (for poultry (meat and eggs) and pork). Other per GVE production costs are doubled in 2020 with respect to SGE2050 value (which is identical to baseline value)

SFP: Swiss Food Pyramid

Refcons: reference consumption (same per capita consumption as in the baseline scenario)

Figure Captions

Figure 1: Model overview. “pc” stands for product category and denotes the 15 plant and animal products represented in the model. Sub-systems (production, consumption, market and environment) are indicated by dark grey boxes. The light grey box, together with the thick, dark grey arrows, denote the exogenous forces impacting on the various sub-systems. The main feedback loops are labeled as either reinforcing (R) or balancing (B).

Figure 2: Total available agricultural land until 2050

Figure 3: Baseline scenario: Production volumes (light grey bars), total food consumption (black bar), and environmental impacts (dark grey bars) 2050 relative to 2019 values.

Figure 4: Changes in consumption and production in the Swiss Food Pyramid scenario. The first bar compares consumption (SFP2050 vs. baseline 2050). The second bar compares production (SFP2050 vs. baseline 2050). The Figure excludes pulses as SFP consumption is almost 7 times higher than baseline consumption (1.8 for production)

Figure 5: Simplified stock-and-flow structure describing the Interlinkages between milk and bovine meat production

Figure 6: Animal production in all SFP scenarios

Figure 7: Temporary meadows 2050 in all SFP scenarios compared to baseline 2050 values. Temporary meadows are a subset of arable land that could also be used for crop production. The use of temporary meadows is thus an indicator of the degree of competition between the production of food for human consumption and fodder for animal consumption.

Figure 8: Environmental impacts in all SFP scenarios

Figure 9: Supply and demand side interventions to decrease sugar consumption and production (refcons: reference consumption, i.e., consumption preferences as in the baseline scenario). Differences in simulated outcomes of the supply and demand side interventions are so small that they are difficult to spot in the figure.

Figure 10: Supply and demand side interventions to increase vegetable consumption and production (refcons: reference consumption, i.e., consumption preferences as in the baseline scenario). Differences in simulated outcomes of the interventions are so small that they are difficult to spot in the figure.